NUMERICAL SIMULATION OF SALT DESORPTION MECHANISMS AT CONCRETE STRUCTURE SURFACE

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Abstract: Numerical simulation has been conducted for the salt desorption mechanisms at concrete structure surface accompanied by surface water flow such as that by heavy rainfall. The velocity measurement method using markers, and the simulation results for velocity, layer thickness of water flow and salt desorption are discussed.

Keywords: Salt desorption, Surface water flow, Simulation, Velocity measurements

1. INTRODUCTION

All concrete structures are subjected to many environmental actions. These actions have an impact on concrete durability. Examples of these environmental actions are wind, moisture, temperature, and rain. One of the most important environmental actions is salt accumulation on concrete structures. Wind is blowing carrying salt particles from sea side. These salt particles are accumulating on concrete surfaces causing decreasing concrete durability. Another environmental action affecting concrete structures is the washing away process by rain. Washing away can help in removing accumulated salt particles on concrete structures. At the same time salt washing away can be used in maintenance process to increase structure durability. Considering these two environmental actions, any concrete structure is subjected to three main processes. These three processes are desorption, adsorption, and absorption. Desorption is a very fast process as it happens by rain (washing away). Desorption process can occur in few seconds, few minutes, or few hours. Adsorption process is the process at which salt is accumulation on concrete surfaces. It is a slow process as it takes days or months. The slowest process is the absorption process as it takes months to years for salt to penetrate inside any concrete structure.

In this paper, desorption process is studied by getting the surface water flow velocity, water velocity distribution, and salt concentration on concrete surface. The water flow velocity on concrete surface was measured experimentally (see El-Desouky (2001)). After that, a simulation to get the water flow velocity was done. A comparison between the numerical and the analytical solution is done to determine numerical constants (wall shear stresses), and to verify the simulated results. By knowing the water flow velocity distribution, the salt concentration and removal rate can be calculated (see Antonius (2011)). The salt concentration was compared with experimental work by Sadatsuki (2011) to verify the calculated results and to get numerical constants.

2. PROBLEM DESCRIPTION

Surface water flow velocity and thickness distribution are measured and calculated for vertical concrete wall of height 120cm and width 20 cm.

In real case water drops are hitting wall concrete surfaces by a certain mass flow rate, and water is flowing on this concrete surface. To simulate this phenomenon, it was assumed that concrete surface is completely exposed to water flow to prevent localization. The reason for doing that is to prevent solving localization problem which is depending on many factors and water flow is moving in random motion. The simulation and the experimental work were done for a vertical flat concrete wall subjected to water flow from the top as shown in Fig. 1.

3. GOVERNING EQUATIONS

Two-dimensional incompressible fluid flow is considered. No phase change or evaporation is considered at interference. The governing equations "equation (1)" are the continuity equation, and 2-D Navier-Stokes equations (see Harvard (1999)). Numerical simulation has been conducted to solve these equations to get the water flow thickness distribution and the water flow velocity. After
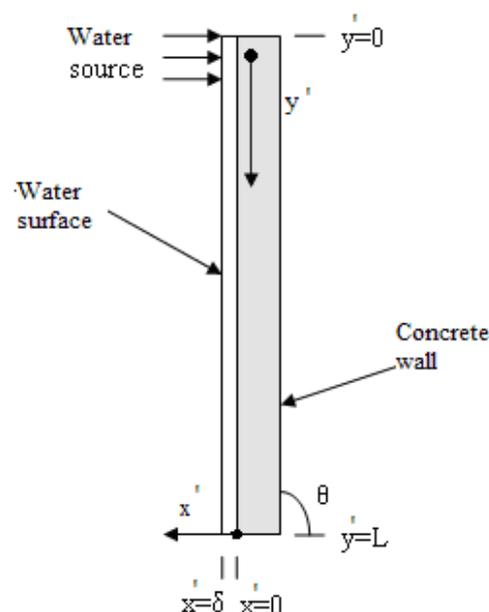
Fig. 1 Problem description

