- Technical Paper-

2-D ANALYSIS OF SALT DESORPTION MECHANISM AT SMOOTH CONCRETE STRUCTURE SURFACE

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ABSTRACT

Salt desorption mechanism is one of the fastest environmental actions which affects concrete structures subjected to chloride attack. 2-D numerical simulation analysis of salt desorption mechanism at concrete surface has been conducted. To conduct this numerical analysis, experimental works have been conducted to get some empirical constants. Desorption mechanisms, water thickness distribution, water velocity, and methods to measure and to calculate the amount of washed away salt are discussed and an empirical function to characterize salt desorption is proposed. Keywords: salt desorption, wash-away mechanism, thin water flow, durability.

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1. INTRODUCTION

Concrete structures are subjected to many environmental actions. These actions have direct impact on concrete durability. Air can carry small salt particles and ions from seashore, and these salt particles can accumulate on concrete surfaces. This process decreases concrete durability as these salt particles penetrate inside concrete and cause corrosion for steel bars. On the other hand rain removes these accumulated particles from concrete surfaces [1]. This process decreases the accumulated salt amount and the salt concentration on concrete structures. Therefore, it slows down the penetration process of salt particles inside concrete structures.

Therefore, there are three main processes affecting steel corrosion rate of concrete structures [2]. By studying these processes, we can control corrosion of steel bars, and therefore structure durability. These three processes can be summarized as follows.

(1) Adsorption: In this process salt particles and ions carried by air are accumulated on concrete surfaces. This process is affected by wind speed and direction, distance between concrete structures and seashore, salt particle size, structural design, and concrete structure surface finish. This process is slower than the desorption process explained below as it takes days or weeks to accumulate salt by a certain amount on concrete surfaces.

(2) Desorption: In this process water removes (washes away) accumulated salt on concrete structures. Many factors are affecting this process such as rain fall intensity, rain direction and speed, wall surface finish, duration of rain fall, period between two successive rain falls, temperature, and surface wetness condition. In general, there are two mechanisms for salt desorption. In the first one, salt is attached to dry wall surface (dry

contact condition). Salt particles are washed away mainly due to mechanical movements of these particles. Diffusion occurs in this case too, but the amount of removed salt by diffusion is still very little compared to the one by mechanical movement. In the second mechanism, salt is attached to wet wall surface (wet contact condition). In this case diffusion is dominant, and mechanical movement is small. Desorption process is very fast. It can take few seconds or few minutes to occur.

(3) Absorption: In this process accumulated salt particles are penetrating by diffusion and salt concentration difference between concrete core (steel bars) and outer face of the concrete cover. This process depends on concrete surface finish, concrete properties, concrete ingredients, W/C ratio, concrete cover thickness, and accumulated salt amount. This process is the slowest one among the mentioned ones. It takes months or years to occur.

Therefore, desorption process can be considered as the most influential process among these processes as it is the fastest one [2]. By studying this process in detail (numerically, and experimentally) accumulated salt amount, washed away salt amount, and salt concentration on concrete surfaces can be obtained. This can help increasing concrete durability and life time of concrete structures.

2. PROBLEM DESCRIPTION

Numerical analysis and experimental works were conducted to study salt desorption mechanism, and to obtain washed away salt amount. A vertical wall of 20cm width and 45cm height with mold surface finish was used. The used water volume flow rate is 3 mL/s. This value is associated to the amount of heavy rain fall [5]. The wall surface is subjected to water flow from.

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Fig. 1 Problem description

the top as shown in Fig. 1

3. GOVERNING EQUATIONS

Before modeling the problem, factors affecting it have to be mentioned and understood. These factors can be summarized in the following points:

1) Mass flow rate: This term is used for water input, rain intensity, and the related parameters are impact angle, water thickness, and water velocity. In the present case, the used volume flow rate is 3 mL/s, and water input direction is perpendicular to the wall surface.

2) Gravity force: Due to gravity force, gravitational acceleration in water flow direction must be considered. 3) Surface tension: The importance of surface tension effects is determined based on the value of two dimensionless quantities [4]: a) Reynolds number Re, and Capillary number Ca. b) Reynolds number Re, and Weber number We. Farther information about surface tension will be mentioned later.

