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Full Length Article

Characterization of chloride penetration in hydraulic concrete structures exposed to different heads of seawater: Using hydraulic pressure tank

Thair Jabar Mizhir Alfatlawi, Riyadh Abdulabbas Ali Alsultani *

Department of Civil Engineering, University of Babylon, Babil 51001, Iraq

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ABSTRACT

Hydraulic Concrete Structures (HCS) must be in good condition during their service, so many studies have been carried out over the last few decades to predict the robustness of their structures. Due to the porous nature of these structures, the chlorides, which are present in seawater, are penetrated and corroding their reinforcing iron. Moreover, these structures are often cracked and become more vulnerable to degradation. Based on the principles of modelling and simulating, there is a difficult issue of similitude the high water head and interaction with HCS, so a new laboratory method called Hydraulic Pressure Tank (HPT) has been submitted for purposes of simulate dozens meters of water heads and its penetration into aforementioned structures. Experimental specimens were used to test this method and to compare them with numerical results. The experimental results, obtained using this new test, agreed fairly with the results obtained from numerical solutions.

1. Introduction

Concrete is one of the most widely material used in hydraulic structures, for control purposes and for the using of water resources. If it correctly designed and produced, it is a very durable material with a service life up to hundreds of years. However, under certain environmental conditions, the service life of reinforced concrete structures is more limited [1,2]. Seawater contains some aggressive agents that are very harmful to concrete materials, so it can be considered as one of the most severe natural environments affect the HCS. As a result of many phenomena such as fresh concrete bleeding, restrained shrinkage, thermal gradients, freeze-thaw cycles, alkali-aggregate reactions, and can also be induced by external loading, these structures are frequently cracked and the presence of cracks in those structures play an important catalyst role of reducing of service life of reinforcement steel bars and producing loss of structural strength, stability and durability [3].

Early detection of chloride penetration has a very valuable subject for engineers, especially of hydraulic structure researcher and engineers. The successful prediction of this phenomena leads to an understanding of the factors that affect the penetration of chlorine and its concentrations within the concrete, so that the behavior of chloride penetration, in Hydraulic Concrete Structures (HCS), has been simulated typically in the laboratory as in the field studies. In reality the chloride transport properties of cracked concrete are influenced by various factors, such as water levels, crack geometry, concrete composition and exposure conditions.

This study aims to develop a new hydraulic media penetration tests on cracked concrete specimens which subjected to different heads of water. The experimental study investigated the simulation of 2 m and 5 m of seawater head (Pressure head) and its influence in concrete specimens with (250 × 250 × 250) mm dimensions and with artificial crack. The specimens were pre-cracked, using a shim copper plate to create artificial cracks in the middle dimension of specimens and before casting the specimens, with a dimensions (0.5 and 1.0) mm as crack width and (6 and 10) cm as crack depth. Assessment was carried out on the basis of some physical properties (chloride contents in seawater and its penetration in mentioned concrete specimens). Therefore the chloride distribution profile was monitored by using electrical technique at 312 h of exposure to water head coupled with 3.5% NaCl to simulate the typical marine environment of seawater [4].

Numerical results were obtained using a develop two dimensional model with finite element analysis (Comsol Multiphysics Software) by simulating chloride penetration depth in cracked concrete considering the real microstructure including cement paste, voids and aggregates. Comparisons between the results, on chloride penetration depth with concentration, concluded that the numerical ones obtained, using the mass diffusion and convection

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* Corresponding author.
E-mail address: Reyadabedalabasali93@gmail.com (R.A.A. Alsultani).

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modulus and Darcy's law, conformable with the experimental ones which analyzed as 2D color images with Matlab Software.

2. Idea details

2.1. Chloride ion transport

Chloride transport in concrete is a complex process, involving mechanisms such as diffusion, convection, capillary suction or by any combination of these, flow with flowing water, accompanied by physical and chemical binding [5].

The governing mechanisms of transport in HCS depend on the exposure conditions and transport mechanisms embodiment in water-retaining structures because of a water pressure which applied, by water head, on apparent face of it structures. Since this study studies the ingress of chloride ions in submerged cracked concrete structures, so that the most important and often governing transport processes, in these fully or semi-fully water saturated structures, are convection and diffusion [6].