that convection-diffusion equation is used to obtain salt concentration distribution on the wall surface. So, the process which is used to obtain the numerical results can be summarized in the following two steps: 1) solving equation (1) to get the water flow thickness distribution and the water flow velocity distribution with respect to time. 2) By using the steady state water thickness distribution and steady state water velocity; equation (2) will be solved to get the salt concentration, the salt removal rate, and the amount of the washed away salt from the wall surface. To do that; boundary conditions must be specified. Eqs. (4)- (7) are presenting the boundary conditions used to solve these equations. Salt desorption process has two mechanisms depending on the wall condition. The first mechanism is for dry contact condition, and the other one for wet contact condition. By specifying the source term value Q in equation (2), salt desorption can be simulated. Q is a source term which is presenting the rate of salt removal from the wall surface. By specifying its value dry and wet contact condition can be simulated. For this study only dry contact is considered.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \,, \quad \frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{\partial p}{\partial x}+\frac{1}{R_{eo}}(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2})+\frac{1}{Fr_{xo}} \,, \quad \frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{\partial p}{\partial y}+\frac{1}{R_{eo}}(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2})+\frac{1}{Fr_{yo}} \quad (1)$$

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}=D(\frac{\partial^2 c}{\partial x^2}+\frac{\partial^2 c}{\partial y^2})+Q(t,y) \quad (2)$$

where the dimensionless variables are defined by

$$x=\frac{x'}{\delta_o}, \quad y=\frac{y'}{\delta_o}, \quad u=\frac{u'}{u_o}, \quad v=\frac{v'}{v_o}, \quad p=\frac{p'}{p_{atm}}, \quad t=\frac{t'}{\delta_o/u_o}, \quad R_{eo}=\frac{\rho u_o \delta_o}{\mu}, \quad Fr_{xo}=\frac{u_o^2}{\delta_o g \cos(\pi-\theta)}, \quad Fr_{yo}=\frac{u_o^2}{\delta_o g \sin(\theta)} \quad (3)$$

where all prime variables are for dimension variables, x: transverse coordinate, y: stream wise coordinate, u: transverse velocity, v: stream-wise velocity, p: pressure, p_{atm}: atmospheric pressure, t: time, R_{eo}: Reynolds number, ρ: water density, μ: water dynamic viscosity, g: gravitational acceleration, Fr_{xo}, and Fr_{yo} : external force acting per unit volume of water flow in x, and y directions respectively, δ_o: initial film thickness, δ: film thickness, u_o: initial transverse velocity, v_o: initial stream-wise velocity, θ: wall inclination angle measured from the horizontal axis, c: salt concentration in water, Q: source term function of contact condition, and D: diffusion coefficient.

4. BOUNDARY AND INITIAL CONDITIONS

The boundary conditions are given as follows.

At $x = 0$　　$u = 0$, (for high friction) $v = 0$, $\frac{\partial p}{\partial x}=\frac{1}{R_{eo}}\frac{\partial^2 u}{\partial x^2}+\frac{1}{Fr_{xo}}$, (for a specific shear) $\frac{\partial v}{\partial x}=\frac{\tau_o}{\mu}$, $\frac{\partial c}{\partial x}=0$ 　　(4)

where τ_o is a specific shear stress in y-direction

At $x = \delta$　　$u = 0$, $\frac{\partial v}{\partial x}=0$, $\frac{\partial p}{\partial y}=0$, $\left[\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right]\left\{1-(\frac{\partial \delta}{\partial y})^2\right\}-2\frac{\partial \delta}{\partial y}\left(\frac{\partial v}{\partial y}-\frac{\partial u}{\partial x}\right)=0$, $\frac{\partial c}{\partial x}=0$ 　　(5)

At $y=0$　　$u = 0$, $v = v(mass\ flow\ rate)$, $\frac{\partial c}{\partial y}=0$, 　　　　**At $y = L$**　　$\frac{\partial u}{\partial y}=0$, $\frac{\partial v}{\partial y}=0$, $\frac{\partial c}{\partial y}=F$ 　　(6)

where F is salt flux

The initial conditions are given as follows.
At $t=0$　　$c = 0$, $u = u_o$, $v = v_o$, $\delta = \delta_o$ 　　(7)

5. EXPERIMENTAL RESULTS

Finite volume and finite difference methods (see Harvard (1999)) were used to solve previous system of equations to get the water thickness distribution, the surface water flow velocity, and the salt concentration on concrete surface. The value of wall shear stress was not known. Due to that, experimental work was conducted to measure the water flow velocity and the water thickness distribution to determine these constants (see El-Desouky (2001)). These results can also be used to confirm the analytical solution.

