Experimental determination and numerical validation of the chloride penetration in cracked hydraulic concrete structures exposed to severe marine environment

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Abstract. Concrete is one of the most broadly materials that used in hydraulic structures. Both in new and service, and for various reasons, concrete structures are oftentimes cracked. The existence of cracks plays as a catalyst role of reduction the target service life. One of the main reasons of the impairment of the durability of these structures is chloride-motivated corrosion of the iron reinforcement. This paper aims to find, for the first time, the effect of cracks, experimentally and numerically, on chloride penetration in Hydraulic Concrete Structures (HCS) exposed to varied heads of seawater. The experimental results were acquired with Darcy law, by using new laboratory method called Hydraulic Pressure Tank (HPT) with artificial cracked specimens, whereas the chloride penetration profiles were obtained with development Electrical Conductivity Technique (ECT). The numerical simulation results were obtained using microstructure finite element models. A good acceptance between experimental and the numerical chloride penetration results was gotten.

1. Introduction
Hydraulic reinforced concrete is famed for its decent structural rendering and toughness. The steel reinforcement supports the concrete and the last shields the rebar from corroding. By and large, reinforced concrete structures are in excellent condition during the period of service. However, the existence of cracks gives trajectories to water penetration. The water flow additionally conveys aggressive agents, for example, chloride particles which encourage the corrosion of the rebar and antagonistically influences the durability of reinforced structures. In this way it is critical to see how cracks would influence the seawater penetration in concrete particularly in the cracking section.

Despite the relatively dangerous effect of the interaction of seawater and concrete structures, and especially in the enduring performance of structures, only a restricted amount of research, or rather it does not exist, has been reported the effect of cracks on seawater flow in Hydraulic Concrete Structures (HCS). Other studies focus on the impact of cracks on the distribution of chloride concentration profiles around the crack after certain time of exposure to saline solution [1-3]. These investigations did not regard the seawater level as a contributing factor of chloride penetration. However, seawater head conditions are very common for field structures such as dams, hydraulic retaining wall, etc. therefore, an understanding of seawater flow would benefit the evaluation and prediction the deterioration of HCS.

This study submits a significant step towards closing this lack, where it tries to emulate the seawater penetration in concrete structures precisely as it's possible with taking into consideration important parameters such as water head, percentage of salts which found in seawater and appropriate HCS mixture.
Depending on the principles of modelling and simulation there is a difficult problem in the representation of high-water heads and interacting with HCS. Therefore, a new laboratory method called the Hydraulic Pressure Tank (HPT) was invented for the purpose of simulating dozens of meters of water head and its interaction with the aforementioned structures.

The Electrical Conductivity Technique (ECT) has been developed for the purpose of evaluating and calculating the accurate degree of saturation and amount of chloride penetration in testing concrete specimens.

The experimental study investigated the influence of cracks on the chloride penetration of concrete specimens with dimensions of (0.25 x 0.25 x 0.25) m and with artificial cracks. The specimens were pre-cracked, using a shim copper plate to create cracks in the middle dimension of specimens, with dimensions (6 and 10) cm as crack depths and (0.5 and 1.0) mm as crack widths. The assessment was carried out on the basis of some physical properties (chloride concentration and electrical conductivity). Therefore, the chloride distribution profile was monitored by using a development ECT after 312 hours (13 days) of exposing to (2 and 5) m of water head coupled with 3.5 % NaCl to simulate the typical marine environment of seawater.

The saturated hydraulic conductivity of the used concrete mix was evaluated by a centrifugal technique. In addition, porosity test has also been taken into account and for samples with the same mixing properties that used in this study. The last two tests were conducted for the purpose of numerical simulation of the process of chloride penetration in real microstructures models.