2.2. Test's principles

Under saturated conditions, as submerged members of concrete structures which are exposed to a marine environment, water flow is driven by a pressure gradient according to Darcy's law.

Darcy's Law can also be expressed in terms of pressure head with the relation of pressure p to the total hydraulic head H or the pressure head H_p:

$$H = H_p + D \tag{1}$$

where: H: hydrostatic head,H_p: pressure head and D: elevation head.

As the retained water in concrete structures, generally water flowing conform to the two laws of motion as in open channels; the law of conservation of linear momentum and the law of conservation of energy. For a cracked hydraulic structures, the law is commonly expressed as "pressure is equal to the change head with respect to time". The law of conservation of energy is commonly expressed in hydraulics that exposed to water head. Fig. 1 shows the flow configuration for the studied cracked concrete structures system:

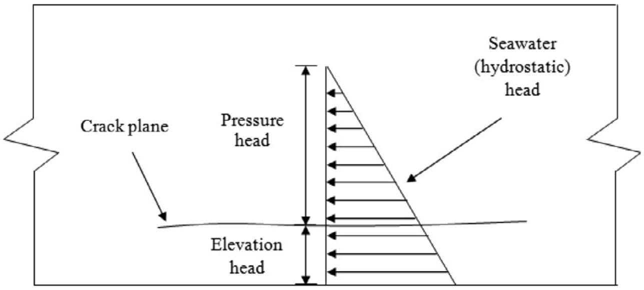


Fig. 1. Section of the HCS.

2.3. Dimensional analysis

Dimensional analysis is a mathematical based approach used to analyze a certain phenomenon or problem having different affected physical quantities to produce a relationship connects them by identifying their fundamental dimensions. For simulation any hydraulic phenomenon, it is necessary to analyze the relevant parameters of the prototype and the laboratory model. Once, the basic (prototype/model) scale ratio is known, collected data from the experimental model can be translated to equivalent value on prototype depending on dimensionless parameters such as (Froude Number, Reynolds Number, Euler Number, Mach Number, etc.).

The current study focuses on the field and hydraulic characteristics of the seawater penetration in concrete structures with presence of cracks. The factors that affect this phenomenon was described by many researchers [7–10] and as arrange in Eqs. (2) to (4):

For seawater characteristics

$$f1(C_s, H, \rho, \mu, g, T) \tag{2}$$

Where:

C_s = surface (seawater) chloride concentration; %,
H = pressure (seawater) head; L,
ρ = solute density; FT^2L^{-4},
μ = seawater dynamic viscosity; FTL^{-2},
g = earth gravity; LT^{-2}, and
T = Temperature; °C

For concrete structures characteristics

$$f2(L_S, W_S, D_S, L_{cr}, W_{cr}, D_{cr}, k) \tag{3}$$

Where:

L_S = concrete structure length; L,
W_S = concrete structure width; L,
D_S = concrete structure depth; L,
L_{cr} = length of crack; L,
W_{cr} = crack width; L,
D_{cr} = crack depth; L, and
k = surface roughness; L.

For flow penetration depth characteristics

$$C_x = f3(K, \sigma) \tag{4}$$

Where:

C_x = chloride penetration depth; L,
K = velocity of solute penetration (Hydraulic conductivity); LT^{-1}, and
σ = surface tension; FL^{-1}.