Experiment setup is shown in Fig. 2. The target of this experiment is to find a suitable marker and a suitable method to measure the water flow velocity distribution. It was found that EVA (Ethylene Vinyl Acetate copolymer) is a suitable marker to measure the water flow velocity. After making image processing of 16 pairs of images (Fig. 3) for water flow of mass flow rate equals to 0.1 kg/s it was found that the velocity at y = 0.6 m

equals 4.84 m/s with coefficient of variation equals 4.5%. The method which is used to measure the water flow velocity is particle image velocimetry (PIV) (see Raffel et al. (2007)). The idea of this method is to take a photo of water flow on concrete surface at different time frames. By comparing floating markers positions on the water surface at those time frames displacement vector can be obtained for each particle. By knowing time difference between these time intervals (Δt), velocity vectors for all marker particles can be obtained by image processing. Fig.3 shows one of these obtained results using this technique. Arrows in Fig.3 are presenting the water flow velocity vectors obtained by image processing. Velocity vectors are obtained in places at which marker particles are located at a certain time.
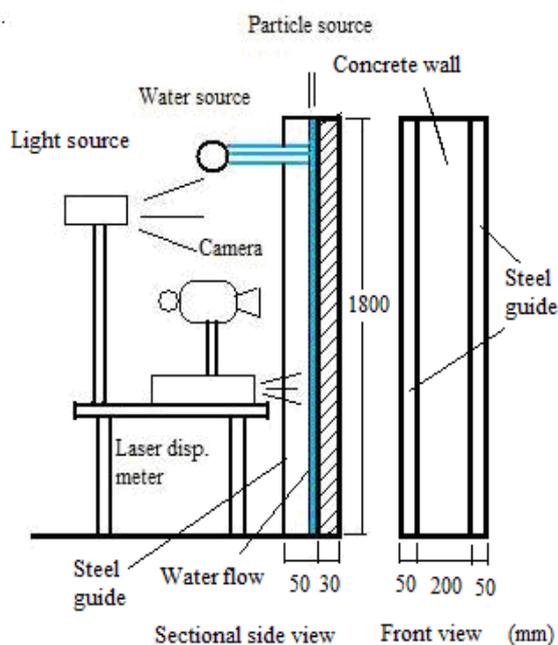
Fig. 2 Experiment setup
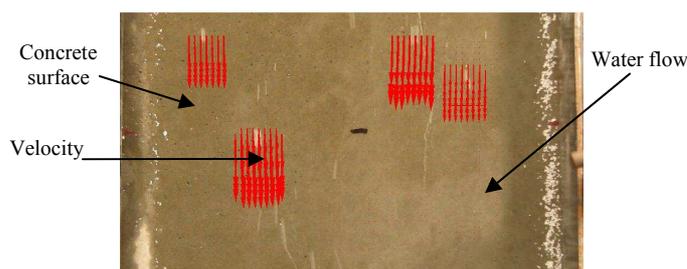
Fig. 3 Velocity measurement

6. NUMERICAL RESULTS

Numerical solution was divided into two steps. The first step is to solve the continuity equation, Navier-Stokes equations "equation (1)" to get water thickness and velocity distribution. In this step Fluent was used to get the analytical solution using finite volume technique. The second step is to solve convection-diffusion equation to get salt removal rate and salt concentration on the wall surface [2]. Finite difference technique was used to solve this equation.

In the first step, numerical simulation was done for different wall shear stress. Fig.4 shows results for wall shear stress at which the velocity of the water layer attached to the wall surface equals zero. Velocity distribution was obtained at different twenty y locations starting from y = 3cm and ending at y = 60cm by step 3cm. By analyzing these curves it can be concluded that for the used mass flow rate surface thickness is decreasing with y and surface velocity is increasing.