4) Concrete surface roughness: It affects water flow velocity, water thickness distribution, and salt contact condition. It can also cause flow localization in case of rough surface. In our case, smooth surface of mold-side concrete was used.

5) Salt desorption mechanism: As mentioned before there are two mechanisms for salt desorption [2]: mechanical and diffusion. In case of dry contact condition, mechanical movements of salt particles are dominant, and in case of wet contact, diffusion of salt particle is dominant. In this study, dry contact condition is presented. A proper boundary condition must present both contact conditions.

6) Temperature: Water and wall temperature must be taken into account as they have influence on the salt desorption rate.

7) Convection-diffusion mechanism: Because salt concentration varies everywhere in the film water layer, diffusion must be considered. Convection must be considered because of salt particles, mechanical movement.

3.1 Flow Equations

Two-dimensional incompressible fluid flow is

considered without considering phase change or evaporation at the water-air interference $(x'=\delta)$. Eq. 1 is the continuity equation, which presents the first affecting factors. Eq. 2 and 3 are momentum equations in x', and y' directions respectively [6]. Gravity force term and surface tension are considered in these two equations. Eq. 4 is the convection-diffusion equation in 2-D which can present the convection-diffusion mechanism.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{R_{eo}} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + \frac{1}{Fr_{xo}} + F_{vol-x}$$
(2)

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \frac{1}{R_{eo}} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{1}{Fr_{yo}} + F_{vol-y}$$
(3)

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} = D\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2}\right)$$
(4)

where

$$R_{eo} = \frac{\rho u_o \delta_o}{\mu}, \ Fr_{xo} = \frac{u_o^2}{\delta_o g \cos(\pi - \theta)}, \ Fr_{yo} = \frac{u_o^2}{\delta_o g \sin(\theta)},$$

$$F_{vol-i} = \sigma_{ij} \frac{\rho \kappa_i \nabla \alpha_i}{\frac{1}{2} (\rho_i + \rho_j)}, \ \nabla \alpha_i = \hat{n}_i$$
(5)

and the dimensionless variables are defined by:

$$R_{eo} = \frac{\rho u_o \delta_o}{\mu}, \ Fr_{xo} = \frac{u_o^2}{\delta_o g \cos(\pi - \theta)}, \ Fr_{yo} = \frac{u_o^2}{\delta_o g \sin(\theta)},$$

$$x = \frac{x'}{\delta_o}, \ y = \frac{y'}{\delta_o}, \ u = \frac{u'}{u_o}, \ v = \frac{v'}{v_o}, \ p = \frac{p'}{p_{atm}}, \ t = \frac{t'}{\delta_o / u_o}$$
where
$$(6)$$

x': transverse coordinate

- : stream-wise coordinate v
- u: transverse velocity
- : stream-wise velocity v
- *p* : pressure

 p_{atm} : atmospheric pressure

t : time

 R_{eo} : Reynolds number

 ρ : water density

 ρ_i , ρ_i : air and water phase densities

 μ : water dynamic viscosity

g : gravitational acceleration

 Fr_{xo} , Fr_{vo} : external force acting per unit volume of water flow in x', and y' directions respectively

- i,j: indices in x' and y' directions respectively
- δ_{α} : initial film thickness
- δ : film thickness
- u_{0} : initial transverse velocity
- v_{o} : initial stream-wise velocity
- F_{vol} : volume force of surface tension
- σ_{ii} : surface tension coefficient
- κ : water surface curvature
- : normal vector to water surface п
- : wall inclination angle measured from the θ horizontal axis
- *c* : salt concentration in water
- D : diffusion coefficient

3.2 Boundary and Initial Conditions

The boundary conditions are given as follows.