Therefore, the variables that affect the chloride penetration depth in HCS, which selected in this study, can be summarized as follow:

$$(C_x, C_s, H, \rho, K, g, \mu, \sigma, W_{cr}, D_{cr}, L_{cr}, k, W_S, D_S, L_S, T) = 0 \tag{5}$$

To make sure that the dimensionless quantities which governing this problem, Buckingham theory (π-theorem), was applied, with using ρ, g, and C_x as repeating variables, and as following below:

$$C_x = \frac{C_s}{H}\varnothing\left(\frac{K}{\sqrt{gC_x}}, \frac{\mu}{\rho g^{\frac{1}{2}} C_x^{\frac{3}{2}}}, \frac{\sigma}{\rho g {C_x}^2}, \frac{k}{C_x}, \frac{W_{cr}}{C_x}, \frac{D_{cr}}{C_x}, \frac{L_{cr}}{C_x}, \frac{W_s}{C_x}, \frac{D_s}{C_x}, \frac{L_s}{C_x}, T\right) \tag{6}$$

Where:

$\frac{K}{\sqrt{gC_x}} = (Fr_{C_x})$ Froude Number denoted by distance C_x as characteristics length; dimensionless,
$\frac{\mu}{\rho g^{1/2} {C_x}^{3/2}} = (Re_{C_x})$ Reynolds Number denoted by distance C_x as characteristics length; dimensionless,
$\frac{\sigma}{\rho g {C_x}^2} = (We_{C_x})$ Weber Number denoted by distance C_x as characteristics length; dimensionless.

$$\text{Hence}C_x = \frac{C_s}{H}\varnothing\left[F_r, R_e, W_e, \frac{k}{C_x}, \frac{W_{cr}}{C_x}, \frac{D_{cr}}{C_x}, \frac{L_{cr}}{C_x}, \frac{W_s}{C_x}, \frac{D_s}{C_x}, \frac{L_s}{C_x}, T\right] \tag{7}$$

From the above equations (Eqs. (6) and (7)), and as pre mentioned, it can concluded that the chloride penetration depth in concrete structures was effect by water head, surface chloride concentration, crack size, structure dimensions and temperature. Also it can notice that surface tension and dynamic viscosity, represented by Webber Number and Reynolds Number respectively, are list as an effect factors. Due to high heads of water that restricted this problem, it can said their affect may not significant or it can do without them (μ and σ), by measuring hydraulic conductivity (K), represented by Froude Number.

2.4. Hydraulic similitude

The correlation between physical quantities in the model and the prototype is called similitude. For complete similarity between model and prototype, three similarities must be satisfied; they are geometric, kinematic, and dynamic similitudes. An important consideration in the design of the experimental model is the length scale ratio, several factors and limitations must be included and taken into account in order to choose a suitable length scale ratio such as: the available space, construction cost, the limitations of other parameters similarity.

There are a lot of problems that have been encountered in modelling such phenomena "Penetration flow within the cracked structures". These problems and the most difficult is the geometry of the cracks, since when the representation of the normal without a scale ratio is in itself very difficult, however, if a scale ratio is used, its size is reduced to such a time. In order to study this phenomenon with high accuracy, scientific application of the simulation principles, and depending on literature [10,11], so it was taken an appropriate size segment of the study structure, with sizes of cracks conform to reality, as well as for the others influencing factors, such as seawater head, salinity ratio (chloride content), velocity of penetration, etc.

Consequently, this approach in terms of the principles for modelling phenomena, the following relationships were found:

$$L_r = \frac{L_p}{L_m} = 1 \text{ for concrete structure and crack geometry} \tag{8}$$

$$H_r, C_{sr}, V_r, \mu_r, \sigma_r, \rho_r, k_r, T_r = 1 \tag{9}$$

Where:

L_r = length scale ratio; dimensionless,
L_p and L_m = length of prototype and model, respectively; L, and,
$H_r, C_{sr}, K_r, \mu_r, \sigma_r, \rho_r, k_r, T_r$ = pressure head, surface (seawater) chloride concentration, velocity of chloride solution penetration (hydraulic conductivity), seawater dynamic viscosity, surface tension, solute density, surface roughness, and temperature, for prototype to model respectively.

2.5. 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 [12–14], 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:

All these samples were done with a same mixture and as reported in Table 1. After 24 h 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.

Table 1
Mixing proportion of concrete materials and concrete properties (adopted from [15]).