2. Transportation of Chloride Ions

Chloride transport in concrete is a complex process, involving mechanisms such as diffusion, permeation, migration and capillary suction, or by any combination of these, flow with flowing water, accompanied by physical and chemical binding [4]. The governing mechanisms of the transport in concrete structures depend on the exposure conditions, actually, on the degree of saturation of pores in concrete. When the pores inside concrete are occupied by both water and gas it is called unsaturated concrete, whereas they filled with water only it is referring to a saturated concrete as submerged concrete structures. Since this research studies chloride ingress in submerged structures and under hydrostatic head, therefore attention will be given mainly to diffusion, where the flow of chloride species, due to the gradient of concentrations, from an area of high concentration to an area with a low concentration, and permeation (convection), where the flowing is under a hydrostatic head in saturated media [5]; therefore, diffusion and convection are the most important and often governing transport process in saturated within submerged concrete structures.

In 1856, a French hydraulic engineer called "Henry Darcy" described the movement of the water through sand filters and showed the discharge of the water was proportional to the hydraulic gradient and the type of material. His conclusion has served as the basis called “Darcy's Law” for all modern analysis of fluid flow in saturated conditions and under water head, in one dimension through a porous media and as follows:

\[ Q = -KA \frac{dH}{dt} \]  

Where: \( Q = \) volumetric discharge, (m³ sec⁻¹); \( K = \) hydraulic conductivity, (m sec⁻¹); \( A = \) cross-sectional area, (m²); \( H = \) hydraulic head, (m) and \( l = \) length of sample, (m).

Saturated hydraulic conductivity, \( K_{sat} \), describes water movement through saturated media By definition, hydraulic conductivity is the ratio of velocity to hydraulic gradient indicating permeability of porous media. A more detailed idea of permeability which is depends on the intrinsic permeability of the media, the degree of saturation, and on the viscosity and density of the liquid. Centrifugal techniques have been used in last years to comprehend and simulate transport mechanisms in concrete under accelerated–gravity environments. The centrifuge can be utilized in a very distinct way as a testing device to obtain a hydraulic conductivity as a modelling device to examine theory and to verify numerical modelling capabilities [6-8].

3. Experimental Program

3.1 Concrete composition
Based on the standard specifications and conforming to ASTM C595, most of the concrete structures exposed to the marine environment must be used blended cement, low water/binder ratio, upper than 5% of silica fume and high value of compressive strength, as an appropriate concrete mixture [9-11], so that depending on the recommended raw materials characterization and concrete mixture features, the concrete mixture utilized in all experimental specimens are report in below table:

Table 1. Mixing proportion of concrete materials and concrete properties [12].

| Material                  | Quantity (kg/m$^3$) |
|---------------------------|---------------------|
| Cement                    | 450                 |
| Silica fume               | 32                  |
| Fine aggregate            | 1232                |
| Coarse aggregate          | 410                 |
| Water                     | 169                 |
| Super plasticizer         | 7                   |
| Water/binder ratio (%)    | 35                  |
| Slump (cm)                | 10–12               |
| 28-day compressive strength (MPa) | 50                 |

The concrete samples were cast as:
- Eight cracked cubic specimens (250 x 250 x 250) mm.
- Eight cubic samples (75 x 75 x 50) mm, for calibration of electrical conductivity.
- Six cylindrical samples (50 mm diameter and 25 mm height) for hydraulic conductivity.
- Five cylindrical samples (100 mm diameter and 75 mm height) for porosity test.

All these samples were done with a same mixture and as reported in table 1. After 24 hours of covered samples with polyethylene sheets to prevent moisture loss from the concrete, then they were named and submerged in a filled water basin in the curing room with a temperature 23± 2°C and RH > 90 % for 28 days.

3.2 Probe preparation

3.2.1 Probes type
A smoothly surface brass probes, to ensure close touch between the probes and concrete specimens [13-15], were used and developed to find the least disturbance of chloride penetration in the concrete specimens. According to simplest electrical conductivity waves of the two-probe configuration, so 12 x 13 probes, grid map covered an area of 525 cm$^2$ around the crack, were inserted and selected as data points to acquire the best resolution of the chloride penetration in concrete specimens.

3.2.2 Probes length, diameter and spacing
In the current study, a 255 mm probe length was selected as a short enough length to fit on most concrete specimens. The probe was carefully chosen with diameter $d=2.5$mm, spacing $D=20$mm to satisfy the mapping of the probes matrix within the cubic concrete specimens.

