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The effect of using internal curing on chloride penetration of self-compacting concrete

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Abstract. In recent years, the use of internal curing has received attention as a solution to reduce problems caused by shrinkage in self-compacting concrete (SCC). However, the use of internal curing agents increases the internal porosity of concrete, which can lead to durability issues in some environmental conditions. This study examines the effects of internal curing on the properties and durability of SCC incorporating recycled Lightweight aggregate (RLWA) and superabsorbent polymers (SAP) as internal curing agents. Mixtures containing 15 % and 30 % RLWA or 0.1 % SAP were evaluated under both saturated and 50 % relative humidity conditions. The tests included compressive strength and rapid chloride migration. The results indicated that under 50 % relative humidity, internal curing agents enhanced compressive strength by up to 6.8 % at 28 days and reduced the chloride ion diffusion coefficient by up to 18.4 % at 360 days. Using the chloride diffusion coefficients obtained, along with the Crank–Nielsen method, the phenomenon of chloride ion penetration in concrete was modeled, and the initiation time for reinforcement corrosion was estimated. SAP extended the corrosion initiation time by 25.8 % compared to Ref.-DW and demonstrated 17.2 % superior durability performance compared to 15RLWA-DW. The findings show that SAP is a more effective internal curing agent for improving the durability and corrosion resistance of SCC in unsaturated environments, offering a valuable approach to enhancing concrete durability.

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1. Introduction

Internal curing methods have gained significant attention as a solution to mitigate the drawbacks of self-compacting concrete (SCC). The higher paste volume and lower water-to-cement ratio in SCC increase the risk of shrinkage compared to conventional concrete [1, 2]. Common internal curing materials include natural lightweight aggregates (LWA) and superabsorbent polymers (SAP), which store water and release it gradually, reducing moisture loss in concrete pores and enabling prolonged curing [1–4].

Studies have shown that internal curing reduces concrete shrinkage and, consequently, the likelihood of cracking within structures. However, contradictory results have been reported regarding the effect of internal curing on the mechanical properties of concrete under saturated conditions. Rajamanickam and Vaiyapuri [5] found that incorporating 5 % LWA by volume reduced the compressive strength of SCC in saturated environmental conditions compared to control concrete. Conversely, Gopi and Revathi [6] observed that using 15 % saturated LWA improved the compressive strength of SCC in saturated conditions. Madduru et al. [7] reported that the tensile and flexural strengths of SCC containing internal curing agents were reduced compared to control SCC under saturated conditions. These findings highlight a lack of consensus regarding the impact of internal curing on the strength characteristics of SCC.

Another critical aspect of internal curing materials is their influence on concrete permeability. Studies indicate that replacing natural aggregate with LWA increases concrete permeability due to higher internal porosity [8]. In general, research suggests that the application of internal curing in saturated environments increases concrete permeability [9–14]. However, as concrete in most structures exists in unsaturated conditions, investigating the mechanical properties and permeability of concrete with internal curing agents in such environments has become increasingly relevant. Despite this, limited research has been conducted on the permeability of concrete containing internal curing agents in unsaturated conditions.

Ahmadi et al. [15] investigated the characteristics of SCC containing LWA for internal curing in an unsaturated environment. Their findings revealed that, after demolding, the depth of chloride ion penetration in SCC with internal curing agents was lower than in SCC without them. However, this study substituted internal curing agents based on the weight percentage of natural fine aggregates and did not explore properties in water-saturated conditions. Similarly, Priya et al. [16] compared the effects of LWA and SAP as internal curing materials on SCC in laboratory environments, concluding that SAP was more effective than LWA.

Previous research has demonstrated that diffusion is the main mechanism of chloride transport in concrete exposed to chloride environments. Fick's second law is widely applied to model chloride ion penetration and estimate the initiation time of reinforcement corrosion. Among numerical approaches, the Crank–Nicolson method, based on the finite volume technique, has been frequently used in previous studies for such modeling purposes [17–20]. Therefore, in the present study, this method was adopted to evaluate the influence of internal curing materials on SCC.

This study investigates the impact of internal curing on the permeability properties of SCC in unsaturated environments with 50 % relative humidity. It evaluates and compares the effects of RLWA and SAP on the compressive strength and chloride ion diffusion coefficient of SCC under both saturated and unsaturated conditions.

