# Experimental and Numerical $FE^2$ Study of Chloride Ions Ingress in Unsaturated Recycled Aggregates Concrete

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**Abstract.** Chloride-induced corrosion poses a substantial risk to reinforced concrete structures. The use of Recycled Concrete Aggregates (RCA) as a substitute for Natural Aggregates (NA) exacerbates durability concerns. Indeed, the adhesive mortar paste reduces the mechanical characteristics of concrete, whilst possibly altering its durability. However, Recycled Aggregates Concrete (RAC) presents a sustainable construction approach that reduces landfill waste and conserves natural resources.

A comprehensive experimental investigation was undertaken on concretes composed of NA and RCA. Their inherent properties in terms of water transport and chloride ion ingress were assessed. A multiscale chemo-hydraulic model was created using the Finite Element Squared ($FE^2$) method, and then verified and calibrated. The model's constitutive equations use intrinsic properties obtained from experimental data.
The results demonstrate the model's accuracy in providing additional insight into chloride ingress in both saturated and unsaturated concrete.

The research findings suggest that the durability of RAC may be comparable to that of NAC under specific mixture quality and environmental conditions. To evaluate this, a modelling application was carried out, which replicated actual conditions on a maritime lock wall.

**Keywords:** Recycled Concrete Aggregates · Chloride Ions · Durability · Multiscale Modelling · Finite Element Method.

## 1 Introduction

Aggregates make up about half the volume of concrete, and have a significant impact on its performance. There are three commonly used types of aggregate: natural, industrial and recycled. The latter is produced by crushing old concrete elements to produce a conglomerate of adherent mortar and natural aggregates. The replacement of natural aggregates with recycled concrete aggregates affects the mechanical [10, 18] and durability [1, 17] properties of the concrete.
A significant degradation process of reinforced concrete in terms of durability is

chloride pitting corrosion. It is responsible for high maintenance costs and structural repairs, especially in the vicinity of roads or marine areas [14, 15]. The adherent mortar of recycled aggregates introduces an additional porous matrix into the concrete mix, which exacerbates the degradation processes taking place in reinforced concrete by promoting the ingress of chloride ions and fluids [1, 13]. Understanding the influence of the substitution of natural aggregates by recycled concrete aggregates in a reinforced concrete structure on its durability therefore requires a comprehensive research programme. In this paper, an in-depth experimental campaign is carried out to determine the intrinsic properties of concrete made from natural and recycled concrete aggregates (with a 100% replacement ratio), as well as of a mortar derived from the concrete compositions. Several experiments were carried out to characterise both the ingress of moisture and the diffusion of chloride ions into the porous matrix.
However, the scale studied in the laboratory is insufficient compared to a civil engineering structure. Therefore, numerical multiscale modelling proved to be necessary. The numerical model developed in this research aims to include the heterogeneities of concrete, in particular due to the presence of aggregates.

## 2 Materials and Methods

### 2.1 Materials

The aim of this research is to understand how the replacement of natural aggregates with recycled aggregates in concrete affects the ingress of chloride ions. To achieve this, several materials were produced in the laboratory and tested in various experiments. These materials include two concretes and a mortar:

- NAC: a micro-concrete containing 2/7 mm natural limestone aggregates and 0/2mm natural Rhine sand;
- RAC: a micro-concrete containing 2/7 mm recycled concrete aggregates with a particle size distribution similar to that of the NAC, and 0/2 mm natural Rhine sand;
- E-M: an equivalent mortar [16, 5] which also employs 0/2 mm natural Rhine sand.

Both NAC and RAC have the same volume fraction of aggregates. The effective water-to-cement ratio is the same for all materials.