3.2.3 Probes installation
In order to gain the exact profile of chloride location, the probes were embedded from the side surface of the specimens, therefore a timber probe holder was intended to keep the probes parallel to each other and vertical to the surface of concrete specimen. The edges of those holes were made with chamfers which enabled the probes to effortlessly go through.

3.3 Creation of cracks
Concrete specimens were cast with two levels of crack depth and width. Cracks were created by molding concrete with a thin copper plate (shims) installed at the canter of the mold. Before casting the concrete mixture, shims, with a (250 x 60 and 250 x 100) mm cross section and thicknesses of 0.5 mm and 1.0 mm, were linked to the side surface of the mold in order to make the cracks. Through 24 hours curing the plate was dragged out totally and as presented in figure (1: a).
3.4 Coating and finishing
Following 28 days of putting in the curing basin, the specimens were painted with epoxy, except the finish surface (crack side), which permitted one dimensional transport of chloride solute inherent concrete specimen and was more illustrative of numerous field hydraulic structures. Before application, all specimens were cleaned by an air compressor blower to remove any dust or debris. Three layers of painting were applied to the specimens to ensure the fill of all open pores in the concrete surfaces (Figure 1: b and c). Care was taken to keep the epoxy from filling the cracks.

![Figure 1](image1.png)

**Figure 1.** Preparation of specimens (a): Creation of crack. (b): Coating with epoxy. (c): Final-finished of specimens.

3.5 Environmental treatment
To get rid the difficult modelling of the wide range of water heads, so that a tank was manufactured and as presented in figure (2: a and b), where all the specimens were exposed to head of chloride solute, as hydraulic structures exposed to seawater head in the site, to find the typical amount of chloride penetration. An air compressor instrument was used to press the solute of 3.5% NaCl, found in the tank, inherent concrete specimens through uncoated faces over time and at any water head that required.

![Figure 2](image2.png)

**Figure 2.** Hydraulic Pressure Tank (a): Manufacture of tank. (b): Final formed of the tank.

The upper tank cover was designed to maintain constant air pressure inside the tank. This was done by refining it (the lower surface) as well as the surface of the tank that contained it, and sealed them with a number of bolts and nuts distributed with equal dimensions around them and as shown in above figure (2: b). Furthermore it, a rubber frame was used between the top cover and tank, to make sure that no air atom or water drop was allowed through it. So that each pressure was kept steady for each time of the tests and that monitored by using a pressure gage and a pressure regulator, instilled at the highest level of the tank. The couple of compressor-regulator were adjusted, so that the pressure gauge...
showed 20000 pa or 50000 pa which will be equal to the 2 and 5 meters of water heads. Subsequently, these driven water causing a penetration of solute in cracked concrete specimens (Figure 3).

Figure 3. Scheme cross section of the process inside HPT.

After end the environmental exposure test, specimens were taken out of the pressure tank and were surface-dried by wiping off any moisture present on the surface with a towel, to ensure that no surface conduction effects on the conductivity measurement. Then they immediately wrapped with a plastic membrane, that can be safely assumed that the saturation of the specimens remained essentially the same during testing, to prepare the specimens to check where chloride depth is present.

3.6 Electrical conductivity test (ECT)

3.6.1 General

The electrical conductivity of concrete has been the focal point of numerous studies on the past 60 years [13, 14, 16-18]. They presented that the conductivity of any material is defined as inverted the value of the resistance between the faces corresponding to the cube unit of the material, where their results focused that the electrical conductivity inherent material properties.

In an attempt to facilitate testing of the chloride penetration in concrete, the ECT was developed by an accurate unique test. The development ECT was designed, through the implantation of a group of sensitive probes in the concrete specimen and with appropriate dimensions, so that the quantity and location of the chloride penetration into the concrete is found as it actually exists. To eliminate the imbalance in the creation of readings, there are many laws that have been relied upon, of which what is available while others have been developed and adopted in this new sophisticate way.

