Relationship between Natural and Laboratory Chloride Diffusion in Concrete

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Abstract: Concrete is tested in laboratory to get surface chloride content and chloride diffusion co-efficient (D). Generally specimen is cured for 28-days and tested for diffusion. Diffusion co-efficient (D) obtained in this way is used for prediction of service life. Concrete is exposed to natural environment during its service life. So, concrete exposed to two environments performs differently. So, to overcome this variation in two different concretes as in laboratory and in natural environment a relationship is essential to find, which relates laboratory tested concrete with concrete in natural environment. So, in present study, data about laboratory tested concrete and concrete placed in natural environment and tested has been collected. Using this data, a relationship between laboratory cured and tested concrete and concrete placed in natural environment and tested. So, this relationship helps to understand the variation between two concretes. Also this relationship may be used, with concrete initially cured and tested in laboratory and then it is expected to be placed in natural environment.

Keywords: Chloride diffusion, Structural concrete, Service life, chloride diffusion, Ageing Factor

1. Introduction

Service life modelling in terms of chloride corrosion involves chloride diffusion co-efficient (D). In laboratory, chloride diffusion co-efficient (D), is obtained by various test methods. Same tested concrete is used in natural environment. Where the tested concrete may perform differently. So, relationship is needed which relates laboratory cured concrete with concrete placed in natural environment.

A number of researchers have conducted research work to get the long term diffusion result based on the real environment test result. Few have investigated existing structures to get the long term diffusion data and performance of existing structure. Seung –Woo Pack et al (2010), conducted survey of concrete bridges in marine environment, for the life ranging of 0.65 to 48.65 years. Masood Mardani (2017) investigated a 50 year old concrete jetty to assess long term performance as well as the structural conditions. Mohammad Shekeerchi et al (2009) to get performance of Silica fume concrete in marine environment tested the concrete samples to determine diffusion co-efficient at the ages of the 3.9 and 36 months. Armande Helllebois (2013) investigated hardened concrete samples from a narrow railway viaduct built in 1904. M.T Liang (2002) as investigated a 69 years old bridge in Taipei, for its service Life performance and have given chloride ions content for its different parts. W. Chalee et al (2008), have investigated the fly ash made concrete exposed in a marine environment ranging from 2 to 5 years. M.D.A Thomas et al (2004) have performed test to get chloride profiles / diffusion in fly ash concrete in marine exposure ranging from one to ten years. Also they tested specimen from 1 to 28 days by immersing in sea water in laboratory conditions. M.D.A Thomas et al (2008), have performed tests on 25 years old slag concrete placed in marine environment to find its performance. R.D. Hooton et al (2009), have tested Silica Fume concrete, obtained from bridge decks which were 15 years old and had been exposed to de-icing salts. Rob Polder has investigated Chloride Profiles obtained from a 30 years old concrete bridge and was exposed to de-icing salts. So, the investigation to get the performance of concrete in long term is important. Generally, concrete in laboratory is tested and its results are used to determine the service life. So, it is important to get the relationship between naturally exposed and laboratory concrete. Although the data for naturally / outdoor exposed concrete is limited but the literature is thoroughly investigated to develop the relationships.

2. Background

Service life estimation of concrete placed in natural exposure is analyzed using Fick's second law of diffusion. Fick's second law of diffusion is based on error function solution. Equation-01 calculates chloride content from surface chloride, diffusion co-efficient, depth of concrete and time for exposure.

$$C(x,t) = C_s\left[1 - \mathrm{erf}\frac{x}{2\sqrt{Dt}}\right] \quad (1)$$

In equation-01, chloride diffusion co-efficient is used from equation-02, which calculates chloride diffusion co-efficient over time D(t), chloride diffusion co-efficient over reference

