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Concrete Structures Exposed to Cyclic Wetting and Drying in Aba Metropolis, Nigeria

G. E. Okore
Department of Civil Engineering, Abia State Polytechnic, Aba, Nigeria
E-mail: geokore9@gmail.com

E. O. Kalu
Department of Statistics, Abia State Polytechnic, Aba, Nigeria

ABSTRACT

An inspection study of concrete structures located within the Aba metropolis reveals that concrete exposed to cyclic rainfall deteriorates relatively faster, compared to those shielded by the cover of shelter, in corrosion. This suggests that ions of chloride alongside dissolved ions of Carbon and Sulphur dioxide are prevalent in rainfall. This is because these dissolved substances penetrate exposed concrete to attack the concrete cover by a de-alkalizing process, or by destruction of the protective barrier to induce corrosion in embedded steel reinforcement. However, attempts to predict the service life of exposed concrete components using existing models of deterioration led to serious difficulties. This is primarily due to a lack of a sufficiently simple functional description of the cyclic attack of rain-borne ions, especially of chlorides. For a simple and accurate description of deteriorations in reinforced concrete exposed to cyclic wetting and drying, this study focuses on developing an empirical algorithm capable of simulating chloride penetration in concrete, considering the effect of concrete mix-design on sorptivity when sorption coupled with diffusion is the mode of transport. For verification, a comparison is made between values calculated using an advanced model and values obtained from experimental simulations on samples of concrete of water/binder ratios 0.3, 0.4, 0.5 and 0.6, prepared from CEM 11/A-L 42.5R and granite aggregates of size 19mm. Very good agreement exists between values calculated using the advanced model and values obtained from experimental simulations.

***Keywords**: Corrosion of reinforced concrete, cyclic ingress of rain-borne chlorides, model of chlorides sorption coupled with diffusion.*

1.0 INTRODUCTION

Inspection report on deteriorating concrete located within the Aba metropolis, show that concrete exposed to cyclic changes of rainfall of warm-humid climate, particularly deteriorates unexpectedly and relatively faster, compared to concrete shielded under cover of shelter or located in the mildly temperate climate. However, it is generally known also that frequent wetting and drying cycles, drive even deeper the ingress of ions of chloride into concrete (Parrot, 1990; ISO 13823 (WD), 2005; Hong & Hooton 1999). This is because concrete exposed to cyclic wetting and drying have proven to be very vulnerable to corrosion triggered as it were, by the ingress of chlorides and carbonation and exposure to cyclic wetting and drying, subjects reinforced concrete structure to carbonation as well as to chlorides contamination (Kari, 2011; Kim & Kim 2010).

While damage to exposed building or bridges represents a major maintenance setback, many exposed concrete structures have suffered severe deterioration, after only about 20 or 30 years into their 50 or 120-year expected service life respectively [Vassie, 1984; Wallbank, 1989]. Attempts to simply and accurately predict the rate of deterioration of affected components did not succeed due to the absence of simple and functional description of sorption coupled with diffusion (Kari, 2011). This is because existing models of chloride penetration ignore the sorptivity influence, on chloride ingress. The indication that the influence of concrete quality (or concrete mix-design) is significant in resisting chloride sorptivity and diffusion [Polder and Peelen, 2002] in part alludes to this hypothesis.

Therefore, the emphasis in this study is on characterizing the effect of concrete mix design, as an influencing factor on chlorides sorptivity in concrete exposed to cyclic wetting and drying**.** Thus, in this investigation, the governing partial differential equations that idealize this problem are solved analytically rather than numerically (Gang Lin et al, 2010) in order to simply and accurately model the service life of concrete exposed to cyclic wetting and drying. This concept develops a design-strategy that minimizes corrosion in concrete exposed to cyclic wetting and drying (Schiessl, 2005).

And with the focus on effect of concrete mix-design on sorptivity of chlorides, better understanding of the movement of chlorides in unsaturated concrete, vital to preservation of required performance of concrete elements as defined by the investor or the structural designer, is achievable. Therefore, developing a means of predicting the incidence of deterioration in concrete is of immense economic interest and innovative solution to peculiar problem in line with global best practice (Umoh and Lugard, 2014).

2.0 MODELING/ANALYSES

2.1 TIME-LAWS OF CHLORIDE-INGRESS:

The rate of deterioration of concrete exposed to cyclic wetting/drying as a result of sorption coupled by diffusion can be expressed by a differential equation based on Fike's second law:

$$\frac{\partial C}{\partial t} = D\,\frac{\partial^2 C}{\partial x^2} = R_o \qquad (1)$$

where,

R_o is the rate of deterioration or effective coefficient of deterioration of concrete exposed to wetting and drying, as a result chloride attack.