Ohm's law states that the resistance of any material is defined as:

$$R = \frac{V}{I}$$

(2)

Where: $R$: resistance of material, (ohms); $V$: applied voltage, (volt) and $I$: passed current, (amber). The resistivity of any material is defined as [13]:

$$\rho_{\text{Elec}} = \frac{R A}{D}$$

(3)

Where: $\rho_{\text{Elec}}$: resistivity of material, (Ω-m); $A$: cross-sectional area, (m$^2$) and $D$: specimen length (distance between two electrodes), (m).

So that the resistivity is defined as the resistance of the interior concrete area between each two probes. And as expressed by the new formula:

$$\rho_{\text{Elec}} = \frac{R A}{D} = \frac{R (L \ast d)}{D}$$

(4)

Where: $A$: interior concrete cross-sectional area between two probes, (m$^2$); $d$: diameter of probe, (m); $L$: length of probe, (m) and $D$: distance between two probes.

The electrical conductivity of a porous material is determined as the mutuality of resistivity [19, 20]:
\[ \sigma_{\text{Elec.}} = \rho_{\text{Elec.}}^{-1} \]  

(5)

Where: \( \sigma_{\text{Elec.}} \) is the electrical conductivity of the materials (Siemens / m).

Conductivity being a fundamental property of the material, whereas it is depends upon the shape and size of material.

There are two main types of tests that can be done to determine a concrete resistivity value, involving either a direct current (DC) or an alternating current (AC) [13, 15]. Direct current resistivity can be measured by applying a voltage between two probes with the concrete sandwiched between them.

The use of a DC voltage results in polarization of the electrolyte and the formation of hydrogen and oxygen gas at the measuring electrodes [13, 15]. This polarization potential opposes the flow and manifests itself in the form of a reduced current for a given applied voltage, \( V \),

\[ R = (V - V_p) I^{-1} \]  

(6)

Where: \( V_p \) is the polarization potential.

If it is assumed that this polarizing effect is constant at different applied voltages, this effect can be accounted for by taking current measurements at two different applied voltages. The polarization potential is given by equation (7) and as mentioned by [13].

\[ V_p = V_1 I_2 - V_2 I_1 (I_1 - I_2)^{-1} \]  

(7)

Where: \( V_1 \) and \( V_2 \) are the two applied voltages, \( I_1 \) and \( I_2 \) are the corresponding currents.

### 3.6.2 Test setup

The conductivity technique used direct current-voltage, to characterize the effect of saturation on the chloride penetration, to measure the electrical conductivity (Equation 5) of the concrete specimens. Conductivity technique consists of a power supply instrument, an electrical multi-meter and tester cables, were connected with each other and with stainless probes which embedded in concrete test specimens. The electrical conductivity was measured from the probes grid as each two vertical neighboring probes formed probe pair, which gave 11X12 data point.

### 3.6.3 Electrical conductivity calibration

Eight calibration samples, (75 x 75 x 50) mm, were casted and cured for 28 days. Following that, twelve times of drying were conducted. Each time, the specimens were placed into a 105°C drying oven for 2 hours; the final drying was conducted for 24 hours. After each drying step, the samples were removed from the oven, wiped, weighted, and then returned to oven drying, finally (after 24 hrs.) the electrical conductivities of all samples were registered. After that, they conditioned in the controlled room and were submerged, wrapped, and sealed in plastic bags, contain a series of NaCl solutions with concentration 0.0 %, 0.5 %, 1.0 %, 1.5 %, 2.0 %, 2.5 %, 3.0 % and 3.5 % by weight of water, and kept for three months respectively. The time allowed for the water to equalize conservative; it was decided based on ASTM D2216-10 [21] whereby a much larger cylinder samples were used.

Each sample had a number of distributed probes with L=55mm, D=2.5mm, d=20mm. For each water level, the water contents of the samples were measured by weights and the electrical conductivity (Calibration data) were read at different locations of the samples. However, the development ECT depending on values data that taken from the calibration samples, geometric constants of the probe configuration used in the ECT test were not taken into account.