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

2.6. Experimental design

The laboratory specimens in this experimental study represent segments of a prototype wall used to retaining water. The vertical section of a typical retaining wall was cracked with varied crack geometries, and was subjected to different direct contact pressure head. A specimen configuration scenario is selected to simulate the real-life situation (Fig. 2). A large governing dimensions to build present study models, 0.25 m long, 0.25 m wide, 0.25 m thickness, to avoid mistake in precise identification of chloride penetration depth in samples, another limitation is the large weight of the model is the largest possible to carry (Fig. 3).

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 center of the mold. Before casting the concrete mixture, shims, with a (250 × 60 and 250 × 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 h curing the plate was dragged out totally and as presented in Fig. 3a.

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

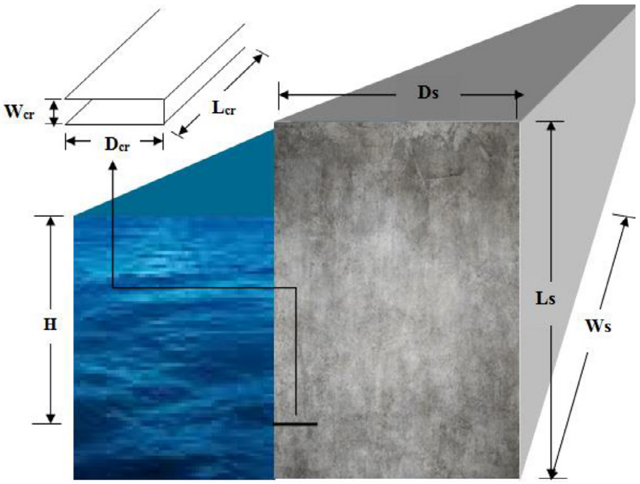


Fig. 2. HCS prototype dimensions.

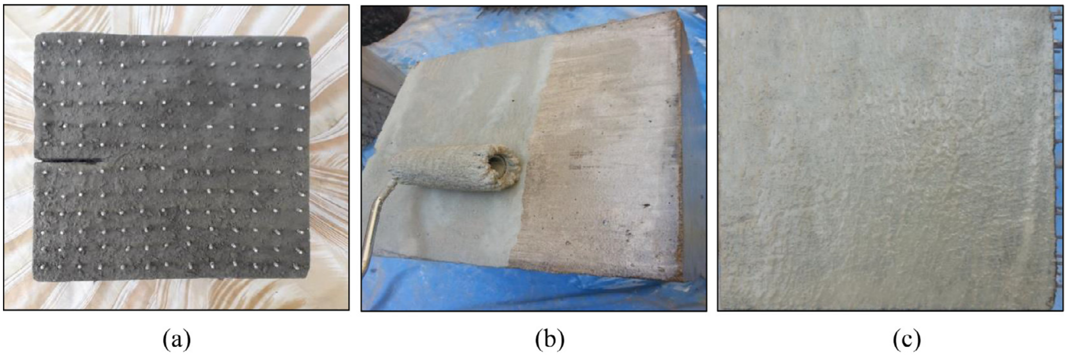

(a) (b) (c)

Fig. 3. Preparation of specimens (a): Creation of crack. (b): Coating with epoxy. (c): Final-finished of specimens.

the fill of all open pores in the concrete surfaces (Fig. 3b and c). Care was taken to keep the epoxy from filling the cracks.

Accordingly, a suitable length scale ratio was found to be used. The studied parameters are varied throughout the present study according to the following:

- Water head (2 and 5) m,
- Crack depth (6 and 10) cm,
- Crack width (0.5 and 1.0) mm.

HCS are exposed to wide level of hydrostatic head, therefore there is a complex to simulate the flow in these structures. The recent laboratory method was innovated to dispose of the medelling onerousness and to get results approached to reality. So that the test method, based on the non-steady state which used predominantly for the chloride penetration in experimental method, involves placing a concrete specimens in tank semi-filled with chloride solution and applying head of water, as required or as simulation of structure prototype, across one face of specimens by using application of an air pressure. A chloride-containing solution is introduced to one face, other faces were coated by epoxy, of the concrete and a pressure is applied. This pressure is maintained for a given period of time after that concrete specimen is removed from the tank and tested for chlorides by electrical technique using group of rode sensors inserted in the specimens. The HPT was manufactured (Fig. 4) to get rid of the difficult modelling of a wide range of water heads. An air compressor instrument (Fig. 5) was used to press the solute of 3.5% NaCl, found in the tank, inherent

Fig. 4. HPT manufactured.