D is the effective diffusivity of chlorides in concrete depending on binder composition [in m^2/s or in $mm^2/year$].

Then, Crank's error-function solution to differential equation (1), can be expressed following the operational model by Alisa et al, 1998, and it approximates the time law of chloride-ingress, as a result of sorption coupled with diffusion,

thus: $$\frac{C}{C's} = [1 - \mathrm{erf}\,[\,\frac{Xcc}{2\sqrt{(Dt)}}]] \qquad (2)$$

Where:

erf = the Gaussian Error Function [Crank, 1956].

Transiting from Crank's error-function solution in equation (2), to Bazant's parabola-function solution, the time laws of chloride-ingress in equation (1) can approximately be expressed as:

$$\frac{C}{C's} = [1 - \frac{Xcc}{2\sqrt{(3Dt)}}]^2 \qquad (3)$$

Where:

C = the total content of chloride ions within concrete at the depth X_{cc}, when background chloride content is nil, in %wt of cement.

D = the effective diffusivity of chlorides in concrete depending on binder composition, in mm^2/year.

C'_s = the apparent surface content of chlorides in concrete exposed to wetting and drying as a result of sorption coupled with diffusion, in % wt. of cement. The apparent surface content of chloride ions can be determined by adjusting representative chloride profiles along Crank's error function solution and extrapolating the resulting chloride profile-curve to concrete surface.

X_{cc} = the cover thickness loss (CTL) of the concrete exposed to wetting and drying, due to chloride attack, in mm.

t = exposure time, in years.

2.2 ACCEPTABLE THRESHOLD FOR CORROSION ONSET

The critical value of chloride adopted for corrosion-initiation is the recommended value by Glass and Buenfeld 1997; Ballim et al., 2009 multiplied by the acceptability coefficient (Okore & Anyanwu, 2017). It should be noted that the acceptability coefficient (or the size factor) is not included in the recommended chloride threshold, however, it should be understood that:

$$\mathbf{C = C_{crit} = \alpha\, C_{th}} \qquad (4)$$

Where,

$\mathbf{C_{th}}$ = the recommended threshold chloride for corrosion initiation.

$\boldsymbol{\alpha}$ = is the acceptability coefficient (or size factor) to recommended threshold value, and its value transfers the recommended threshold from laboratory to real life sizes of structural components.

$\boldsymbol{\alpha}$ = 0.7 $\mathbf{C_{crit}}$ – is the acceptable threshold or critical value of chloride for corrosion initiation.

Thus, by replacing **C** in equation (1.3) with $\mathbf{C_{crit}}$, in equation (1.4) and re-arranging equation (3): $\frac{\mathbf{Ccrit}}{\mathbf{C's}} = [\mathbf{1} - \frac{Xcc}{2\sqrt{(3Dt)}}]^{2}$ (5)

2.3 SURFACE CONTENT OF CHLORIDES:

2.3.1 Effect of Carbonation on Chlorides Sorptivity

For unsaturated concrete exposed to cyclic wetting and drying, the result of experimental observations shows that carbonation rate in medium to high quality concrete is much less than the rate of chloride penetration, in all exposure condition. Except in poor quality concrete exposed to marine atmosphere, where the rate of carbonation can be very high especially in dry climates (Costa & Appleton, 2001). Variation in apparent surface-content of chlorides on account of carbonation can be avoided altogether by use of high-quality concrete and relevant rebar cover. Nevertheless, protection of concrete from the combined effect of carbonation with chlorides shows that with high quality concrete, carbonation is negligibly of little significance (Costa & Appleton, 2001).