### 2.2 Description and Results of the Experiment

Most degradation processes require water to initiate or support a chemical reaction, as is the case with chloride attack [15]. Water transfer properties are therefore essential when dealing with the durability of concrete structures [6]. In order to obtain their macroscopic homogenised water transfer properties, several experiments have been carried out on the aforementioned materials:

1. Water Absorption by Immersion (NBN B 15-215:2018 and NBN EN 772-4) [6]: the water absorption and water-accessible porosity of the materials;
2. Water permeability test (NBN EN ISO 17892-11:2019) [6]: the intrinsic permeability of a porous medium is calculated using Darcy's law and the constant head method;
3. Static Sorption and Desorption experiment [6]: the Water Retention Curves (WRCs) express the degree of saturation of the porous system with respect to environmental conditions, such as relative humidity and temperature, through the expression of suction. This understanding helps to clarify the exchanges between a material and its environment.

Focusing on the ingress of chloride ions within the porous structure of concrete, additional experiments have been carried out [7]. These experiments aim to determine the diffusion coefficients of chloride ions within the material under different conditions:

1. Steady-state Chloride Diffusion experiment [7]: the effective diffusion coefficient is calculated by applying Fick's first law of diffusion;
2. Unsteady-state Chloride Diffusion experiment [7]: Fick's second law can be applied to the results of this experiment to determine the apparent diffusion coefficient.

Those experiments are detailed in other papers, specifically for the water transfer properties [6] and the chloride intrusion experiments [7]. Similarly, the experimental results are detailed in Fanara et al. (2023) [7]

## 3 FE$^2$ Model

Multiscale modelling and numerical homogenisation techniques allow the homogenisation of material properties from a subscale to a macroscale while keeping the computational cost relatively low [3]. It is specially used for concrete-like materials where the subscale incorporates the heterogeneities of the material, with each constituent having its own set of properties and constitutive equations. The macroscale is assumed to be homogeneous and the mixture theory is therefore used to introduce multiple phases (water and gas) in a single porous medium [4, 2]. The FE$^2$ multiscale model developed in this paper is considered to be multi-physical, accurately representing the flow of water and gas, and the diffusion and advection of chloride ions within the porous structure of the concrete. The subscale has a characteristic length of the order of several centimetres and represents a slice of concrete in which the aggregates are impermeable and the mortar (either fresh or adhering to the recycled aggregates) has been homogenised and has its own set of properties. At this scale, the problem is solved under steady-state conditions due to the required temporal and spatial separation between the two scales used. The macroscale, on the other hand, has a characteristic length of the order of a metre and represents a civil engineering structure. The model considers both saturated and unsaturated conditions.

Three degrees of freedom, including water pressure, gas pressure and chloride ion concentration, are defined at the macroscale. Further details, such as the constitutive equations governing the described degrees of freedom, are elaborated in another paper by Fanara et al. (2024) [8].

### 3.1 Representative Volume Element

The model incorporates the subscale by using a Representative Volume Element (RVE) that includes the relevant material heterogeneities. For this study, given the objective of replacing natural aggregates with recycled ones, the scale chosen is that of the aggregates, with the smaller phases homogenised in a mortar matrix. Figure 1 shows two RVEs representing both NAC and RAC.

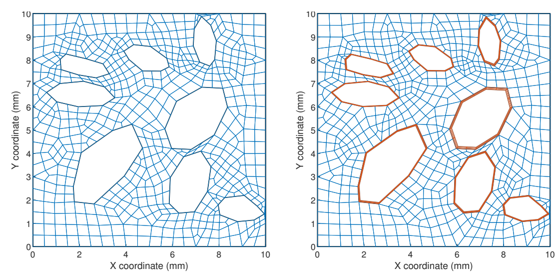


Fig. 1: RVE mesh representing the two types of concrete used: NAC (left) and RAC (right).

Each phase of the RVE, namely the adherent mortar or the new mortar matrix, has unique properties that are used in the subscale constitutive equations. The only exception is the WRC of the material, which is intrinsically homogenised at the macroscale. An algorithm has been developed to generate the RVE, based on the random packing of octogonal inclusions [12]. It requires several intrinsic properties of the material mixture:

- Particle Size Distribution (PSD) of the aggregates only;
- Surface Fraction (SF) of the aggregates within the mixture, which in this study is equal to their volumetric fraction;
- Aspect Ratio (AR) of the aggregates.

The algorithm is explained in Fanara et al. (2022) [9]. Once the RVE is generated, it is meshed using the gmsh software from the University of Liège [11].