$$\frac{at \ y'=0}{u=0, \ v=v(mass \ flow)}$$
(7)

$$\frac{\partial u}{\partial y} = 0, \ \frac{\partial v}{\partial y} = 0, \ \frac{\partial c}{\partial y} = F$$
(8)

where F: salt flux

$$u = 0, v = 0 \text{ (in case of high friction)}$$

$$\frac{\partial v}{\partial x} = \frac{\tau_o}{\mu} (\text{for a specific shear})$$

$$\frac{\partial p}{\partial x} = \frac{1}{R_{eo}} \frac{\partial^2 u}{\partial x^2} + \frac{1}{Fr_{xo}}, \quad \frac{\partial c}{\partial x} = F_2$$

$$F_2 = au^b + d, \quad d = rc^X$$

$$r = Ae^{-E_a/KT}$$
(9)

where

X : kinetic order of desorption= 2 in this case (for recombinative molecular, diatomic and Polyatomic molecules)

A : attempt frequency= 10^{13} s⁻¹ [10]

$$E_a$$
: activation energy of desorption $\approx 2e^{-19}$ J [10]

K : Boltzmann const=1.38×10⁻²³ m² kg s⁻² K⁻¹

$$T$$
 : temperature

at x'= δ

$$u = 0, \ \frac{\partial v}{\partial x} = 0, \ \frac{\partial p}{\partial y} = 0, \ \frac{\partial c}{\partial x} = 0,$$

$$\left[\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right] \left\{1 - \left(\frac{\partial \delta}{\partial y}\right)^2\right\} - 2\frac{\partial \delta}{\partial y} \left(\frac{\partial v}{\partial y} - \frac{\partial u}{\partial x}\right) = 0$$
(10)

The initial conditions are given as follows. at *t*=0

 $c = 0, u = u_0 \approx 0, v = v_0 = 0.21 \text{ m/s},$

$$\delta = \delta_o(x) = 0.7e^{-4}$$
 m at $y' = 0$ and ≈ 0 anywhere

else. Notes:

1) In case of dry contact condition $d \approx 0$ which can be satisfied by substituting by previous values in Eq. 9. 2) Surface tension must be taken into account in the following cases:

I) If *Re*<<1:

$$Ca = \frac{\mu v}{\sigma} \tag{11}$$

If Ca>>1 surface tension can be neglected. II) If *Re*>>1:

$$We = \frac{\rho L v^2}{\sigma} = \frac{(1000)(0.001)(0.3)^2}{0.0728} = 1.236$$
(12)

If *We*>>1 surface tension can be neglected.

After conducting the experiment, and obtaining the numerical solution, it was found that Re>>1 and We=1.236. From Eq.12 surface tension must be considered.

4. EXPERIMENT AND RESULTS

Experimental work was conducted to measure the water flow velocity, the water thickness distribution, the salt removal rate, and the salt concentration [3]. The main purpose of doing this experimental work is to determine unknown constants in previous equations to conduct numerical simulation. Examples of these constants are: wall shear friction coefficient, and empirical constants to determine the salt removal rate.

Different methods were used to obtain water flow velocity. One of these methods is PIV (Particle Image Velocimetry) [8]. The idea of this method is to put proper marker (tracer) in the flow. By taking two photos (two time frames) of these particles and by knowing the time difference between these two frames, and the marker particles displacement vector, velocity vectors can be obtained [8]. Another method to get the average water flow velocity is to measure the water thickness distribution using laser displacement transducer and by knowing the mass flow rate, the average velocity can be obtained by using continuity equation.

After conducting the same experiment for different mass flow rates and/or for different wall inclination angles (θ) , and by comparing the obtained measurements with numerical simulation results, the wall shear friction coefficient can be obtained [2]. Numerical analysis can be confirmed by comparing obtained and measured results for different flow conditions [2]. Fig. 2 shows experimental setup and procedure to measure the washed away salt amount.



Fig. 2 Experimental setup and procedure

Now, to conduct the salt removal experiment many factors and conditions must be considered.

1) Temperature of rainfall water drops: The used water temperature in this experiment is 20°C. This factor is important as it can affect the salt desorption rate.

2) Salt particle size: Typical salt particle size for accumulated salt on real concrete surfaces equals 10µm [5]. It is important to use particles of the same size. The average used salt particle size in this experiment is 13.1~13.3µm. The used salt is NaCl. Salt was grinded many times to get this size. Fig. 3 shows the measured particles size using microscope.