2. Methods

2.1. Experimental Program

The cement used in this study was manufactured by Sepahan Cement Factory. Its composition included 24 % C_2S, 52 % C_3S, 9.5 % C_3A, and 9 % C_4AF, with a specific surface area of 2860 cm^2/g. The cement demonstrated a standard mortar compressive strength of 38.9 MPa and conformed to the ASTM C150 specifications for Type I cement regarding chemical composition, compressive strength, specific surface area, and setting time.

Concrete mixtures were prepared using P10N, a polycarboxylate ether-based superplasticizer from the Construction Chemicals Company, and tap water sourced from Rasht. Fine and coarse aggregates were procured from the North Pipe Factory. The natural fine aggregates (sand) had a saturated surface dry density of 2.61 g/cm^3, a water absorption rate of 13.3 %, and 1.14 % passing through a 200-mesh sieve. The coarse aggregates, with a nominal size of 12.5 mm, exhibited a saturated surface dry density of 2.65 g/cm^3, a water absorption rate of 1.74 %, and 0.16 % passing through a 200-mesh sieve. Both fine and coarse aggregates adhered to the ASTM C33 specifications.

Recycled lightweight aggregate (RLWA) particles used in this study were obtained from recycled autoclaved aerated concrete and ranged in size from 0.075 to 2.36 mm, with a saturated surface dry density of 0.836 g/cm^3. Particles smaller than 0.075 mm were excluded due to their powdery texture and insufficient water retention capacity.

The SAP employed was a polyacrylic polymer branded under TAISAP, with particle sizes ranging from 0.3 to 0.075 mm. A critical factor in using internal curing agents in concrete is quantifying the water released into the cement mixture. For LWA, the water released is calculated based on their water absorption percentage as outlined in ASTM C1761.

According to this standard, the water released by lightweight fine aggregates is determined by measuring the difference between their saturated surface-dry mass (achieved by removing them from water and gently drying the surface with a paper towel) and their stabilized mass at a relative humidity of 94 %. A controlled environment with 94 % relative humidity was maintained using a device equipped with temperature and humidity regulation. Results revealed that RLWA had a saturated surface dry water absorption of 19.3 %, and 66.3 % of the absorbed water was released under 94 % relative humidity conditions.

The adsorption and desorption behavior of SAP was evaluated using methods adopted from Huang et al. [21] and Lothenbach et al. [22]. The SAP was submerged in water for 72 hours, weighed, and then placed in a 0.7 mol/L sodium chloride solution for an additional 72 hours to assess mass loss, simulating the ionic conditions of cement pore solutions. Results showed that SAP absorbed water equivalent to 3.65 times its dry weight, with a desorption rate of 2.50 % in the sodium chloride solution. The 0.7 mol/L sodium chloride solution was selected to represent the typical ionic concentration of cement paste pore solutions prior to setting [19, 20].

2.2. Mixtures and Curing Methods

SCC mixtures were prepared with a water-to-cement ratio of 0.4 and a cement content of 500 (kg/m^3). The selected design was based on commercially available SCC mix designs provided by ready-mix concrete factories. The compositions of the studied mixtures are presented in Table 1. In addition to the control mixture, three other designs were prepared: one containing 0.1 % SAP by weight of cement (code S) and two mixtures with 15 % and 30 % by volume of natural fine aggregate replaced by RLWA (code RLWA).

Prior to mixing, the RLWA and SAP internal curing materials were soaked in water for 48 hours. To equalize the moisture content in these materials, they were placed on a drain for 3 hours, during which they were periodically moved to ensure even drainage. In accordance with ASTM C192, the moisture content of the aggregate materials was measured before concrete mixing. If necessary, adjustments were made to maintain a consistent free water-to-cement ratio in the mixtures. A portable moisture meter was used to measure the moisture content. In all mixtures, the dosage of high-range water-reducing admixture (superplasticizer) was kept constant to isolate and clearly observe the effect of SAP and RLWA on the fresh and hardened properties of SCC without the interference of other variables affecting workability.

The amount of internal curing agents in SCC was limited to avoid adverse effects on the fresh properties of the concrete. Excessive use of these agents can cause segregation in SCC.