Fig. 5. HPT with air compressor instrument.

concrete samples through uncoated faces over time and at any pressure that required.

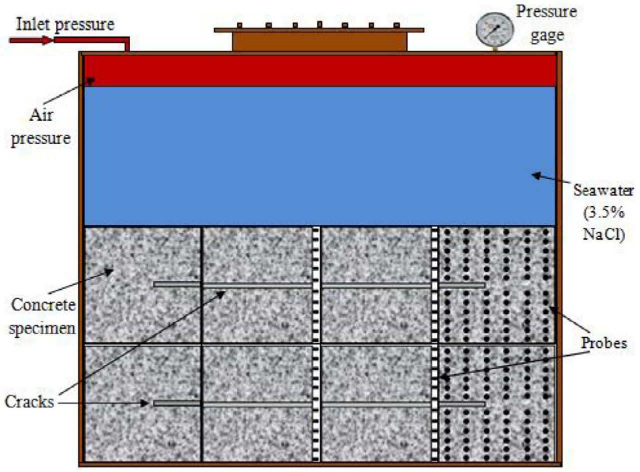
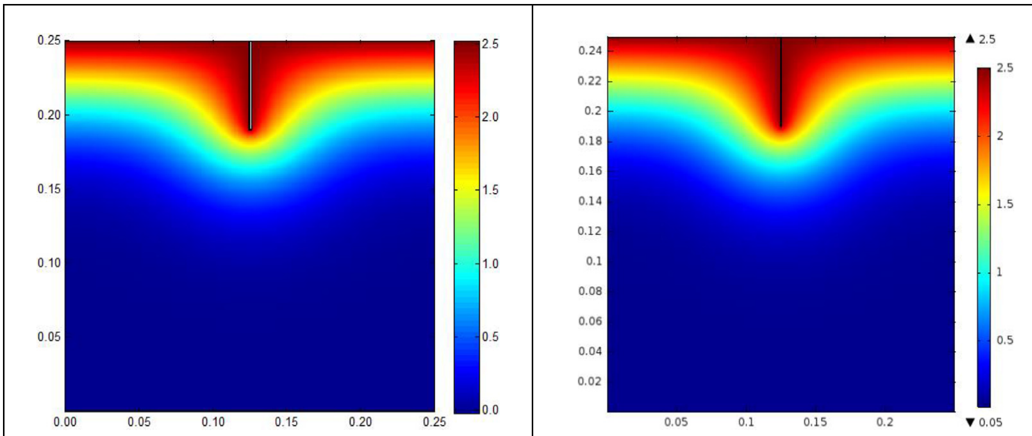


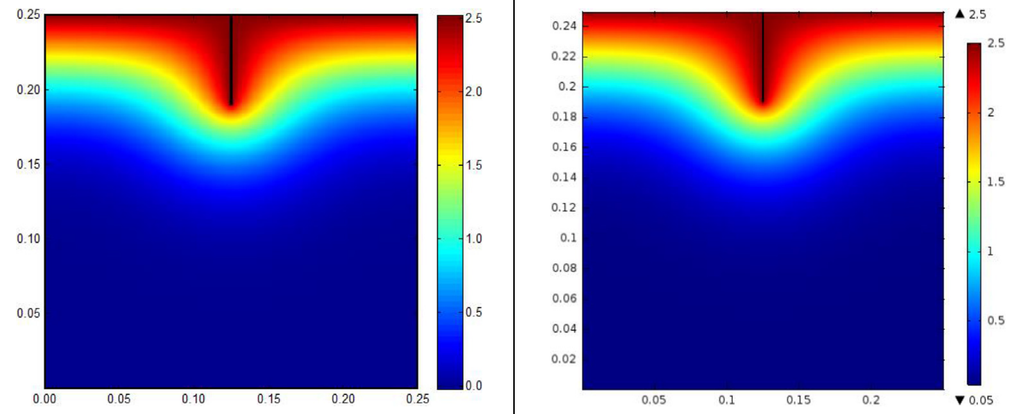
Fig. 6. Scheme cross section of the HPT.