### 3.7 Porosity test
For numerical modelling, ASTM C 642-97 saturation technique was used to determine the porosity of five concrete samples. ASTM standard procedures were employed in water saturation samples by using cylinder samples 100 mm diameter with 50 mm height (Figure 4: a). The samples were dried in the oven at 105°C for 48 h to determine the oven-dry mass (Figure 4: b). In order to determine the saturated surface-dry mass in water saturation technique, the samples were simply immersed in water at approximately 48 h.

3.8 Hydraulic conductivity test (centrifugal technique)

For purposes of the numerical modelling, a centrifuge test was performed to determine the saturated hydraulic conductivity of the concrete samples.

The electrical machine rotor of the centrifuge (Figure 5: a) consists of six tottering type cylindrical buckets capable of carrying six test samples (Figure 5: b) in one test turn on. All of the six buckets can be used with each other with six sample holders for testing. The combined mass of the sample, the holders and the buckets should be equal to avoid rotary imbalance.

For all samples, during its 25-30 hours of experimental time period, the centrifuge was stopped nearly five to six times to get a number of data sets. Each data set consisted of initial and final level of solute in the water tube (Figure 5: c), centrifugation time, and initial and final weight of concrete sample holder set up. The diameter-length of the samples was measured at three locations by means of dial gauge and the average value was used for calculations.

4. Experimental Results

4.1 Calibration of development ECT

In order to decrease the mistake of electrical conductivity polarization, two different voltages (V) were applied to each specimen and the current (I) corresponding to each voltage was measured. The polarization potential was calculated for each set of measurements using equation (7). Once the polarization potential was known, the resistance was obtained using equation (6). The use of higher voltage levels was avoided since the higher voltage produces heat during measurement that could
change the saturation of the specimens. It was noticed that the voltage levels (5.0V and 2.5V) were all above the level of polarization potential drop, which is typically ~ 1.8 V.

4.2 Chloride content and electrical conductivity relation

After the 28 days of the eight samples curing, the electrical conductivities, of each sample, were measured. Water contents (w) of samples, according its weight, were recorded during the oven drying steps, and after that the electrical conductivities were measured for all samples. After 90 days of the immersing these samples in the series of chloride solutions and as mentioned earlier. Currents, of the seven steps of electrical conductivity tests, were made for every 15 days, then collected and converted to electrical conductivities by using equation (5). For each sample, twenty-four readings were made from twenty-four pairs of probes formed by sixteen probes in each sample. Considering the penetration of solutions into the samples during this test, almost two readings near the sample center were not taken into account. For each samples, the results did not show an uneven reading of electrical conductivity values; therefore, the average value was taken for each sample and test. The samples soaked in fresh water have a lower electrical conductivity than a sample soaked in salty water. For samples soaked in salt solutions of different concentrations, the σ-w curves were drawn together. This fact suggests that the electrical conductivity results measured by this development Technique are very sensitive to chloride concentrations in the concrete medias. From the electrical conductivity values of the samples, it can notice the chloride concentration of solution did not fully absorbed in samples due to the porous nature of concrete samples. Mathematical analysis of these values was done and the concentrations were converted to corresponding values. For the seven reading data of each sample, a calibration equation was suggested for these results with 0.9963 linear regression value, and as shown below (Figure 6).

![Figure 6. Electrical conductivity verse chloride contents.](image)

So that the relationship between chloride content (%) and electrical conductivity (S/m) is can be gotten by the following calibration equation:

\[ C_x = 5.3236 \times EC - 0.1735 \]

Where: \( C_x \): typical concentration inside specimens.

Therefore, in this project, the electrical conductivity measurement is a chief used as a supplementary data for the measurement of the chloride contents change inside concrete specimens.

4.3 Effects of cracks on chloride profile
In order to get insights inside the concrete specimens and to compare the effect of the exposure conditions on the chloride penetration, the profile of chloride penetration for the full depth levels were chosen and presented as:

4.3.1 Chloride penetration of surfaces (1.5 cm from the corner of specimens), where it was found that the concentration increased with increasing of water head and as illustrated in Figure 7.