## 4 Application on a Real Life Scenario

Once the model has been developed and validated, it can be used to model an application based on real environmental conditions and inspired by a civil engineering structure: a reinforced concrete sea lock wall in direct contact with salt water. The modelled lock wall is shown in Figure 2. It is 50cm wide (symmetrical loading), 4m high out of the water and 2m deep under water. These dimensions are smaller than in real life: the effect of increasing them would not change the results, but would greatly increase the computation time. A transition zone was defined between the hydrostatic and atmospheric conditions to smooth the gradient of the water pressure acting on the wall.

Table 1: Intrinsic properties of the NAC and RAC used in the application.

| Property | NAC | RAC | Adherent mortar of RCA |
|---|---|---|---|
| Intrinsic Permeability [$m^2$] | 5.02E-18 | 5.02E-18 | 5.02E-17 |
| Porosity [% Volume] | 29.68 | 29.68 | 59.36 |
| Diffusion Coefficient [$m^2/s$] | 1.86E-11 | 1.86E-11 | 1.86E-10 |
| $n_{VG}$ [-] | 1.51 | 1.51 | - |
| $\alpha_{VG}$ [MPa] | 3.45 | 3.56 | - |

The environmental conditions applied to the lock wall are those of Zuquan et al. [19], and shown in Table 2. The chloride concentration in the water was chosen to be 17g/L [19], which is equivalent to a surface concentration of 0.11% for the NAC and 0.17% for the RAC, as it depends on the material porosity. The chloride concentration in the air was assumed to be 0%.

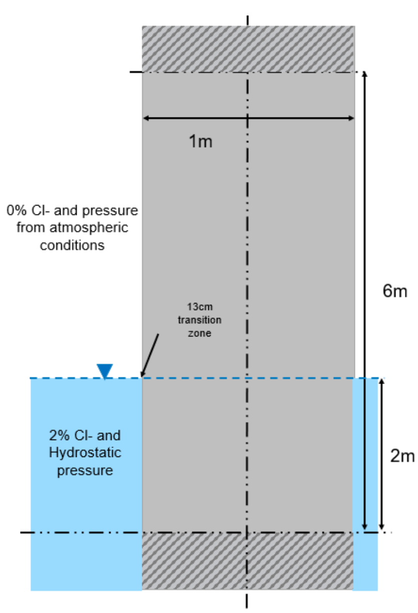


Fig. 2: Representation of the lock wall.

Table 2: Environmental conditions (temperature and relative humidity) applied to the wall, and the corresponding water pressure.

| Month | RH [%] | T [K] | $P_w$ [MPa] |
|---|---|---|---|
| Jan. | 62.5 | 273.4 | -593.1 |
| Feb. | 63.9 | 275.4 | -569.1 |
| Mar. | 65.3 | 279.3 | -549.7 |
| Apr. | 69.5 | 287.6 | -477.8 |
| May | 72.5 | 290.1 | -430.5 |
| Jun. | 81.9 | 293.9 | -270.9 |
| Jul. | 86.1 | 297.9 | -205.8 |
| Aug. | 81.4 | 298.8 | -283.7 |
| Sep. | 69.3 | 295.4 | -500.0 |
| Oct. | 65.2 | 289.6 | -571.7 |
| Nov. | 66.3 | 282.2 | -535.3 |
| Dec. | 63.9 | 276.0 | -570.5 |

For this application, two RVEs were used: one for each concrete (see Figure 1). The properties of the experimental mortar were used for both compositions, increased by 30% to account for 2D effects [8]. The water retention curve is defined as a macroscale parameter in the model and was therefore defined based on the experimental results of NAC and RAC respectively [7]. The parameters used in the model for both concretes are given in Table 1. The simulation is run for 5 years, before analysing the response of both concretes. Figure 3 shows the results in terms of water pressure. The pressure inside the NAC is lower than inside the RAC. It implies that the NAC had a more substantial moisture exchange with its environment. These findings are in contradictions with what one could expect, that is RAC would have higher water and chloride exchange rates compared to NAC [7]. However, RAC has a tendency to desaturate more rapidly than NAC, inducing a decrease in the relative permeability of concrete.