Film water layer mainly is subjected to two external forces. The first external force is the gravitational force. Gravitational force is trying to accelerate the flow. This leads to increasing the water flow velocity and decreasing the film thickness with respect to space. The second force is the friction force. For film layers friction force has a great effect on the water speed and the water thickness. This force is trying to decelerate the flow. This leads to decreasing the water flow velocity with respect to space and increasing the film thickness with respect to it. The dominant force mainly depends on the water mass flow rate and the wall surface finish. The used concrete in this experiment has mould concrete surface finish. Wall shear stress is used to present the surface finish roughness in this numerical simulation

It was found that for high water mass flow rate (as the one used to obtain results in Fig.4) the dominant force is the gravitational force. The used water mass flow rate in this case was 0.1kg/s. Different mass flow rates are examined to get the effect of these two forces.

(a)

(b)

(c)

(d)

(e)

(f)
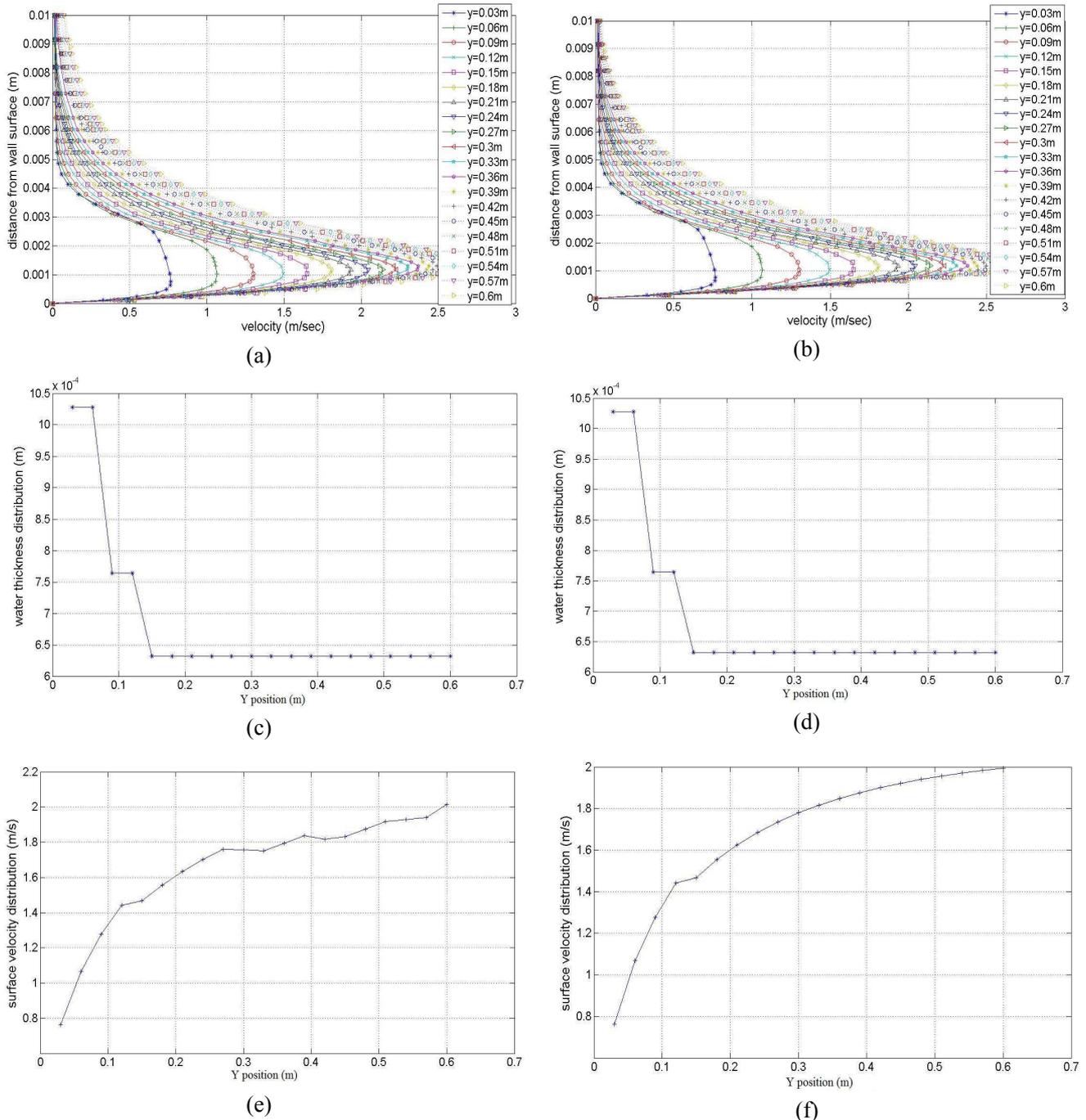
Fig. 4 (a), (c), (e) Velocity distribution, Water thickness, and Surface water velocity respectively at t=3s
(b), (d), (f) Velocity distribution, Water thickness, and Surface water velocity respectively at t=6s