3) Salt amount on the concrete surface: in this experiment, the used salt amount is assumed to be the same as the accumulated salt amount on a concrete structure exposed to wind for 3 successive days and located 10m away from the seashore. This assumption is used as it normally rains every 3 days in Japan [5]. The amount of accumulated salt under these conditions can be calculated. It was found that this amount equals to $0.15 \text{ mg/cm}^2/\text{day}$.



Fig. 3 Salt particle size (x1000)

This amount can be calculated by using the following equation [7]:

$$C_{air} = C_I R^{-B} \tag{13}$$

where

 C_{air} : airborne salt concentration (mdd)

 C_1 : concentration corresponding to airborne salt concentration at distance of 1 km. it is equal to 0.95 mdd (mg/dm²/day) *R*: distance from coast (km)

B: constant equals to 0.6

By substituting these values in Eq. 13 airborne salt concentration can be obtained as $15.056 \text{ mdd} \approx 0.15 \text{ mg/cm}^2/\text{day}$. The total amount of used salt in this experiment equals to (0.15)x(3 days)x(20 cm x 45 cm) = 405 mg of NaCl.

Salt particles can be attached to the tested concrete wall by the following steps:

i) Sprinkle salt particles uniformly onto the surface of concrete plate specimen which is placed horizontally.

ii) Remove and drop the salt particles which are not attached to the concrete plate specimen by inclining the concrete plate specimen. The removed salt particles are dropped onto a metal sheet. Inclining direction of the concrete plate specimen should be different each time so that salt particles attach uniformly on the specimen surface.

iii) Repeat i) and ii) until all salt particles are attached to the surface of the concrete plate specimen.

4) Water drop size and water distribution: Average rain water drops size is 1mm in diameter. For that reason water source must have the same size, and water must spread uniformly to prevent water localization.

5) Salinity sensor calibration: Calibration of the used salinity sensor was done before starting conducting the experiment to get the salinity allowable range.

6) Temperature of the test site, relative humidity, and wind speed: These conditions must be checked not to influence much the obtained experiment results. Experiments were conducted at temperature $T=10\pm4^{\circ}C$,

no wind condition, and relative humidity = $40 \sim 50\%$. 7) Condition of sprinkled and attached salt particles:

The concrete plate surface is dried using a dryer for 5min, and the surface moisture ratio(%) is measured by a surface moisture measuring device before sprinkling salt particles onto the surface of the concrete plate. The average measured moisture surface ratio is 4.2%.

This experiment was conducted three times for $\theta=90^{\circ}$ under calm laboratory conditions. Table 1 shows the washed away salt amount with respect to time. Washed-away chloride can be measured by the following steps:

i) The water containing chloride is collected into a plastic container at every 20s interval separately up to 120s from the beginning. Then, the water is collected at every 120s separately up to 600s from the beginning.

ii) The water containing chloride obtained at every time interval is put into a small plastic container with a lid. The weight of the small plastic container is measured without and with the water by using a balance with minimum reading of 0.01g.

iii) Each plastic container is shaken sufficiently so that salt particles dissolve into the water uniformly.

iv) The chloride concentration is measured by a salinity sensor.

Fig. 4 shows the washed away salt percentage during the first two minutes. It indicates that during the first 40 seconds salt removal rate is very high and after that it decreases with respect to time. This emphasizes that most of the salt movement has occurred due to mechanical movement and diffusion has a minor effect in this physical problem.