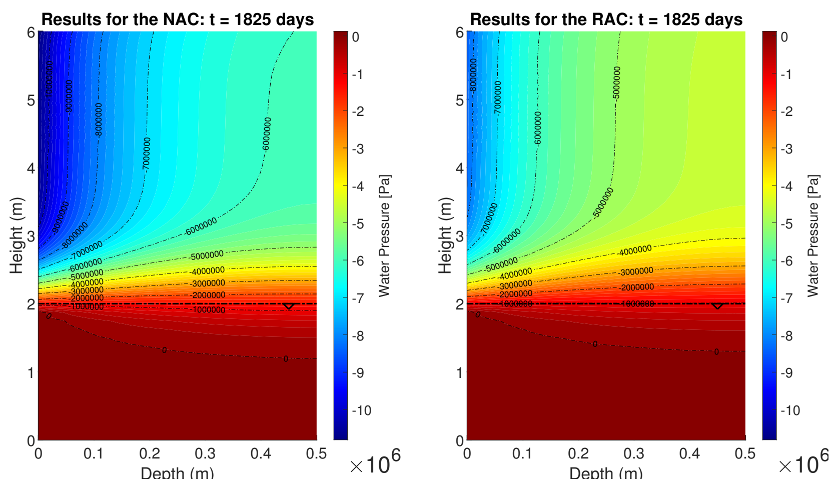


Fig. 3: Water Pressure for the NAC (left) and RAC (right) after 1825 days.

Another indicator is the chloride concentration, expressed as a percentage of the binder mass. The chloride concentration of RAC is greater than that of NAC, in unsaturated conditions, due to the greater chloride surface concentration. However, both chloride fronts seem to progress similarly, as demonstrated in Figure 4.

## 5 Conclusion

This paper investigates the ingress of chloride ions into RAC. A dual approach, consisting of experimental characterisation of materials, followed by the implementation of a $FE^2$ model, was used to better understand the influence of replacing NA with RCA. The validated model was used in an application based

on a realistic scenario: the study of a maritime lock wall. It was demonstrated that RAC is not less durable than NAC, mainly due to the non-linearity of the water retention curve. In fact, the decrease in the degree of water saturation over the life of the concrete is associated with a decrease in the relative permeability, which protects the concrete against chloride ingress.
The conclusion is that, under unsaturated conditions, replacing 100% of natural aggregates with recycled concrete aggregates doesn't necessarily reduce the durability of the reinforced concrete structure exposed to chloride ingress in a marine environment.

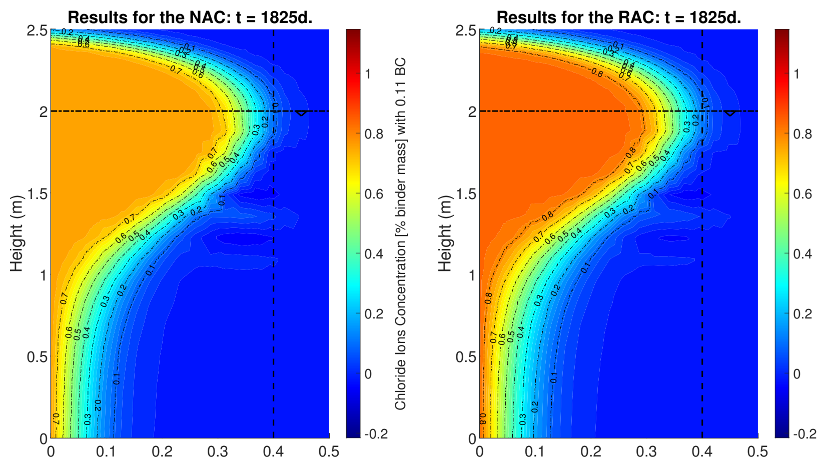


Fig. 4: Chloride Ions concentration for the NAC (left) and RAC (right) after 1825 days, expressed as a percentage of the binder mass.

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