4.3.2 Chloride concentration of crack end and as illustrated in figure (8: a and b). It can be observed that cracked specimens with the crack depth 10 cm and 6 cm have the same influence of chloride concentrations with depth, whereas the penetration depth decrease with a long line of flow. This fact was due to semi uniform of concrete texture and for the good and self-compacting of all specimens in this study or the selected cracks depths with widths were not had a significant affect, so that the whole used of water heads were had same energy of penetration. The differences in chloride concentrations were appeared clearly near the crack tip, whereas these differences began to hidden with depth. Meanwhile, the increasing of water head had great impact on depth of chloride concentration in crack category. It can notice that smallest and the largest difference in concentrations due to crack width affect smaller than the smallest concentrations of water head affect. So that these above data gives an indication that the water head has the largest impact factor from crack width, on the concentrations of chloride penetration.

4.4 Centrifuge and porosity tests
The saturated hydraulic conductivity and porosity values were obtained of the test samples. The test values were not appearing with gap of results, so that the average value was taken of each test.

5. Numerical Simulation
The finite element method was used to numerically solve the penetration equation (1). For the numerical simulation the COMSOL Multiphysics software was used to investigate the chloride penetration in concrete specimens. COMSOL software utilizes Transport of Diluted Species (TDS) to compute the concentration field of a convection dilute solute in a porous material. Numerical solutions of the problem are based on the compressible flow physics solved by Darcy equations for conservation momentum and continuity equation of conservation mass. For a higher coupled flow the non-steady (time-dependent) analyses have been used.

The 2D numerical model was set according to the cracked wall specimens used in the experimental test for purposes of comparison with the model. It consists of specimens with square domain (0.25m and 0.25m in width and depth, respectively) representing the concrete wall with a varied crack size at mid of the specimens.

Determining the appropriate grid domain along with a suitable mesh cell size is a critical part of any numerical model simulation. In COMSOL, grid generation is the most user-friendly tools to obtain the accurate solution. If good quality of mesh is generated, one can obtain realistic results from the numerical models. The mesh statistics of all models were meshed into 6776-7226 triangular elements; the number of boundary elements was between 364 and 412.

Figure (9) shows the boundary condition that applied to solve the mathematical equations govern chloride solute penetration into concrete structures. In the model system, the top line and crack line were exposed to solute chloride in water as boundary conditions. The other boundaries had a no flow condition imposed to represent an impermeable coating on the real specimens.

![Figure 9. Model boundary conditions.](image)

Concrete Material properties, used for the modelling, are listed in table 2. The initial chloride concentration inside the concrete was assigned to be 0.05 for all the analyses, due to the concentration values were measured at time 0 hr. of the EC test. The data matrices reported in the chloride concentrations of calibration samples which tested by the ECT (Section 4.2) were linearly interpolated automatically to the node resolution of the model, so that chloride concentration values outside of the data matrix were extrapolated to be a constant value (2.5%) as the maximum boundary of the concentration data matrix. The temperature was kept constant during the analysis at 36°C since all the experiments were carried out at this temperature. Concrete porosity was taken to be equal to 0.1056 according to the average results of the porosity test reported in Section (4.4). To simulate the diffusion into the model, the average hydraulic conductivity value was reported as centrifugal test results for testing of the six samples. The time dependent solver was used to solve the model with 312 hours of exposing to request boundary conditions and as shown in figure (10).

| Property name | Symbols | Value | Unit |
|---------------|---------|-------|------|
| Pressure (Seawater) Head | H | 2 or 5 | m |
| Parameter                                      | Symbol | Value     | Unit   |
|-----------------------------------------------|--------|-----------|--------|
| Exposure chloride concentration              | $C_s$  | 2.5       | %      |
| Initial solute content of matrix             | $C_0$  | 0.05      | %      |
| Density of concrete                           | $\rho$ | 2435      | Kg/m$^3$ |
| Porosity of matrix                           | $\Theta$ | 0.1056   |        |
| Hydraulic conductivity                        | $K_{sat}$ | 3.5E-12  | m/sec |
| Temperature                                   | $T$    | 36        | $^\circ$C |
| Gravity                                       | $g$    | 9.81      | m/sec$^2$ |

2m water head, 0.5mm crack width and 6cm crack depth.