Table 1 Washed away salt amount

Test	Elapsed time (s)	Washed away chloride (mg)	Washed away chloride ratio (mg/cm ²)
Exp.1	20	47.01	0.052
	40	40.53	0.045
	60	17.11	0.019
	80	13.36	0.015
	100	12.03	0.013
	120	8.16	0.009
Total		138.20	0.153
Exp.2	20	44.70	0.050
	40	41.91	0.047
	60	15.82	0.018
	80	12.90	0.014
	100	10.59	0.012
	120	8.20	0.009
Total		134.12	0.149
Exp.3	20	44.99	0.050
	40	21.90	0.024
	60	18.74	0.021
	80	11.98	0.013
	100	14.12	0.015
	120	2.15	0.002
Total		113.88	0.127

It can be seen that washed away salt percentage is around 35% in the first 20 seconds, and this percentage decreases with time. By using this finding, budget and manpower can be saved during maintenance process of concrete structures from chloride. This can be done by washing accumulated salt on concrete structures by using the following concepts washing the concrete wall for a short period of time is enough to remove the accumulated salt. A detailed experimental works for the same concrete specimen under the same conditions for time more than two minutes can be found in [5].



Fig. 4 Washed away salt percentage with respect to time

As it can be seen from Fig. 4 and Table 1 the majority of the washed away salt is removed during the first two minutes, and to be more precise during the first 40 seconds. These results agree with [5].

5. NUMERICAL SIMULATION AND RESULTS

Numerical analysis was conducted to simulate this problem. In this analysis many factors are considered and assumed. The following points describe these factors in detail.

5.1 Surface Tension

Water surface flow velocity is measured using particle image velocimetry (PIV) technique [1], [8]. Water thickness distribution was measured using laser displacement transducer at different locations. By knowing the mass flow rate, and the water thickness distribution, average water velocity can be calculated (using continuity equation) with respect to space, and velocity profile can be obtained. By getting the velocity distribution, Reynolds number can be calculated. It was found that Re>>1. Therefore, to examine if surface tension should be considered or not, Eq. 12 must be tested. As it is mentioned before, if We>>1 surface tension can be neglected [4]. In the present case We= 1.236. A comparison between the solutions with considering surface tension and without considering is shown in Fig. 5.



Fig. 5 Comparison between solutions with and without considering surface tension

5.2 Water Thickness Distribution

Water thickness distribution is highly dependent on the mass flow rate. Film water layer is subjected to three forces. The first one is the gravitational force which accelerates the water flow and decreases the water flow thickness with respect to space. The second force is the friction force. This force decelerates the water flow velocity and increases the water flow thickness with respect to space. The third force is the surface tension force which was discussed in the previous section. For volume flow rate equals 3mL/s it was found that the dominant force is the friction force. Because of that water thickness increases with respect to space as it can be seen in Fig. 5. Due to numerical difficulties, the used water thickness is the one obtained experimentally.

Values of empirical constants used in Eq.9 are obtained by comparison between numerical results and experimental works, as shown in Fig. 6 and b=2.



Fig. 6 Used empirical conhistants values with respect to time

5.3 Velocity Distribution

Velocity was calculated using the previous set of equations, and it was found that velocity is a function of x' and y'. Fig. 7 shows y'-velocity component distribution.



Fig. 7 y'-velocity component distribution

5.4 Salt Concentration Distribution

Continuity and momentum equations, Eqs. 1, 2, and 3 were solved using the finite volume method [6].

After getting the velocity distribution, and the water thickness distribution, Eq. 4 was used to get the salt concentration and the washed away salt amount. Eq. 4 was solved using the high order finite difference technique [9] to overcome numerical instability.

Fig. 8 shows the salt concentration distribution in the physical domain. It shows that salt concentration is increasing with respect to space in the flow direction, and is decreasing in the direction normal to flow.



Fig. 8 Salt concentration distribution at t= 120s.



Fig. 9 Comparison between the washed away salt amount numerically and experimentally

Fig. 9 shows the washed away salt amount calculated numerically and obtained experimentally. As it can be seen from this figure numerical result agrees with the experimental results.

6. CONCLUSIONS

After conducting experiments to measure the washed away salt amount, and after simulating the same problem the following points can be concluded.

- (1) In case of dry contact condition, the main salt removal mechanism is due to salt particles movement velocity.
- (2) In case of dry contact condition the first two minutes are the most influential ones. During these two minutes the majority of the removed salt is washed away.
- (3) More than 20% of the removed salt (in dry contact case) during the first two minutes is washed away in the first 40 seconds.
- (4) An empirical equation is proposed to characterize the salt desorption by thin water flow.

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