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The effects of structural cracking on carbonation progress in reinforced concrete: is climate change a concern?

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ABSTRACT

There is nearly unanimous consensus among scientists that increasing greenhouse gas emissions, including CO_2 generated by human activity, are affecting the Earth's climate. One essential area which will be affected is the durability of concrete infrastructure.

Past research indicates that climate change will exacerbate the rate of carbonation of reinforced concrete structures, potentially leading to premature corrosion of embedded rebar. Cracking of the covering concrete could further increase carbonation rates, but the extent of the increase is unknown. The purpose of this study is to investigate the carbonation of cracked concrete under accelerated test conditions, and to numerically model the movement of the carbonation front in cracked concrete using the concept of effective diffusivity.

It was found that the presence of a deep structural crack in a concrete specimen greatly increases the rate of carbonation, possibly leading to premature, localized corrosion within the specimen. The effect of cracks is likely to be much greater than the effect of increased temperatures and increased atmospheric CO_2 concentrations. As a result, emphasis must be placed on designing durable infrastructure and following proper maintenance practices so that cracks are less likely to form, thereby extending the longevity of the structure in question.

1. INTRODUCTION

During its service life, the durability of concrete is often controlled by its ability to impede ion and fluid transport. The transport properties of concrete are likely to be affected by the formation of cracks.

Cracks may be either Structural or Non-Structural in nature. Structural cracks tend to be wider (>0.1 mm) in width while Non Structural cracks are generally finer (<0.1 mm). Structural cracks usually occur due to one, or a combination of several factors:

- Low strength of concrete
- Insufficient reinforcement
- Excessive loading
- Impact loading
- Movement of subgrade

Non-Structural cracks may occur due to:

- Thermal expansion/contraction
- Plastic shrinkage
- External chemical attack
- Improper placement/consolidation
- Aggregate/cement interactions
- Surface abrasion
- Weathering

Cracks are inevitable in most concrete members due to the weakness of concrete in tension. These cracks influence the diffusivity of the medium. However, current transport models often do not cover the effect of cracks, voids and defects in concrete on corrosion initiation, rendering them less robust then desired (Pacheco and Polder, 2010)

A number of studies have investigated the diffusion properties of deleterious substances through cracked concrete (Gerard and Marchand, 2000; Alahmad et al, 2009; Song et al, 2006; Jang et al, 2011; Odeh et al, 2006). All these studies have concluded that cracks increase the total molar flux of gases/fluids through concrete. Sappakittipakorn (2010) found that the time to chloride-induced rebar corrosion of reinforced concrete significantly decreased when concrete was loaded and cracked. Therefore, concrete which will inevitably crack under service conditions will be significantly more permeable and will deteriorate more quickly due to penetration of a deleterious substance than sound, virgin concrete. One such important deleterious substance is CO_2.

CO_2 diffusing into concrete at a given point in time will react with dissolved aqueous $Ca(OH)_2$, and CSH to form $CaCO_3$, thereby lowering the overall concentration of CO_2 at that location and time. The naturally high pH of uncarbonated concrete forms a barrier preventing corrosion of embedded steel reinforcing bar. However, the formation of $CaCO_3$ in carbonated concrete causes a decrease in the pH of concrete from 12-13 to < 9. Concrete carbonation can therefore be thought of as a process by which a carbonation front progresses from the outer edges of a specimen, inwards, with the carbonated concrete having a lower pH. When the carbonation front reaches the depth of the reinforcing bar, it becomes susceptible to corrosion.

Talukdar et al (2012a) developed a model which could be applied to forecast carbonation depths of uncracked concrete structures subject to the effects of global climate change. While it was found that the effects may be quite severe (Talukdar et al, 2012b), it was suggested that the effects may be even more pronounced in damaged, cracked concrete. The purpose of this study was to determine the effect of structural cracking on the rate of carbonation in a concrete section.