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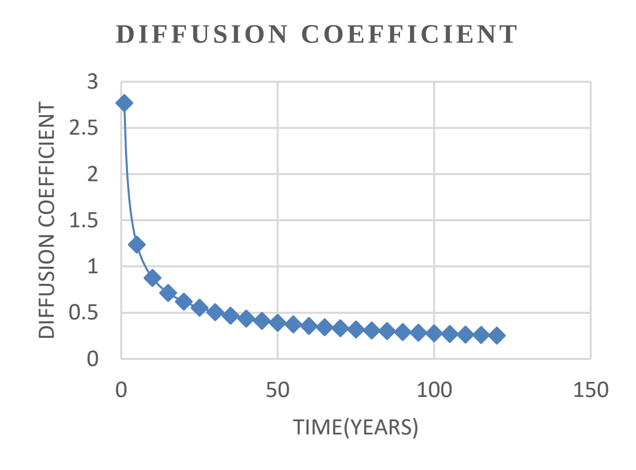
time (D_{ref}) , reference time (t_{ref}), time (t) and ageing factor (m). Graph-01 shows a typical diffusion curve, generally obtained by using equation-02

$$.D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^{m} \qquad (2)$$



Graph 01: Diffusion Curve

3. Laboratory Chloride Diffusion

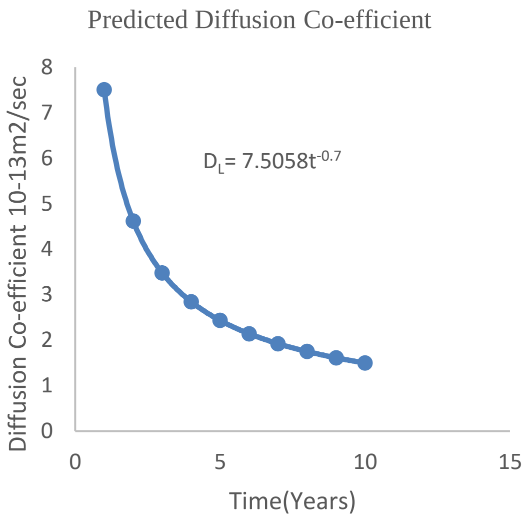
Diffusion co-efficient (D) is used in equation-01 to calculate the chloride content. This D is generally obtained from laboratory testing. D is obtained at various curing ages but normally concrete is tested at 28-days. D value generally a property of concrete and its exposure. Laboratory concrete is a concrete which has only been cured in laboratory and tested. Laboratory test result for concrete with 30% fly ash was collected from literature. The D value was obtained from the test results of Song (2014). Table01 shows D value.

Table 01- Laboratory Diffusion co-efficient

Concrete	**90-Day-Diffusion Co-efficient (D)**	**Strength**
	($10^{-13}m^2/sec$)	**N/mm^2**
PFA, 30 %	**20**	45

The value shown in table-01 has been used to get chloride diffusion co-efficient for range of time using ageing factor of 0.7 as given by Thomas and Bamforth. The values are shown in table02.

S. No	**Time, Years**	**Predicted Diffusion Co-efficient**
	Years	**$10^{-13}m^2/sec$**
1	1	7.505761
2	2	4.620338
3	3	3.478643
4	4	2.844152
5	5	2.432852
6	6	2.141356
7	7	1.922322
8	8	1.750781
9	9	1.612223
10	10	1.497596



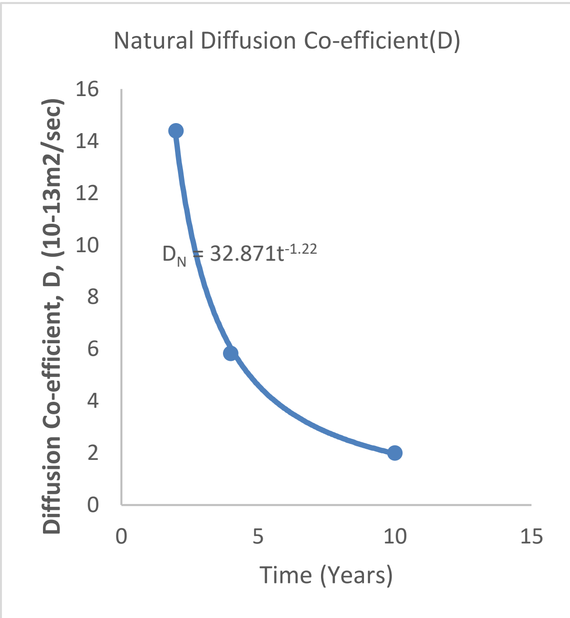
Graph-02- Predicted Diffusion Co-efficient

4. Natural Chloride Diffusion

Literature was surveyed to find concrete placed in chloride exposure. So, that value Natural D value of concrete may be obtained. As concrete made with 30% Fly Ash has been selected for the present study. D value for 10 years old concrete was taken from the test results of Thomas (2004). This concrete was exposed to laboratory curing for 28 days and later it was placed in marine environment for 10 years. Selected concrete results can be seen in table -02. Graph-03 shows plotting values of D as shown in table-02.