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. Furthermore it, a rubber frame was used between the top cover and tank, to make sure that no



Exp.(2m, 6cm and 0.5mm as water head, crack depth and crack width, respectively.

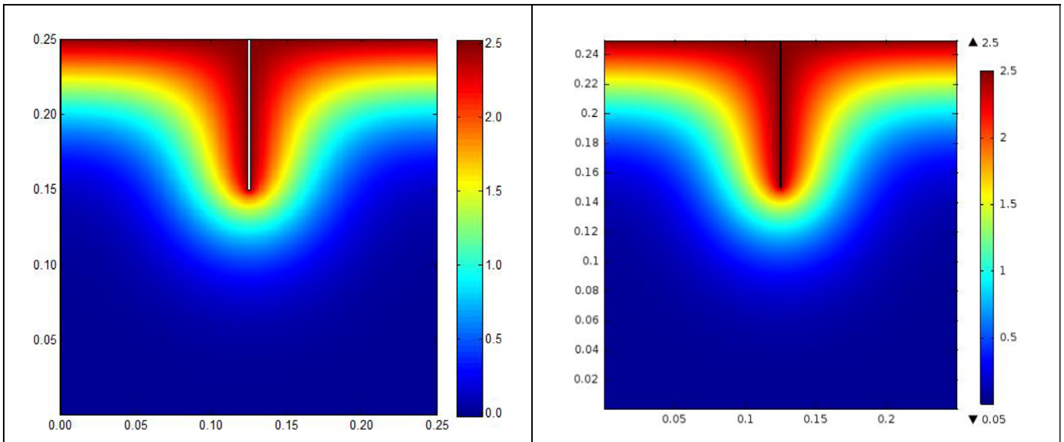
Num.(2m, 6cm and 0.5mm as water head, crack depth and crack width, respectively.



Exp.(2m, 6cm and 1.0mm as water head, crack depth and crack width, respectively.

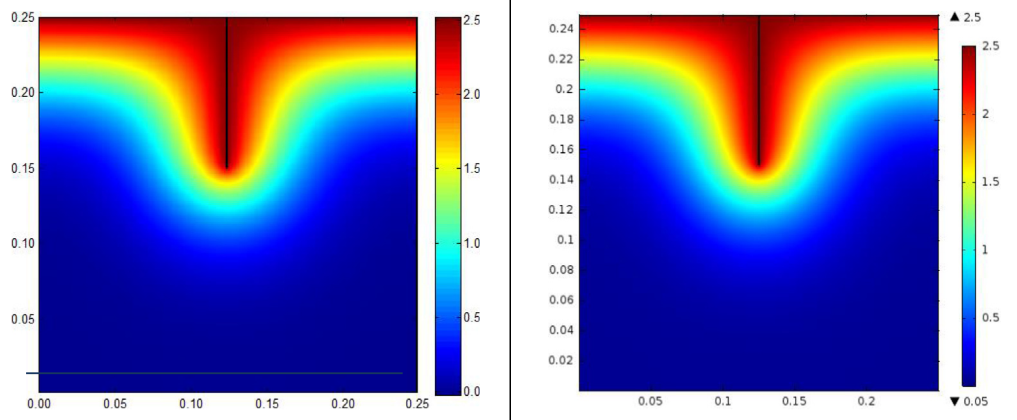
Num.(2m, 6cm and 1.0mm as water head, crack depth and crack width, respectively.

Fig. 7. Experimental and numerical results at 312 h of the exposure conditions.