2.3.2 Effect of Concrete Quality (Mix-Design) on Sorptivity

(A) Basic Hypothesis and Model Algorithm: In concrete exposed to cyclic wetting and drying, the influence of concrete mix design otherwise called the quality of concrete on sorptivity of chlorides can strongly affect this concrete

(Pocock & Bamforth, 1991). However, the apparent surface-content of chlorides **C'$_s$** in concrete exposed to cyclic wetting and drying, as in figure 1, becomes:

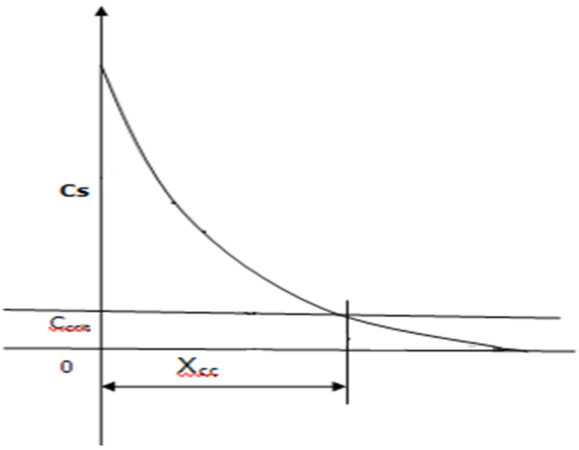

Figure 1: Schematic of chloride profiles in concrete.

Characterizing the effect of concrete quality (or concrete mix-design) on the ingress of chlorides via capillary sorption, let the water to cement ratio of concrete be adopted, because there is a linear relationship between concrete mix-design (or concrete quality) and its water to cement ratio. Incidentally, the relationship between the apparent surface-content of chlorides and the water to cement ratio of concrete is also linear (Frederiksen, 1996). And capillary sorption decreases with decreasing water to cement ratio of concrete [Parrott, 1992; Dhir et al, 2004; Kolias & Geargio, 2005]. Assuming that the effect of concrete mix-design on sorptivity of chlorides result in chloride penetration decreases as the water to cement ratio of concrete decreases.

Therefore, increase in apparent surface content of chloride, as a result of the effect of concrete mix-design on sorptivity will be proportional to the relative increase in penetrated ions of chlorides, as can be illustrated graphically in fig. 2.

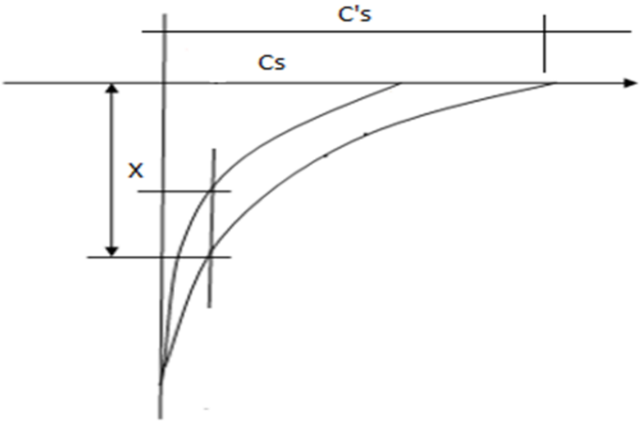

Fig 2: Schematic of the rise in apparent surface-content of chlorides.

As a consequence of the foregoing, let:

$$\frac{C's - \mathrm{Cs}}{\mathrm{C's}} = \frac{\Delta l}{\Delta} \qquad (6)$$

Where,

$(C's - \mathrm{Cs})$ = represent the difference between the apparent surface-content of chlorides as a result of sorption coupled with diffusion and surface content of free chlorides, in concrete exposed to diffusion.

Δl = is assumed to represent the quantity of movable free chlorides as a result of the effect of concrete mix-design on chlorides sorptivity.

Δ = is the sum total of all movable free chlorides, in concrete exposed to cyclic wetting and drying, as a result of sorption coupled with diffusion.

$\mathbf{C's}$ = is the apparent surface-content of chlorides in concrete exposed to cyclic wetting and drying, as a result of sorption coupled with diffusion.

Cs = is the surface content of free chlorides, in concrete exposed to diffusion.

By re-arranging equation (6):

$$\frac{\mathrm{Cs}}{\mathrm{C's}} = \left(1 - \frac{\Delta l}{\Delta}\right) \qquad (7)$$

$$\mathbf{C's} = \mathbf{Cs}\ (\mathbf{1} - \frac{\Delta \boldsymbol{l}}{\Delta}) \qquad (8)$$

Where,

$(\mathbf{1} - \frac{\Delta \boldsymbol{l}}{\Delta})$ – is the modifier to **Cs.**

A Suggested Approach to Multiply Time Dependency C’s(t) With the Exponential Modifier:

Since apparent surface-content of chlorides **C’s** increases continuously with exposure time, in both saturated and unsaturated concrete (Tang & Gulikers 2007; Tang & Nilsson 2000; Thomas & Bentz 2000; Kim & Kim, 2010), then **C’**$_{\mathbf{s(t)}}$ becomes the time-dependency to equation (8), especially in concrete exposed to cyclic wetting and drying. However, Kassir & Ghosn (2002) had shown that time-dependency of apparent surface-content of chlorides can be expressed by an exponential variation of with time thus:

$$\mathbf{f_{(t)}} = (\mathbf{1}\text{- } e^{-gt}) \qquad (9)$$

where,

the exponent (**-gt**) = a product of the rate of change per year and time of exposure, in years. Furthering the implication however, the time function $\mathbf{f_{(t)}}$ could be approximated (Kim & Kim, 2010), to equal ‘**t**’ as:

$$f_{(t)} = (1\text{- } e^{-gt}) = \frac{(t)}{(tref=1)} = t. \qquad (10)$$

where **t** = is the duration of exposure in years, per year.

This approach calls for combining equations (8) with (10), gives the equation for time dependency of C’$_{s(t)}$ is expressed as thus:

$$C'_{s(t)} = f_{(t)}\ Cs.\ (1 - \frac{\Delta l}{\Delta}) = Cs.\ (1 - \frac{\Delta l}{\Delta})\ t \qquad (11)$$

Secondly, by equating the multiplier of **Cs** above:

$$(\mathbf{1} - \frac{\Delta \boldsymbol{l}}{\Delta})\ \mathbf{t} = \mathbf{t^v} \qquad (12)$$

Where:

v = an exponential modifier denoting the rate of change in apparent surface chloride per year, in **t**-years, as a result of the influence of concrete mix-design on sorptivity of chlorides, when sorption is coupled with diffusion.

Recalling equation (11) above: $C'_{s(t)} = Cs \,.\, t^{v}$ (13)

A CORRELATION OF EXPONENTIAL MODIFIER WITH $(1 - \frac{w}{c})$

Assuming that the exponential modifier (v) is correlated to the expression $\mathbf{(1 - \frac{w}{c})}$ with a coefficient of correlation less than unity, and reflecting the influence of concrete mix-design on sorptivity of chlorides, then, the relationship between both values can be expressed as:

$$v = (1 - \frac{w}{c}) \qquad (14)$$

where

$\frac{w}{c}$ - is the water to cement ratio of concrete which characterizes the effect of concrete mix-design on chlorides sorptivity (Okore & Ogbonnaya, 2017).

Therefore, equation (13) reflecting the influence of concrete mix-design on sorptivity of chlorides, and can simply become:

$$\mathbf{C'_{s(t)} = Cs \,.\, t^{(1 - \frac{w}{c})}} \qquad (15)$$

2.4 Suggested Model of Deterioration of Exposed Concrete

Recalling equation (1.5), and the influence of concrete mix-design on sorptivity of chlorides in equation (1.15), then, the time-dependent solution to equation (1.1) above, in concrete exposed to cyclic wetting and drying representing our suggested new model can simply be expressed thus:

$$\left[\frac{Ccrit}{Cs \,.\, t^{\left(1 - \frac{w}{C}\right)}}\right] = \left[1 - \frac{Xcc}{2\sqrt{(3Dt)}}\right]^2 \qquad (16)$$

Wherefore, the cover thickness loss ***ctl*** for concrete exposed to cyclic wetting and drying, by a re-arrangement of equation (1.16), can thus become:

$$\mathbf{X_{cc} = 2\ [1 - \surd\ [\frac{Ccrit}{Cs\ .\ t^{\left(1-\frac{w}{C}\right)}}]]\ \surd(3Dt)} \qquad (17)$$

Reverting to the error function solution in equations (2) and in harmony with equation (17), the cover thickness loss (CTL) in concrete exposed to cyclic rainfall, reflecting the time-dependent influence of concrete mix-design on sorptivity of chlorides is expressed as:

$$Xcc = 2\ \mathrm{erf}^{-1}\ [1 - \frac{Ccrit}{Cs\ .\ t^{\left(1-\frac{w}{C}\right)}}]\ \surd(Dt) \qquad (18)$$

2.5 Experimental Verification

Experimental simulations for generating comparative data involving the use of parameters computed from material history and advanced model. This comparative data is particularly useful because it supplies the basis for logical acceptance or rejection of research hypothesis.

2.6 Exposure Condition In Experimental Environment

For purposes of this study, the weather condition is assumed to be approximately 6-months of wetting and 6-months of drying.

The monthly averages of temperature and other parameters such as monthly content of dissolved chlorides in raindrops and monthly averages of relative humidity, within the exposure environment are found in table 1.