The concrete was prepared using a pan-type mixer. After mixing, the specimens were molded following ASTM C192 specifications and stored in an environment with 95 % relative humidity for the first 24 hours. After demolding, the specimens were subjected to two different curing processes. In the external curing condition, the specimens were immersed in saturated lime water for up to 360 days. In the non-external curing condition, the specimens were kept in an environment with 50 % relative humidity and ambient temperature for up to 360 days.

2.3. Test Methods

In this study, the properties of fresh SCC, including the diameter of flow and flow rate, were assessed following the ASTM C1611 standard method.

Compressive strength tests were conducted in accordance with BS EN 12390 Part 3, under both saturated and unsaturated conditions. The tests were performed on three cubic specimens, each measuring 10×10×10 cm, at the ages of 28, 56, 90, 180, and 360 days.

Table 1. Concrete mixture proportions investigated in this study.

Mix Destination	W/B	Cement (kg/m^3)	Saturated Surface Dry aggregates (kg/m^3)			SAP (kg/m^3)	SP (%)	Internal curing water (kg/m^3)
			Fine Aggregate	Coarse Aggregate	RLWA			
Ref	0.4	500.0	988.0	669.0	0.0	0.0	1.19	0.0
0.1SAP	0.4	500.0	976.0	651.0	0.0	0.5	1.19	16.0
15RLWA	0.4	500.0	840.0	669.0	47.0	0.0	1.19	7.3
30RLWA	0.4	500.0	691.0	669.0	95.0	0.0	1.19	14.5

The Rapid Chloride Migration Test (RCMT) was performed in accordance with NTBuild 492 [23], under both saturated and unsaturated conditions. Three cylindrical specimens, each measuring 10 cm in diameter and 5 cm in thickness, were tested at the ages of 28, 56, 90, 180, and 360 days. During the test, one side of each specimen was exposed to a 10 % sodium chloride solution, while the opposite side was subjected to a 0.3 N sodium hydroxide solution. To accelerate chloride ion penetration, an electrical potential was applied, with the voltage determined based on the initial current passing through the specimen. The test setup is shown in Fig. 1.

After the test, the specimens were split, and a 0.1 N silver nitrate solution was applied to the exposed surfaces. The silver nitrate reacted with the chlorides, forming white silver chloride, which marked the chloride penetration front. This visible boundary was used to identify the extent of chloride penetration, and the migration coefficient was then calculated using Equation 1 [23].

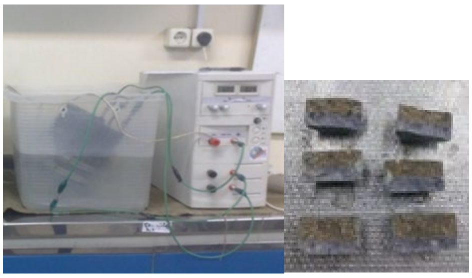

Figure 1. Test setup for rapid chloride migration test and splited specimens.

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right), \quad (1)$$

where D_{nssm} is non-steady-state diffusion coefficient (×10^{-12} m^2/s); U is absolute value of the applied voltage (V); T is average of the initial and final temperatures in the sodium chloride solution (°C); L is thickness of the specimen (mm); x_d is average value of the penetration depths (mm); t is test duration (hours).

3. Results and Discussion

3.1. Workability

Considering the constant amount of superplasticizer and water-cement ratio, the changes in the diameter of flow (slump flow) and flow rate are solely related to the effect of internal curing agents on the properties of fresh SCC. Table 2 presents the results for the diameter of flow and flow rate of the investigated mixtures. Fig. 2 shows the diameter of flow for the SCC of the control mixture.

The use of the internal curing agents studied did not have a significant effect on the diameter of flow and flow rate of SCC. The maximum reduction in diameter of flow was about 6 %, and the maximum increase in flow rate was about 4 %. The use of SAP caused a very small increase in the diameter of flow and a slight decrease in flow rate. Replacing 15 % by volume of natural fine aggregate with RLWA resulted in a decrease in diameter and an increase in flow rate. Increasing the replacement to 30 % by volume caused a further reduction in diameter of flow and an additional increase in flow rate. The effects of internal curing agents (RLWA and SAP) on the diameter of flow and flow rate of SCC are similar to the results obtained in the studies of Rajamanickam and Vaiyapuri [5], Kamal et al. [24], Madduru et al. [7], Ahmadi et al. [15], Gopi and Revathi [6], and Priya et al. [16].