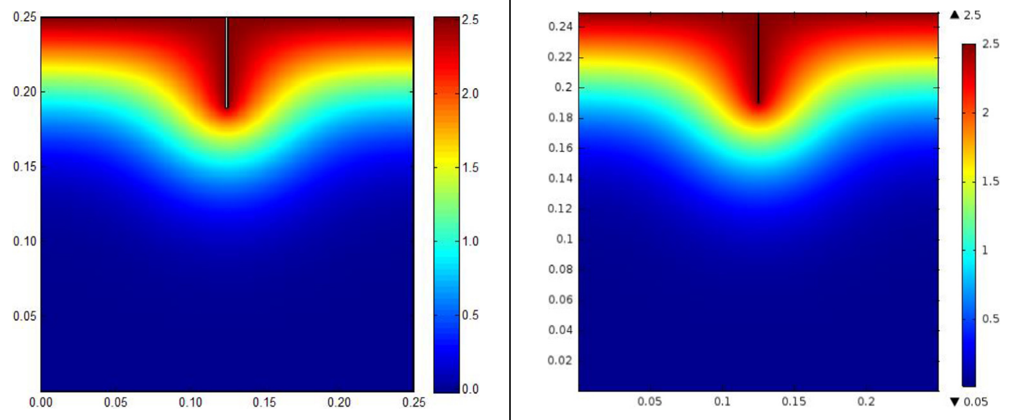
Exp.(2m, 10cm and 0.5mm as water head, crack depth and crack width, respectively.

Num.(2m, 10cm and 0.5mm as water head, crack depth and crack width, respectively.



Exp.(2m, 10cm and 1.0mm as water head, crack depth and crack width, respectively.

Num.(2m, 10cm and 1.0mm as water head, crack depth and crack width, respectively.



Exp.(5m, 6cm and 0.5mm as water head, crack depth and crack width, respectively.

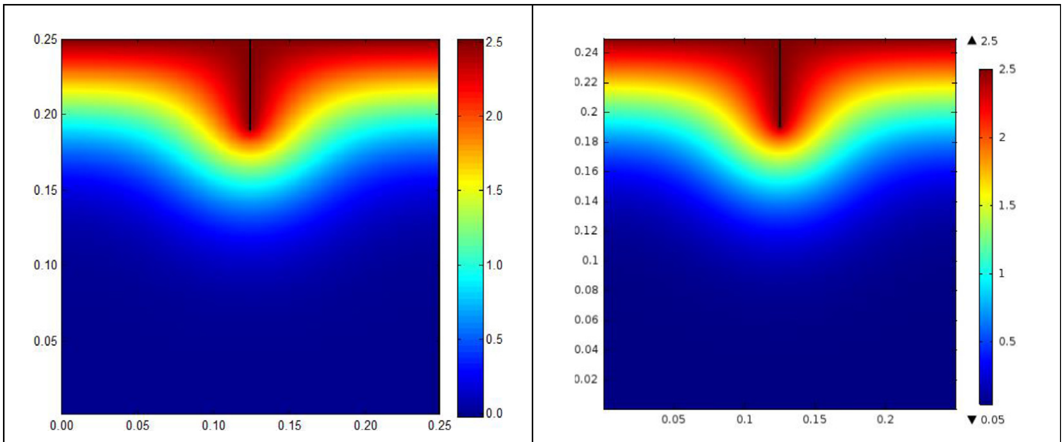
Num.(5m, 6cm and 0.5mm as water head, crack depth and crack width, respectively.

Fig. 7 (*continued*)

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 20,000 pa or 50,000 pa which will be equal to the 2 and 5 m of water heads. Subsequently, these driven water causing a penetration of solute in cracked concrete specimens (Fig. 6).