Table 1: Characteristics of the experimental environment

Conditions of exposure environment.	Wetting months = 9 Feb – Oct	Drying months = 3 Nov – Jan
Average monthly temp.	28°C	32°C
Average monthly Content of rain-borne chlorides, mg/l	30.6	-
Monthly Average of Relative Humidity	85%,	65%,

3 MATERIALS

The 4 batches of in-situ concrete of water to cement ratio 0.3 for mix-1; 0.4 for mix-2; 0.5 for mix-3 and 0.6 for mix-4, are made from Portland cement (CEM 11/A-L 42.5 R), river sharp sand and granite aggregates with sizes ≤ 19mm. A super-plasticizer is added to mix-1 to enhance workability while reducing water consumption.

Table 2: Composition of concrete mixes for experimental verifications

	Mix 1	Mix 2	Mix 3	Mix 4
w/b ratio	0.3*	0.4	0.5	0.6
Cement, kg/m^3	425	350	300	300
Sharp Sand, kg/m^3	677	726	822	822
Granite, kg/m^3	1231	1231	1231	1231
Water, kg	128	140	150	180
plasticizer	1.0	-	-	-

(*with plasticizer in amount 0.2% wt of cement)

3.1 EXPERIMENTAL PROCEDURE

The experimental procedure adopted for this verification will be those adopted by Lee & Yoon (2003). The procedure involves exposing concrete specimens to 12 consecutive cycles of 1-week wetting in PVC containing 0.5M of brine (i.e. water containing 5% NaCl2, filling over each specimen to at least 13mm) followed by 1-week drying in air containing 0.3% by volume of CO2 at 65% of relative humidity at room temperature, to simulate combined deterioration involving carbonation with chloride attack. Prior to performing a combined deterioration procedure, manually determined data based on this model are obtained, to include the water to cement characteristics of concrete mixes, characteristic chloride diffusivities of concrete mixes constants as well as the calculated values of the apparent surface-content of chlorides for 1, 3 and 12-year. And these parameters are summarized in table 3.

4.0 ANALYSES OF EXPERIMENTAL RESULTS AND DISCUSSION

The purpose is to compare:

- The changing rate of **(v)** in table 1.4 with changing $(1-\frac{w}{c})$ in table 3.
- The apparent surface-content of chlorides after 1, 3 and 12-years, as calculated using $Cs\,.\,t^{\left(1-\frac{w}{c}\right)}$ from model, in table 3 and experimentally determined $Cs.\ t^{(v)}$, in table 4.
- The loss of cover concrete at exposure duration of 12-years, $\mathbf{X_{12}}$.

Table 3: Near-term Summary of material parameters from material history

		Mix 1	Mix 2	Mix 3	Mix 4
w/c ratio		0.3	0.4	0.5	0.6
$(1 - \frac{w}{c})$		0.7	0.6	0.5	0.4
D_c, mm^2/year		2.84	2.84	7.88	15.77
Cs @ 2-2.5mm ctrs. Experimentally determined from control specimen prior to carbonation, % wt of binder.		0.08	0.10	0.12	0.14
@ t = 1-year	**$C'_{s(1)} = Cs\ .\ t^{\left(1-\frac{w}{c}\right)}$ % wt of binder**	0.08	0.10	0.12	0.14
@ t = 3-year	**$C'_{s(3)}$** = $Cs\ .\ t^{\left(1-\frac{w}{c}\right)}$ **% wt of binder**	0.17	0.19	0.21	0.22
@ t = 12-year	**$C'_{s(12)}$** = $Cs\ .\ t^{\left(1-\frac{w}{c}\right)}$ **% wt of binder**	0.46	0.44	0.42	0.38
C_{crit} = 0.17, α = 0.7	**X_{12},** in mm	5.7	5.7	9.0	12.0

Table 4: Near-term Summary of experimentally simulated parameters

		Mix 1	Mix 2	Mix 3	Mix 4
w/c		0.30	0.40	0.50	0.60
V		0.68	0.61	0.54	0.46
$D_{ref} = k_t.\ D_{RCM}$, mm^2/year @28 days		2.80	2.81	7.87	15.64
Cs @ 2-2.5mm ctrs. Experimentally determined from control specimen prior to carbonation, % wt of binder.		0.08	0.10	0.12	0.14
@ t = 1-year	**$C'_{s(1)} = Cs.\ t^{(v)}$, % wt of binder**	0.08	0.10	0.12	0.14
@ t = 3-year	**$C'_{s(3)} = Cs.\ t^{(v)}$, % wt of binder**	0.17	0.20	0.22	0.24
@ t = 12-year	**$C'_{s(12)} = Cs.\ t^{(v)}$, % wt of binder**	0.43	0.46	0.46	0.48
C_{crit} = 0.17, α = 0.7	**X_{12}, in mm**	5.7	5.7	9.5	13.6