2m water head, 1.0mm crack width and 6cm crack depth.

2m water head, 0.5mm crack width and 10cm crack depth.

2m water head, 1.0mm crack width and 6cm crack depth.

5m water head, 0.5mm crack width and 6cm crack depth.

5m water head, 1.0mm crack width and 6cm crack depth.
6. Discussions and Comparison of Results

To evaluate how much the similarity can reflect the concentration and depth of the chloride penetration from numerical models to experimental specimens and how much the efficiency of COMSOL Multiphysics to simulate such problems, the comparison between experimental and numerical results were done. A vertical section was taken for both surface side and crack side, where all concentrations across the vertical line (section), are sketch as concentration over depth. For surface side, the experimental specimen and numerical model have a similar action; therefore, a line distanced 0.015 m from one external edge (left) was used as reference data for all simulation results. For both crack types, also a vertical line was drawn from the crack end. The experimental results were imported, as data tables, in COMSOL Software.

6.1 Surfaces comparison

The comparison results of the surfaces (specimen surface and model surface) were revealed an acceptable coincidence and as shown in figure (11: a and b). It is important to confirm that due to precise values of simulation inputs (hydraulic conductivity, porosity, initial value of chloride, densities, etc.), furthermore, that good modelling of water heads with experimental specimens (HPT) and perfect measurements of the development ECT.

6.2 Cracks comparisons

Due to the crack was treated as an open surface in numerical modelling, where the whole model meshed with same mesh cells, so that comparisons, observed from figure (12), indicated that cracks don’t give similar behaviours. A deviation from the expected perfectly symmetric behaviour of crack
of specimens with the model, was observed. This was probably caused by the non-uniform compaction around the shim insertion in specimens. And this is the target of using this type of cracks (artificial crack) instead of natural cracks, where a micro cracks induced during the shim pull-out process after literature time limits. The difference between results clearly visible with 2m water head (Figure 12: a, b, c and d), but with increased water head, this effect begins to decline and as observed in figure (12: e, f, g and h), where the difference in results is often observed in the proximal depths (nearest to exposure positions). However, we note that the distant depths give an approximate result. All this indicates that the energy of the water head dissipates in the distant depths of concrete media. From this it can be concluded that the crack with high water head, can act as a free surface or as an equivalent porous medium with a very small error rate that can be neglected. Same trend in the low water head can achieved, but to improve results, slightly lower finer mesh must use in crack mesh geometry, which is faced by specific experiments should be performed to find the roughness of the crack through the experience of hydraulic conductivity for crack itself, then to reach the exemplary solution and standard model.

(a): 2m water head, 0.5mm crack width and 6cm crack depth.
(b): 2m water head, 1.0mm crack width and 6cm crack depth.
(c): 2m water head, 0.5mm crack width and 10cm crack depth.
(d): 2m water head, 1.0mm crack width and 10cm crack depth.
Figure 12. Cracks comparison with varied seawater heads.

7. Conclusions
In this paper, the influence of crack sizes (depth and width) on the chloride penetration in hydraulic concrete structures, which exposed to varied seawater heads, is experimentally and numerically studied. After all that hard and interesting work, some final conclusions can be inferred:

Higher concentration of chloride is obtained at the crack side in comparison with the open surface side of the test specimens, whereas this difference was decrease with increasing head of water.

Chloride penetration depth is increasing with an increasing crack depth, where the most influential factors of the water head and the crack width, on the concentration of penetration chloride, was share of the water head.

Crack depths with widths, at the same exposure of water head, were not having a significant effect on chloride penetration depth. This probably that two used of water heads have the same energy of penetration, or this due to the recently used of concrete mixture of specimens.

Comparisons between the experimental and numerical results, concluded that the numerical ones, which obtained using Finite Element analysis (COMSOL Multiphysics Software), agreed well with the experimental ones which gained from experiment tests for the cracked specimens.