It is noteworthy that the use of 30 % by volume of RLWA, due to the change in grain size, reduced the stability index and caused observed segregation in the SCC mixture. Although the amount of internal curing water required for this SCC is estimated to be about 30 liters per cubic meter, it is not possible to provide this amount of internal curing water with the lightweight fine aggregates under study as the requirements of SCC are not met.

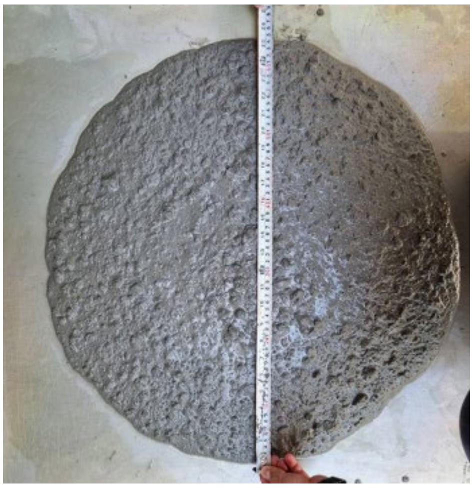

Figure 2. Diameter of flow of Ref.

Table 2. Diameter of flow and the flow rate for concrete mixture studied.

Mix Destination	Diameter of flow (mm)	flow rate (Sec)	Visual Stability Index Values
Ref.	630	2.11	0
0.1SAP	633	2.06	0
15RLWA	615	2.12	0
30RLWA	592	2.21	1

3.2. Compressive Strength

The results of the compressive strength test are presented in Fig. 3 up to the age of 360 days. The results for the externally cured specimens (cured in lime water) up to the desired ages are labeled with code "W," while the specimens without external curing (stored in a relative humidity of 50 %) are labeled with code "D." As expected, the compressive strength of the concrete remained almost constant after the age of 90 days. The results show that exposure to a relative humidity of 50 % between the ages of 28 and 360 days caused a decrease of about 8 % in the compressive strength of SCC compared to the standard curing conditions. This decrease in strength is attributed to the formation of microcracks caused by the confinement of the aggregate due to shrinkage and a decrease in cement hydration reactions [2, 25].

It should be noted that the compressive strength of the reference mixture under conditions without external curing at the age of 360 days decreased compared to the age of 180 days. A similar trend was observed in mixtures containing internal curing agents. These results suggest that microcrack development between the ages of 180 and 360 days under the studied conditions caused a slight decrease in compressive strength.

The use of SAP slightly increased the compressive strength under both exposure conditions. Replacing 15 % by volume of fine aggregate with RLWA reduced the compressive strength under externally cured conditions. The use of 30 % by volume of RLWA as an internal curing agent at the age of 28 days in externally cured conditions reduced the compressive strength decrease by 12.1 %.

The use of 15 % by volume of RLWA at the age of 28 days under conditions without external curing increased the compressive strength by about 5.0 % compared to the control mixture. This is because the presence of RLWA helps prevent the reduction of internal moisture in the concrete, thereby promoting more hydration reactions compared to the control mixture. However, by the age of 90 days, the increase in strength for designs containing internal curing agents under non-curing conditions decreased compared to the control mixture. This is because, at 90 days, more moisture has been lost from the concrete mixture, and since the amount of internal curing water provided by these agents is less than the required amount, the rate of hydration reactions and prevention of microcracks caused by aggregate confinement decreases [2, 25]. The results show that despite the positive effect of the internal curing agent RLWA on compressive strength under non-curing conditions, its use cannot completely eliminate the reduction in the strength of SCC caused by inadequate curing.