Table 02- Natural Diffusion co-efficient

Concrete	**Diffusion Co-efficient (D)**		
	$10^{-12}m^2/sec$		
	2 Years	**4 Years**	**10 Years**
PFA,30 %	14.4	5.84	2.01



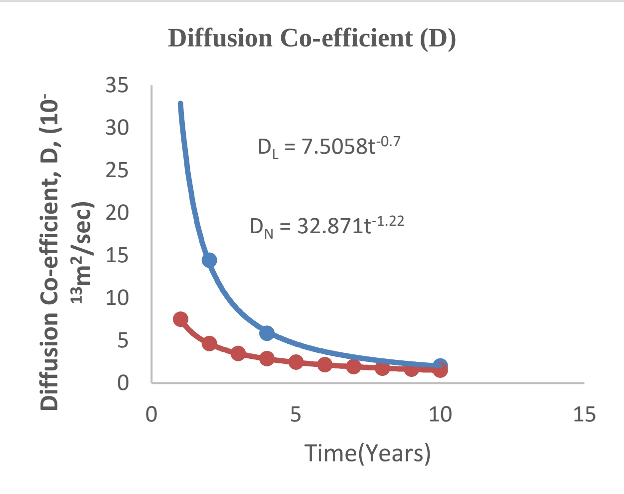
Graph-03: Diffusion Curve

5. Comparison Between Calculated Chloride Diffusion and Natural Chloride values

Table -03 show natural chloride diffusion values and laboratory chloride diffusion values. These values have been plotted in graph-04. Graph-04 shows a difference in two different exposure. Generally natural chloride diffusion values are higher as compared to laboratory chloride diffusion values. It can be easily observed that difference is slowly decreasing for a longer time period. Reason for difference is, environmental effect on diffusion. Environmental effect is mainly due to temperature and relative humidity. Calculation of D was done using equation-02, which gives D-values over time period by using ageing factor. So, for this purpose D was as 0.7. Thomas et al (2004) have given ageing factor as 0.7. To compare natural chloride diffusion values it was necessary to plot laboratory chloride diffusion values. So, that a difference may be observed. This approach helps to find a difference between two values. As in equation-02, D obtained from laboratory is used, whereas concrete is placed for its service in natural environment.

Table 03- Natural Diffusion Co-efficient(D) and Calculated Diffusion Co-efficient(D)

S. No	Time, Years	Natural Diffusion Co-efficient(D)	Calculated Diffusion Co-efficient(D)
	Years	$10^{-13}m^2/sec$	$10^{-13}m^2/sec$ [Note- m = 0.7]
1	1		7.505761
2	2	14.4	4.620338
3	3		3.478643
4	4	5.84	2.844152
5	5		2.432852
6	6		2.141356
7	7		1.922322
8	8		1.750781
9	9		1.612223
10	10	2.01	1.497596



Graph-04 Comparison Between Natural Diffusion Co-efficient D_N and Laboratory Diffusion Co-efficient D_N

Table 04- Variation in the values of Natural and Laboratory Diffusion Co-efficient

Natural Diffusion Co-efficient(D)	Calculated Diffusion Co-efficient(D)	Variation
$10^{-13}m^2/sec$	$10^{-13}m^2/sec$ [Note- m = 0.7]	%
14.4	4.6	213.0435
5.84	2.87	103.4843
2.01	1.51	33.11258

6.0Relationships developed in present work

6.1 Natural Diffusion Curve Over Time,

Graph-04 shows a variation between natural and laboratory diffusion values. From these values of natural diffusion equation for D_N has been obtained. Equation-03 is developed for concrete with Fly Ash content of 30 % with compressive strength of concrete as 45 N/mm^2.

$$D_N = 32.87\, t^{-1.22} \quad (3)$$

In equation-03**,** D_N is Natural diffusion over time in m^2 /sec and t is time.