2. EXPERIMENTAL PROGRAM

2.1 Sound Concrete

In order to test the applicability of the uncracked model (Talukdar et al, 2012a) when multiple atmospheric conditions were simultaneously varied, a number of sound concrete specimens were cast, water cured for 28 days, and subjected to accelerated testing in an ESPEC PR4-KPH carbonation chamber. Two separate concrete mixes (A+B) were designed, and details are specified in Table 1. Slump was maintained at 225mm +/- 25mm and an air content of 6% +/- 1% The carbonation chamber was able to control the CO_2 concentration, temperature, and relative humidity (RH). Specimens were removed from the water bath and allowed to come to equilibrium with laboratory conditions (20^{o} C, 60% RH) over a further 28 days before being placed in the carbonation chamber. Five 100 mm x 100 mm x 350 mm prismatic block specimens were prepared per batch, and each batch of specimens was placed in the chamber for 12 weeks. As CO_2 concentrations were linearly increased from 4%-10%, temperature was concurrently raised from 24 to 60^{o} C, while the RH was held constant at 60%. This is expressed mathematically in Table 2:

Table 1. Concrete Mixes A+B

	Mix A (w/c=0.6)	Mix B (w/c=0.65)
Type 10 Ordinary Portland Cement (kg/m^3)	380	290
Water (kg/m^3)	228	188.5
Coarse Aggregate (kg/m^3)	770	990
Fine Aggregate (kg/m^3)	820	740
Air Entrainment Admixture (mL/m^3)	150	150

Table 2. Chamber Conditions

$T(t)= 24+(3/7)t$	T: Temperature (C), t:Time (days)
$H(t)=60$	H: Relative Humidity (%), t:Time(days)
$C(t)=4+(1/14)t$	C: CO_2 Concentration (%), t:Time(days)

2.2 Cracked Concrete

In order to study the effects of cracking on carbonation progress, several batches of specimens were cast, and then cracked using a manual loading device.

Two different mixes were investigated. One batch had the same Mix Design as Mix B, and the other, Mix C is specified in Table 3:

Table 3. Concrete Mix C

	Mix C (w/c=0.5)
Type 10 Ordinary Portland Cement (kg/m^3)	380
Water (kg/m^3)	190
Coarse Aggregate (kg/m^3)	800
Fine Aggregate (kg/m^3)	850
Air Entrainment Admixture (mL/m^3)	150

For each batch, seventeen 100 mm x 100 mm x 350 mm prismatic block specimens were cast with each block containing a piece of 10M rebar with 15 mm of cover. Slump was maintained at 225 mm +/- 25 mm and an air content of 6% +/- 1%. The specimens were tested as follows:

- 12 specimens were loaded into 4-point loading devices and cracked (Figures 1+2). These specimens remained loaded so that the cracks were kept open over the course of the experiment. Each week, one of these specimens was removed from the carbonation chamber, saw cut, and the carbonation depth was measured by spraying the cut surface with phenolphthalein and noting the color change. Saw cuts were taken at 3 different locations on each block in order to examine the variation in diffusion rates, depending on the distance to the vicinity of a crack (Figure 2).

- Five specimens were loaded and cracked in the same type of 4-point loading device. These specimens were removed from the chamber on a weekly basis and were subjected to Linear Polarization Resistance (LPR) Tests to monitor the change in the corrosion potential of the embedded rebar in cracked concrete. After LPR Testing, these specimens were reloaded into the chamber to be retested the following week.

Figure 1. Concrete Specimen under 4 point loading (L) and after being removed from the loading device (R).

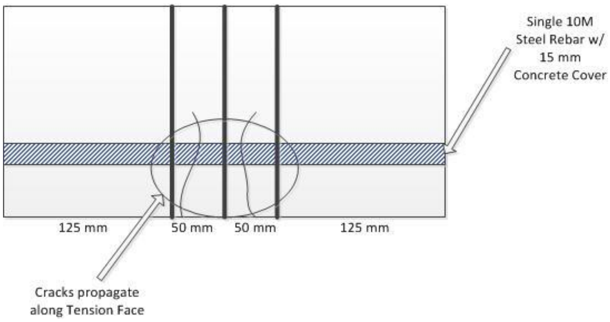

Figure 2. Sawcut locations.

3. RESULTS

3.1 Sound Concrete

Numerically predicted carbonation depths, and experimentally measured depths are shown in Figures 3 and 4.

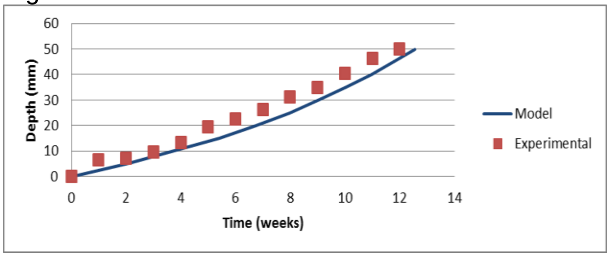

Figure 3. Model vs Experimental Results (w/c=0.6).