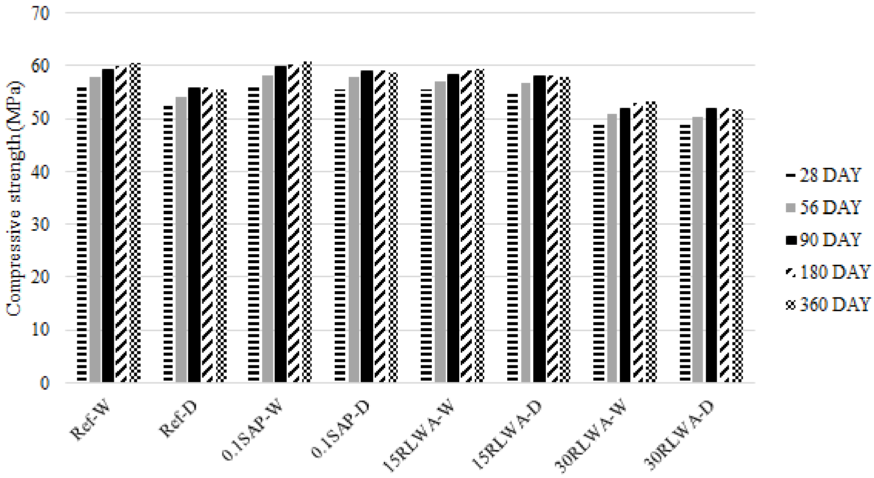

Figure 3. Compressive strength of mixture in saturated and unsaturated conditions.

In the study by Gopi and Revathi [6], it was also shown that the use of 15 % LWA improved the compressive strength compared to the conditions without external curing. However, the compressive strength of SCC with an internal curing agent was still lower than that of the control mixture cured under standard conditions. The results of the study by Rajamanickam and Vaiyapuri [5] show that increasing the amount of LWA replacement between 15 % and 25 % reduced the compressive strength of SCC under external curing conditions compared to the control mixture. It should be noted that the results of published studies on the effect of SAP and LWA curing agents in concretes with a low water-to-cement ratio indicate that, similar to the results obtained in the present study, the compressive strength of concrete under conditions without external curing was improved by using internal curing agents. However, the use of these materials could not eliminate the need for external curing [21, 26–32].

3.3. Chloride Diffusion Coefficient

Fig. 4 presents the results of the chloride ion diffusion coefficient. The chloride ion diffusion coefficient decreases with increasing age due to the progress of hydration reactions and the closure of the internal pores of the concrete. The use of the SAP curing agent caused a slight decrease in the chloride ion diffusion coefficient between the ages of 28 and 360 days under saturated conditions compared to the control mixture. However, the use of the RWLA curing agent led to an increase in the chloride ion diffusion coefficient between the ages of 28 and 360 days under saturated conditions compared to the control mixture. The results obtained in the study by Alaskar et al. [10] are consistent with those of the present study. In the study by Alaskar et al. [10], at the age of 28 days, the accelerated chloride ion permeability of reinforced concrete containing 20 % lightweight fine-grained aggregate as an internal curing agent under saturated conditions was 7 % higher than that of the control mixture.

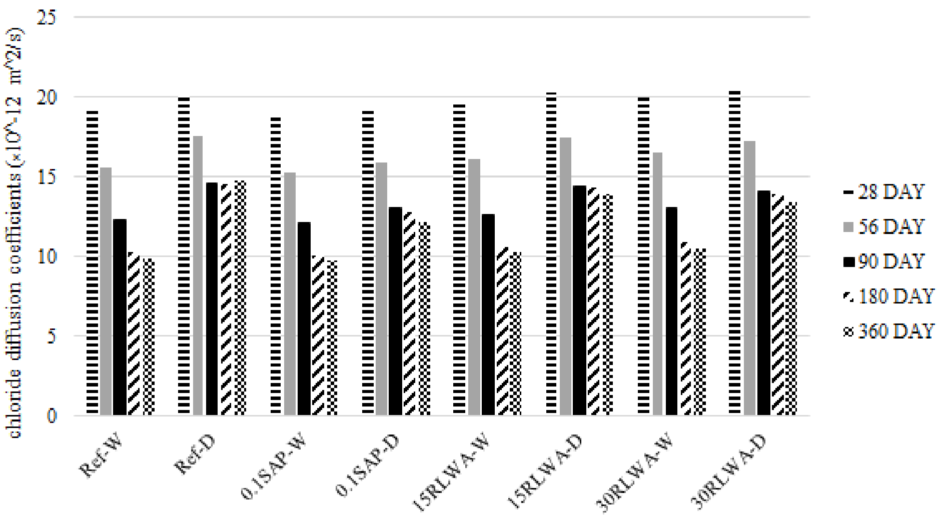

Figure 4. Chloride diffusion coefficient of mixture in saturated and unsaturated conditions.