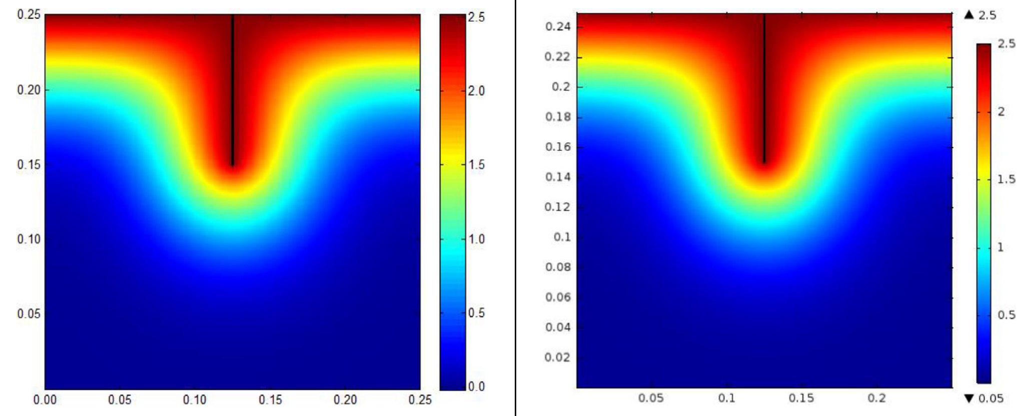
3. Results and discussion

The experiments were carried out for the four laboratory specimens by using the new test method, where the pressures were exerted to find results and through which to find the accuracy of the device manufactured. The specimens were then extracted from the pressure tank and the penetration and spread of the chloride was tested using the electrical test. Then the results were con-



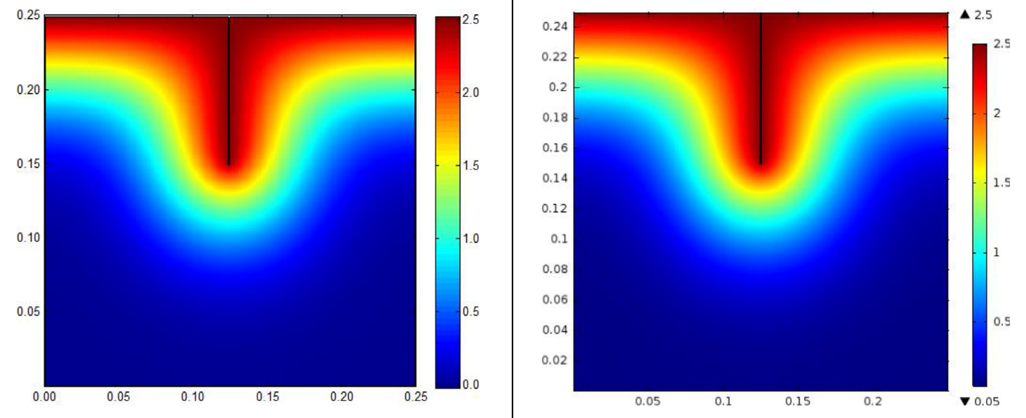
Exp.(5m, 6cm and 1.0mm as water head, crack depth and crack width, respectively.

Num.(5m, 6cm and 1.0mm as water head, crack depth and crack width, respectively.



Exp.(5m, 10cm and 0.5mm as water head, crack depth and crack width, respectively.

Num.(5m, 10cm and 0.5mm as water head, crack depth and crack width, respectively.



Exp.(5m, 10cm and 1.0mm as water head, crack depth and crack width, respectively.

Num.(5m, 10cm and 1.0mm as water head, crack depth and crack width, respectively.

Fig. 7 (*continued*)

verted to a two-dimensional image using Matlab Software for each time test and specimen.

The results that were found through the numerical solutions, “Fluid Flow in Porous Media and Subsurface Flow with Darcy’s Law” coupled with “Transport of Diluted Species (TDS) with convection and diffusion transport”, captured and put in the nature statement as a two-dimensional image using Comsol Multiphysics Software for each time test and model.

After tested and gotten the results of the numerical models and experimental specimens. The comparing between them were done and as shown in Fig. 7. The artificial crack forms are shown as a straight line at the middle position of images.

After analyzing the above experimental and numerical results, it can be concluded that the 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.

4. Conclusion

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:

- 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.
- The new laboratory technique "HPT" is the more suitable method for determining the degree of saturation and penetration of chloride ions into HCS for the following reasons: 1) Typical and very accurate results comparing with numerical results, 2) The experimental data could be used to determine the necessary parameters required in specimens when predicting the transport of chlorides in saturated concrete and 3) the experimental has a low cost, easy set-up and the experiment can be performed in a very short time compared to other experiments.

Competing interests

The author declare that they have no competing interests.

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