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References
[1] C.-M. Aldea, S. P. Shah, and A. Karr, "Effect of cracking on water and chloride permeability of concrete," *Journal of materials in civil engineering*, vol. 11, pp. 181-187, 1999.

[2] P. P. Win, M. Watanabe, and A. Machida, "Penetration profile of chloride ion in cracked reinforced concrete," *Cement and concrete research*, vol. 34, pp. 1073-1079, 2004.

[3] M. Ismail, A. Toumi, R. Francois, and R. Gagné, "Effect of crack opening on the local diffusion of chloride in inert materials," *Cement and Concrete Research*, vol. 34, pp. 711-716, 2004.

[4] T. Luping, L.-O. Nilsson, and P. Basheer, *Resistance of concrete to chloride ingress*: Taylor and Francis, London, 2012.

[5] H. Hilsdorf and J. Kropp, *Performance criteria for concrete durability*: CRC Press, 2014.

[6] M. Alemi, D. Nielsen, and J. Biggar, "Determining the Hydraulic Conductivity of Soil Cores by Centrifugation1," *Soil Science Society of America Journal*, vol. 40, pp. 212-218, 1976.

[7] R. Mitchell, "Centrifuge modelling as a consulting tool," *Canadian Geotechnical Journal*, vol. 28, pp. 162-167, 1991.

[8] D. N. Singh and A. K. Gupta, "Modelling hydraulic conductivity in a small centrifuge," *Canadian Geotechnical Journal*, vol. 37, pp. 1150-1155, 2000.

[9] A. Niwa and R. W. Clough, *Shaking table research on concrete dam models*: University of California, Earthquake Engineering Research Center, 1980.

[10] M. Otieno, M. Alexander, and H.-D. Beushausen, "Corrosion in cracked and uncracked concrete— influence of crack width, concrete quality and crack reopening," *Magazine of Concrete Research*, vol. 62, pp. 393-404, 2010.

[11] A. Blagojević, "The influence of cracks on the durability and service life of reinforced concrete structures in relation to chloride-induced corrosion: A look from a different perspective," TU Delft, Delft University of Technology, 2016.

[12] M. Safehian and A. A. Ramezanianpour, "Assessment of service life models for determination of chloride penetration into silica fume concrete in the severe marine environmental condition," *Construction and Building Materials*, vol. 48, pp. 287-294, 2013.

[13] G. Monfore, "The electrical resistivity of concrete, Portland Cement Association," *Research and Development Laboratories, Skokie, IL*, 1968.

[14] H. Whittington, J. McCarter, and M. Forde, "The conduction of electricity through concrete," *Magazine of concrete research*, vol. 33, pp. 48-60, 1981.

[15] I. Hansson and C. Hansson, "Electrical resistivity measurements of Portland cement based materials," *Cement and Concrete Research*, vol. 13, pp. 675-683, 1983.

[16] M. Saleem, M. Shameem, S. Hussain, and M. Maslehuddin, "Effect of moisture, chloride and sulphate contamination on the electrical resistivity of Portland cement concrete," *Construction and Building Materials*, vol. 10, pp. 209-214, 1996.

[17] R. Polder, C. Andrade, B. Elsener, Ø. Vennesland, J. Gulikers, R. Weidert, et al., "Test methods for on site measurement of resistivity of concrete," *Materials and Structures*, vol. 33, pp. 603-611, 2000.

[18] J. Weiss, K. Snyder, J. Bullard, and D. Bentz, "Using a saturation function to interpret the electrical properties of partially saturated concrete," *Journal of Materials in Civil Engineering*, vol. 25, pp. 1097-1106, 2012.

[19] A. Atkinson and A. Nickerson, "The diffusion of ions through water-saturated cement," *Journal of materials science*, vol. 19, pp. 3068-3078, 1984.

[20] E. J. Garboczi, "Permeability, diffusivity, and microstructural parameters: a critical review," *Cement and concrete research*, vol. 20, pp. 591-601, 1990.

[21] C. J. Korhonen, V. C. Janoo, and C. M. Berini, "Time-domain reflectometry of water content in Portland cement concrete," COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH1997.