The chloride ion diffusion coefficient of the control specimen placed in an environment with a relative humidity of 50 % at ages 28, 56, 90, 180, and 360 days increased by 5.8 %, 12.8 %, 18.7 %, 40.8 %, and

49.5 %, respectively, compared to the specimens in saturated conditions. The increase in the diffusion coefficient grew with increasing age. This is because the longer exposure to an environment with a relative humidity of 50 % causes the expansion of concrete microcracks and their greater interconnection [30]. As can be seen, the increase in the diffusion coefficient of Ref. mixture at the age of 180 days is significantly greater than at the age of 90 days. This is because, with increased exposure time in an unsaturated environment, the development of microcracks accelerates, and their interconnection increases. These results show that microcrack development after 90 days of exposure to the studied unsaturated environment significantly impacts the chloride ion diffusion coefficient. At the age of 360 days, the chloride ion diffusion coefficient of the Ref., 0.1SAP, 15RLWA, and 30RLWA mixtures in conditions of exposure to a relative humidity of 50 % increased by 49.5 %, 24.7 %, 35.0 %, and 27.6 %, respectively, compared to the diffusion coefficient of the specimens in saturated conditions. As seen, the use of internal curing in the 0.1SAP, 15RLWA, and 30RLWA mixtures reduced the increase in the chloride ion diffusion coefficient of specimens placed in an environment with a relative humidity of 50 %. However, it should be noted that the use of internal curing materials in saturated condition specimens did not reduce the chloride ion diffusion coefficient, and even the RWLA increased the chloride ion diffusion coefficient of concrete in the saturated condition specimens.

For SCC specimens placed in an unsaturated environment, the results obtained by Ahmadi et al. [15] also indicate that the use of a curing agent increases the resistance of concrete to chloride ion penetration compared to the control specimen. In the study by Mullem et al. [33], the diffusion coefficient for both the control mix and the SAP-containing mix with a water-to-cement ratio of approximately 0.36 was about 4.2. Their results indicate that at similar water-to-cement ratios, the addition of SAP does not significantly affect the chloride ion diffusion coefficient, which remains very close to that of the control mix.

3.4. Estimation of Corrosion Initiation of Rebar

Numerical modeling was employed to predict the time required for corrosion initiation in reinforcement embedded within concrete. The chloride ion penetration process was characterized using Fick's Second Law of Diffusion. Assuming a constant surface chloride concentration and a steady chloride diffusion coefficient, the differential equation governing Fick's Second Law was solved using the Crank–Nicolson numerical method, applying the finite difference approach as expressed in Equation 2 [18, 19]:

$$C(x,t) = C_i + (C_s - C_i)\left[1 - erf\left(\frac{x}{2\sqrt{D_a t}}\right)\right]. \quad (2)$$

Here, $C(x,t)$ represents the chloride concentration (as a percentage of the concrete's mass) at a depth x and the time t, C_i is the initial chloride concentration (% mass of concrete) before exposure to the chloride environment, C_s represents the surface chloride concentrations (% mass of concrete) on the exposed surface, erf is the error function, x is the depth below the exposed surface (m), t is the exposure time (s), and D_a is the apparent diffusion coefficient of chlorides m^2/s.

The Crank–Nicolson method was employed to evaluate the resistance of concrete to chloride ion penetration, using data derived from the Rapid Chloride Migration (RCM) tests. The temporal variation in the chloride diffusion coefficient was determined according to Equation 3 [18, 19]:

$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m. \quad (3)$$

In this equation, $D(t)$ represents the concrete's diffusion coefficient at time t, D_{ref} is the concrete diffusion coefficient at time t_{ref}, and m is the aging factor. In this study, a constant chloride diffusion coefficient was assumed across the concrete cross-section to simplify the model and facilitate direct comparison among mixtures, consistent with the approach taken in many similar comparative investigations [18–20].

In this study, the critical chloride concentration was assumed to be 0.18 % of the concrete's weight, while the surface chloride concentration was set at 0.8 % of the concrete's weight [18, 19]. It is important to note that for submerged conditions in the Life 365 software, the surface chloride concentration is fixed at 0.8 % for specific scenarios [20].