It was found that after 6 second the water flow becomes steady, and the maximum water velocity equals 2m/s. Therefore, different shear stress coefficient should be used to get water velocity distribution and water thickness distribution obtained from the experimental works. After examining shear stress of values 2, 5, 10 and 20Pa it was found that a shear stress of value equals to 10Pa is proper value to get results agreeing with the experimental ones. It was found that the error between the measured velocity and the computed one is 8% and the error between the measured water thickness and the computed one is less than 6%. Fig.5 shows the velocity distribution, the water surface velocity, and the water thickness distribution obtained for 10Pa shear stress at t = 2s compared with experimental results. It was found that by decreasing the shear stress the water speed is increasing and the water thickness is decreasing. At the same time, it was found that by decreasing the shear stress the steady state velocity distribution can be reached faster. That is to mean increasing the shear stress is increasing the water flow velocity transient response. For high shear stress, it takes 6s to reach the steady state velocity and for shear stress equals 10Pa it takes around 2s to reach the steady state velocity. In all simulations wave propagation on water surface is not considered for simplicity and for this research targets. In the experimental work no developing wave is noticed.

(a)

(b)
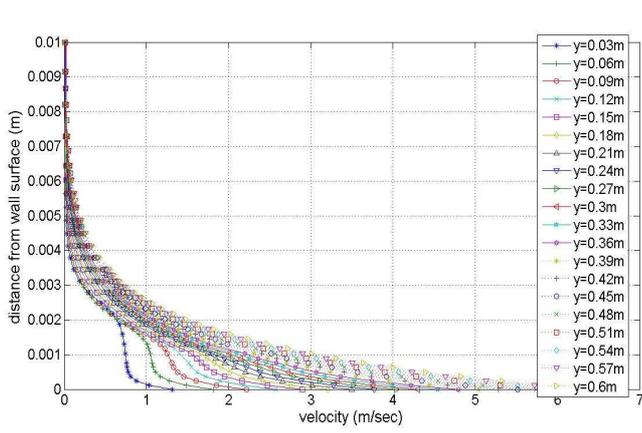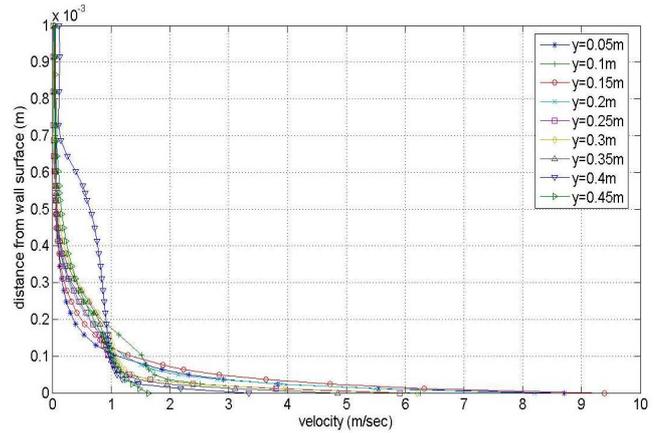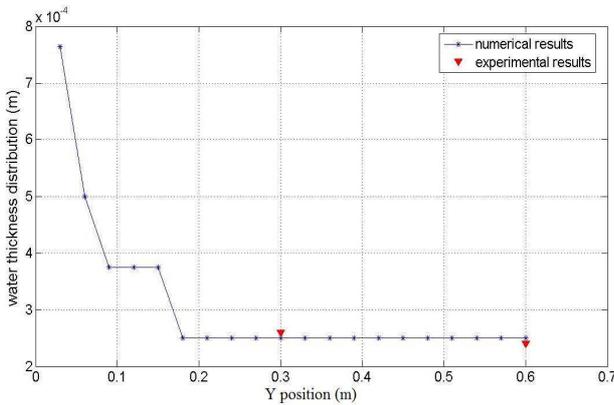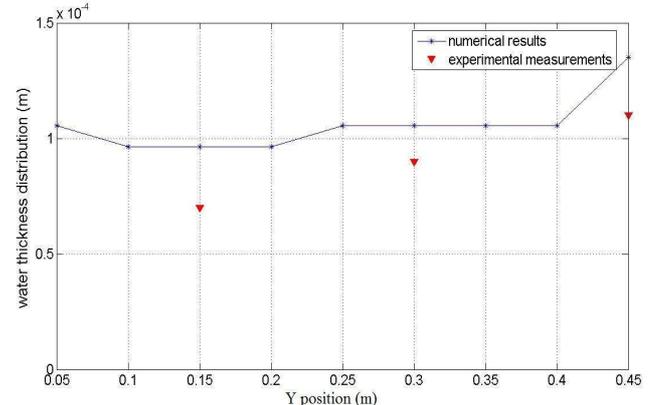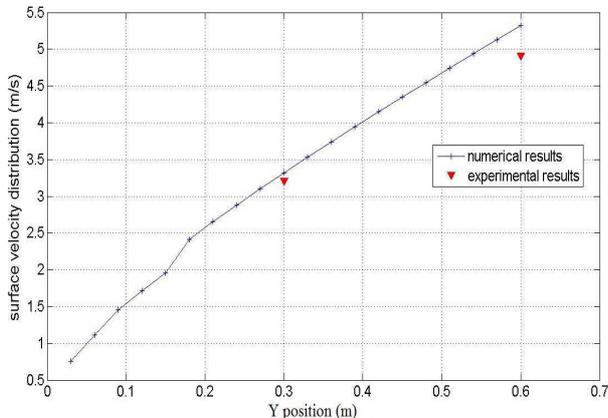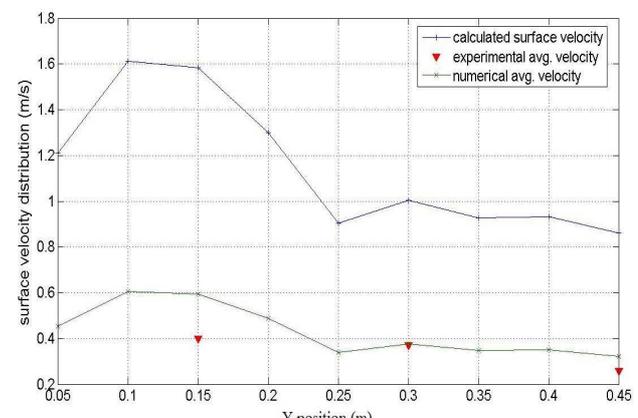
(c)

Fig. 5 (a) Velocity distribution. (b) Water thickness. (c) Water surface velocity for shear stress = 10Pa at t = 2s

(a)

(b)

(c)

Fig. 6 (a) Velocity distribution. (b) Water thickness. (c) Water surface velocity

7. SALT CONCENTRATION

By knowing the wall shear stress and solving the previous governing equations, the water flow velocity distribution can be obtained for different mass flow rate. By using the computed velocity distribution and substituting in (4) we can get the salt concentration distribution at different time steps. An experimental work was done to get the salt concentration distribution on the same concrete specimen by (Sadatsuki (2011)). The volume flow rate used in this case equals 3ml/s. For this reason, the numerical simulation to get the water flow velocity, and the water thickness distribution was redone to calculate the salt concentration and compare it with the experimental data. It was found that by using this mass flow rate friction force is dominant. As it is explained before, the water thickness is increasing with space and velocity is slightly decreasing, and because of that the water thickness distribution trend differs to the one presented in Fig. 4 and Fig. 5. In Fig. 4 and Fig.5 water flow rate is high enough to make the gravitational force is the dominant force