Table 5: Long-term predictive ability of model in comparison with laboratory simulations of deteriorations

w/c		Mix 1	Mix 2	Mix 3	Mix 4
		0.30	0.40	0.50	0.60
$(1-\frac{w}{c})$		0.7	0.6	0.5	0.4
V		0.68	0.61	0.54	0.46
D_c, mm^2/year		2.84	2.84	7.88	15.77
$D_{ref} = k_t . D_{RCM}$, mm^2/year @28 days		2.80	2.81	7.87	15.64
Cs @ 2-2.5mm ctrs. Experimentally determined from control specimen prior to carbonation, % wt of binder.		0.08	0.10	0.12	0.14
$f_{(s)}$ $f_{(T)}$ $f_{(a)}$ = 0.29 @ t = 50-year Ccrit = 0.17, α = 0.7	**$C'_{s(50)}$ = $Cs . t^{(1-\frac{w}{c})}$ % wt of binder**	1.2	1.0	0.8	0.7
	$X_{(50)}$ in mm	14.6	14.6	22.6	30.9
	$C'_{s(50)}$ = Cs. $t^{(v)}$, % wt of binder	1.1	1.1	1.0	0.8
	$X_{(50)}$ in mm	14.8	14.8	24.4	31.8
$f_{(s)}$ $f_{(T)}$ $f_{(a)}$ = 0.29 @ t = 100-year Ccrit = 0.17, α = 0.7	**$C'_{s(100)}$ = $Cs . t^{(1-\frac{w}{c})}$% wt of binder**	2.0	1.6	1.2	0.9
	$X_{(100)}$ in mm	23.0	23.0	35.9	47.4
	$C'_{s(100)}$ = Cs. $t^{(v)}$, % wt of binder	1.8	1.7	1.4	1.2
	$X_{(100)}$ in mm	23.1	23.1	37.2	50.9

For this particular composition of concrete, both near and longer-term predictive ability of advanced model and experimental verifications are tested. For exposure durations greater than 12-years, especially for concrete having w/c ratio 0.3; 0.4; 0.5 and 0.6, the loss of cover concrete is: X_{12} = 5.7; 5.7; 9.0 and 12.0mm respectively for advanced model, as against 5.7; 5.7; 9.5 and 13.6mm respectively for experimental verification. Poorer quality concrete in longer-term exposure duration, with w/c ratio 0.5 and 0.6, can experience loss of cover concrete as high as: X_{50} = 22.6 and 30.9mm respectively for advanced model as against: X_{50} = 24.4mm and 31.8mm respectively for experimental verification. On the other hand, concrete exposed for up to 100-years when w/c ratio 0.5 and 0.6 can induce loss of cover thickness as high as: X_{100} = 35.9mm and 47.4mm respectively for advanced model as against: X_{100} = 37.2mm and 50.9mm respectively for verification. These comparisons show good agreement between advanced model and experimental verification. The slight variations are tolerable within design cover-thickness which is usually assigned 10mm more and cannot be of any consequence in the long run.

5.0 CONCLUSION

However, indicated good agreement between simulated and calculated results show that corrosion-deterioration of concrete exposed to cyclic wetting and drying can simply and reasonably be described by the functional equation which takes the effect of concrete mix-design on chlorides sorptivity into account and the empirical algorithm developed in this study is correct**.** It could also be said that the assumptions made and the analyses algorithm developed here in this study satisfactorily represent the service life design/model of reinforced concrete structure exposed to cyclic wetting/drying. Therefore, the estimation of service life of structural concrete exposed to cyclic rainfall and similar conditions is thus possible by use of model. It could be seen that for concrete exposed to rainfall (severe mode of exposure), the design minimum for concrete cover thickness depends on water to cement quality of the concrete rather than fire resistance of practice codes. It could be seen also that the apparent surface chloride increases as the water to cement ratio of concrete decreases. Therefore, the ingress of chlorides into concrete exposed to cyclic wetting and drying depends on the mix-design of the concrete. These explain the comparatively faster corrosion- deterioration experienced by poor quality structural concrete, exposed to rainfall in the warm and humid zone.

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