In some structures, such as bridge decks or desalination tanks, concrete remains in an unsaturated state for an extended period before being exposed to chloride ions. In this study, it is assumed that the concrete was in an unsaturated environment for 360 days and then exposed to chloride ions. In this modeling, the corrosion initiation time is simulated for concrete in submerged conditions after contact with chloride ions. To calculate the age coefficient using the RCMT test results, tests were performed at ages of 450, 540, and 630 days according to the method described in Section 2-2. Only the specimens exposed to an environment with a relative humidity of 50 % were transferred into saturated lime water after 360 days, and the desired tests were conducted on them at the specified ages. Fig. 5 shows the diffusion coefficients obtained for these specimens. The abbreviation “DW” indicates that these specimens were first placed in an environment with 50 % relative humidity and then transferred into water. In Table 3, the aging factor (m) was calculated based on Equation 3, and the 360-day chloride diffusion coefficient obtained from the RCMT method is presented for use in the modeling.

The results in Fig. 5 show that between the ages of 360 to 630 days, the diffusion coefficient decreased with increasing age. It is noteworthy that the test specimens that were exposed to an environment with 50 % relative humidity before the age of 360 days and then placed in humid conditions exhibited a trend in chloride ion diffusion similar to the specimens that were in saturated conditions from the start. The aging coefficient calculated based on Equation 3 for the mixes is nearly identical.

Table 3. Aging factors and the reference diffusion coefficients.

Mix Destination	m	D_{ref} (×10^{-12} m^2/s)
Ref-W	0.2692	9.9
Ref-DW	0.2574	14.8
0.1SAP-W	0.2706	9.7
0.1SAP-DW	0.2656	12.1
15RLWA-W	0.2691	10.3
15RLWA-DW	0.2604	13.9
30RLWA-W	0.2694	10.5
30RLWA-DW	0.2612	13.4

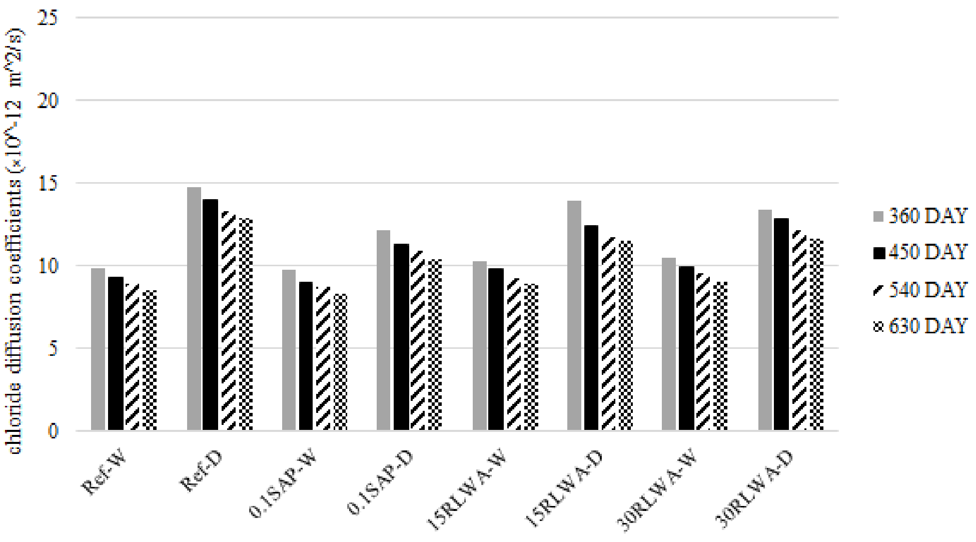

Figure 5. The chloride diffusion coefficient of mixtures used in modeling.

Fig. 6 shows the results of the estimated corrosion initiation time for the studied mixtures, with reinforcement at a depth of 5 cm. In a 5 cm cover, the estimated corrosion initiation times for the mixtures Ref-W, Ref-DW, 0.1SAP-W, 0.1SAP-DW, 15RLWA-W, 15RLWA-DW, 30RLWA-W, and 30RLWA-DW were 8.28, 5.25, 8.51, 6.61, 7.93, 5.64, 7.77, and 5.86 years, respectively. The results show that the use of internal curing for specimens that remain in saturated conditions decreases durability, causing these mixtures to initiate corrosion faster than the control mixture. Furthermore, exposure to an environment with a relative humidity of 50 % for one year before chloride ion penetration reduced the corrosion initiation time by approximately 40 %. This reduction in concrete durability is attributed to microcracks caused by shrinkage due to the loss of internal moisture. However, the use of internal curing improved the durability of concrete in these conditions. The corrosion initiation times for the 0.1SAP-DW, 15RLWA-DW, and 30RLWA-DW mixtures were 25.8 %, 7.4 %, and 11.6 % higher than that of the Ref-DW mixture, respectively. Internal curing with SAP material was more effective in improving the corrosion initiation time than RLWA.