In this simulation the wall shear stress value is higher than the value used before. The reason for that is putting salt particles on the wall surface increases the wall surface roughness. The used value in this simulation is 14Pa. It was found that the thickness distribution agrees with the test data as shown in Fig. 6. Now, using this velocity distribution and getting the mean velocity in x-direction at different y-position 1-D simulation for salt concentration can be conducted. These results can be compared with tested data to get the flux value (F), and the source term value (Q). It was found that these values are changing with respect to time. Fig. 7 shows F and Q values at different time frames. By using these values simulation was conducted to evaluate the salt removal rate, amount of washed-away salt, and salt concentration distribution. The initial salt concentration in water flow which is used to simulate this problem was c equals zero everywhere. Table 1 presents a comparison between washed-away salt amounts obtained numerically and washed-away salt amounts obtained experimentally at different time frames. It was found that the maximum error between the calculated washed-away chloride and the measured one is 7.2% in the first ten minutes, and the average error is 5.2%.
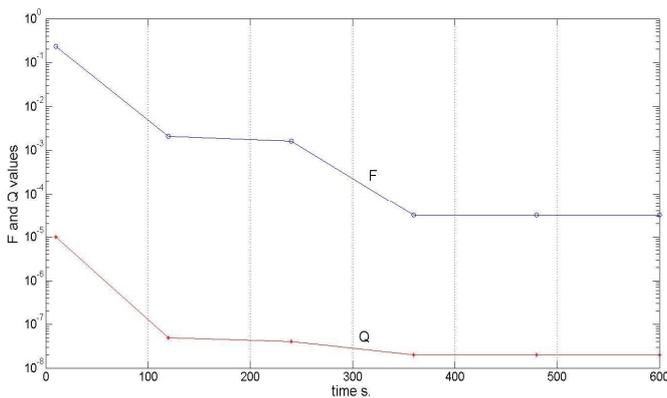
Fig. 7 F and Q distribution with respect to time
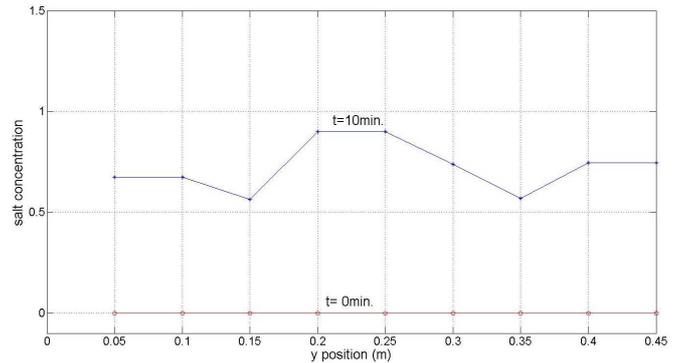
Fig. 8 Salt concentration distribution on the wall surface at t= 10min.

Table 1 Washed-away chloride amounts numerically and experimentally (kg)

	0s < t < 120s	120s < t < 240s	240s < t < 360s	360s < t < 480s	480s < t < 600s
Experimentally	6.436e-5	6.768e-5	6.888e-5	6.96e-5	6.82e-5
Numerically	6.6018e-5	7.257e-5	7.267e-5	7.277e-5	7.287e-5
Error	2.6%	7.2%	5.5%	4.6%	6.85%

8. CONCLUSIONS

Water flow velocity distribution, water thickness, surface water velocity, washed-away chloride amount, and salt concentration distribution could be simulated analytically for film water layer on vertical concrete surface. It was found that water thickness and water velocity depend on the wall shear stress and the input mass flow. For high mass flow rate velocity is increasing with space and water thickness is decreasing and vice versa. Results are confirmed experimentally. Salt concentration distribution was calculated and it was found that for 0.3ml/s volume flow rate salt concentration is slightly increasing with time, and reaches 0.75 after 120s as it was obtained by experimental work. It was found that when velocity is increasing salt concentration is decreasing and the amount of removed salt from wall surface is decreasing and vice versa. It was found that the amount of washed-away salt is increasing rapidly during the first few seconds and after 10 seconds this amount is slightly increasing till it is becoming constant after 6 minutes. For this reason the source term and the flux term in the governing equations are functions of time only.

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