6.2 Laboratory Diffusion Co-efficient,

In graph-04 calculated values of laboratory chloride diffusion are shown. Using these values equation-04 has been obtained. So, equation-04 gives the chloride diffusion value for time. These values were plotted using ageing factor as 0.7 in equation-02. In this equation D_L is laboratory diffusion over time in m^2 /sec and t is time

$$D_L = 7.45\, t^{-0.693} \quad (4)$$

To get a relationship between D_N and D_L , we solving for t. So that,

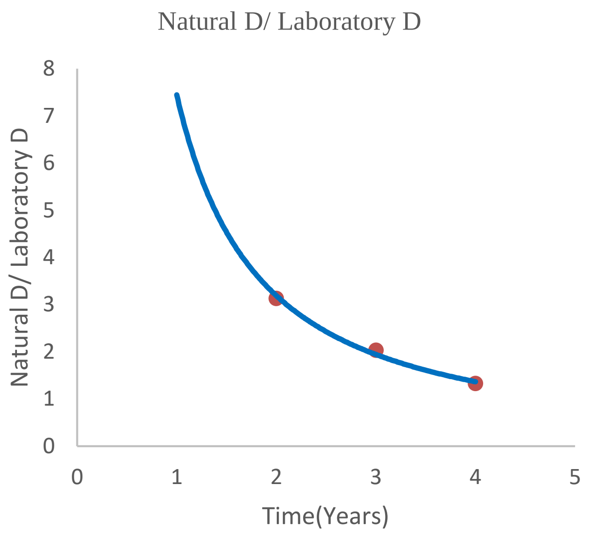
$$t = \left(\frac{D_L}{7.45}\right)^{1.693} \quad (5)$$

By placing the value of the t form equation-05 in equation-01 we get,

$$D_N = 32.87 \left(\frac{D_L}{7.45}\right)^{1.76} \quad (6)$$

7. Estimation Steady State

Estimation of reinforced concrete structures service life exposed to natural environment in terms of durability involves a number of parameters. Specially, when concrete is exposed to chloride environment, to apply repair measures before time of start of corrosion, it is essential that a more accurate knowledge about diffusion properties of concrete may be obtained. Generally laboratory diffusion value is used in quation-02 to get the further values of chloride diffusion over time. Generally, chloride diffusion value decreases over time and reaches in equilibrium state, where further decrease is very slow and generally a value of diffusion is uniform. So, this stage is called steady state of diffusion in concrete. From this point chloride diffusion value is used as a constant for estimation. It can be seen in graph-04, that the steady state is obtained in 17th year. Therefore, at this stage value of D_N obtained may be used a constant.



Graph-05: Steady State Diffusion

8. Discussion

Calculated values from 90-days diffusion values have been plotted in graph-04. These values have been calculated using ageing factor as 0.7. To compare these values with natural diffusion values, values for 10-years for chloride in natural environment has been collected from literature. Concrete with Flay Ash with content of 30 % has been selected for present study. In graph-04, it can be easily seen that chloride diffusion values obtained in laboratory are generally higher as compared to values of concrete exposed in natural exposure. With the increasing time, this difference is decreasing. Both values are converging to a constant value at the 17th year. This time is described as the steady state. In equation-05 a relationship has been developed which gives a relationship between two diffusion values. So, this equation may be used to get the new value of D_N from the D_L. Later this may be used in equation-02 to get values of D to use in equation-01.

9. Conclusion

Service life of concrete structures depends on many parameters such as material, environment and loading as well. For analysis of reinforced concrete structures in chloride exposure, analysis mainly depends on the proper selection of D. If this value is higher, a low corrosion ignition period may be obtained, where as a low value may result a higher time to start a corrosion. So, present study was focused to find a relationship between laboratories cured and tested concrete with naturally cured concrete. So, for his purpose concrete made with Fly Ash 30% was selected. Its D values from literature were obtained. Key observations are as under

a. For first two years, difference in diffusion values is higher than 200%.
b. In the range of two to four years, difference in values is comparatively as 100%.
c. In the range of four to ten years, this difference is decreasing and it is only, more than 30%.
d. This pattern continues till is achieved 17th year, where a steady state diffusion reaches.
e. In general, difference between two values is decreasing with time
f. Also, it shows chloride content inside concrete increases with time.

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