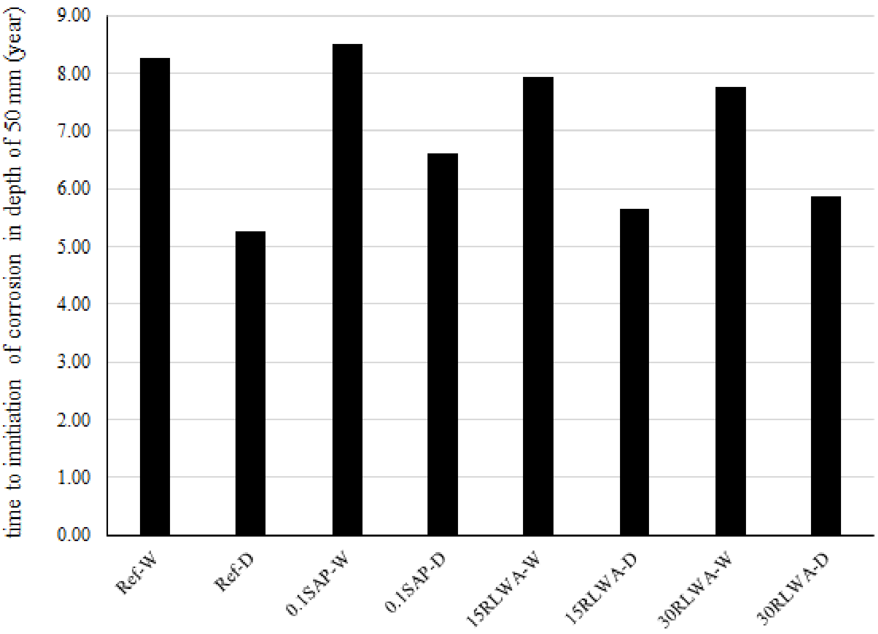

Figure 6. The predicted time of the corrosion initiation at depths of 50 mm.

4. Conclusion

Based on the findings of a laboratory study conducted on mixtures containing SAP internal curing agent and RWLA lightweight aggregates, the following results can be summarized:

1. The amount of internal curing agents in SCC is limited due to their potential influence on segregation.
2. The compressive strength and chloride ion diffusion coefficient of SCC containing SAP did not change significantly under saturated conditions compared to the Ref. mixture. However, mixtures containing RWLA exhibited a reduction in compressive strength by up to 12.1 % under saturated conditions at the age of 28 days. The chloride ion diffusion coefficient of mixtures containing RWLA increased by a maximum of 6.1 % under saturated conditions.
3. The use of internal curing materials in specimens placed in an environment with 50 % relative humidity improved compressive strength. The maximum enhancement in compressive strength with SAP internal curing agents was 6.8 % at the age of 28 days.
4. For specimens exposed to an environment with 50 % relative humidity, the use of internal curing materials resulted in a decrease in the chloride ion diffusion coefficient of concrete. The maximum reduction in the chloride diffusion coefficient of concrete containing internal curing agents was 18.4 % at the age of 360 days.
5. The results show that the predicted corrosion initiation time of Ref.-DW was reduced by 40 % compared to concrete exposed to saturated conditions. For specimens stored in an unsaturated environment, the use of an internal curing agent significantly improved the corrosion initiation time. The highest corrosion initiation time was observed for the 0.1SAP-DW mix, with a 25.8 % increase compared to the Ref.-DW mix.
6. In an environment with 50 % relative humidity, the performance of SAP in improving the mechanical properties and durability of SCC is better than that of RWLA.
7. The results show that the effect of the concrete placement environment on the concrete diffusion coefficient is significantly greater than its effect on the concrete compressive strength.
8. The results suggest that the application of internal curing agents can enhance the durability of SCC mixtures placed in unsaturated conditions prior to exposure to chloride environments. It also seems that exposure to an unsaturated environment for more than 90 days can have a significant impact on the durability of concrete. Therefore, it is recommended that concrete not be left in unsaturated

conditions for more than 90 days before being exposed to environments containing destructive ions. However, it is important to highlight that further research is required on this subject.

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