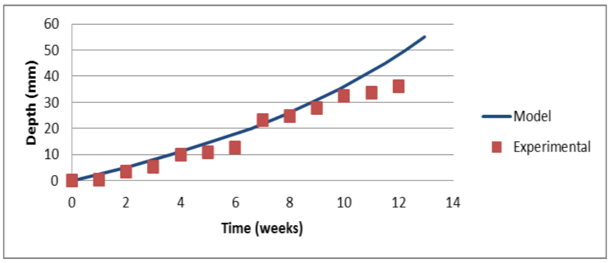

Figure 4. Model vs Experimental Results (w/c=0.65).

Clearly, the model predictions match the measured experimental values very well. These results provide additional evidence that the original model holds for sound, uncracked concrete when being subjected to multiple changes in ambient conditions.

3.2 Cracked Concrete

Under steady-state conditions, cracked concrete has been depicted by many researchers (Jang et al, 2011; Odeh et al, 2006; Song et al, 2006; Gerard and Marchand, 2000) as a two-phase parallel medium where the deleterious substance diffuses through the sound matrix and the cracks separately. The diffusion rate through each phase is dependent on the diffusion coefficient of the phase itself. Wilke (1950) established the concept of the *effective diffusion coefficient*, which can be used to estimate rates of diffusion in multicomponent systems such as cracked concrete. The effective diffusion coefficient may be used to represent a multicomponent system with multiple diffusion coefficients as a single component system with a single, effective diffusion coefficient. As per Gerard and Marchand (2000), the diffusion coefficient is given by:

$$D_{eff} = \frac{A_{ucr}D_{ucr} + A_{cr}D_{cr}}{A_{tot}} \qquad (1)$$

where:
-A_{tot}, A_{cr} and A_{ucr} are the total, cracked and uncracked surface areas of concrete respectively
-D_{eff}, D_{cr} and D_{ucr} are the effective, cracked and uncracked diffusion coefficients of CO_2 respectively

An empirical formula for Diffusivity of CO_2 in sound/uncracked concrete is given in Talukdar et al (2012a). Furthermore, considering that structural cracks in concrete are ideally simply void spaces filled with air, the diffusion coefficient of CO_2 in cracks should be equal to that of CO_2 in air. However, account must also be taken of tortuosity, connectivity and constrictivity of the crack path which would retard the effective diffusion rate. Therefore, a 'crack geometry factor' β (Jang et al, 2011) can be incorporated to account for these, and Equation 1 is rewritten as:

$$D_{eff} = \frac{A_{ucr}D_{ucr} + A_{cr}\beta D_o}{A_{tot}} \qquad (2)$$

where:
-β is a crack geometry factor to account for tortuosity, connectivity and constrictivity of a crack
-D_o is the diffusion coefficient of CO_2 in air $=1.65\times10^{-5}$ m^2/s @25^oC (Marrero and Mason, 1972)

One approach considered was to measure or estimate the cracked area of a deteriorating concrete surface, then calculate the Effective

Diffusion Coefficient of the cracked concrete from Equation 2, and substitute it in place of the Diffusion Coefficient for sound concrete given in Talukdar et al (2012a). The model for sound concrete could then predict the increased rates of carbonation due to the presence of damage/cracks at the surface.

Concrete was loaded and cracked as described in the Experimental Program section. The cracks tended to form along the tension face of the concrete, and traversed in a direction normal to the tension face (Figure 1). The maximum crack width varied between 0.1-0.3 mm. In general one or two cracks would form of varying depths. Cracks traversed in the middle 1/3 section of the concrete. Crack areas on the tension face and the depth of the longest crack were measured using an optical crack microscope. Areas were calculated by measuring the average length and width of a crack. The values are presented in Tables 4 and 5.

Table 4. Carbonation Depths (w/c=0.5)

Week	Crack Area (mm^2)	Carbonation Depth (mm)	Max Crack Depth (mm)	Predicted Carbonation Depth (mm)
1	10	0.0	70	2.5
2	20	8.2	70	5.0
3	20	11.9	50	8.0
4	10	16.0	60	11.1
5	12	24.5	55	14.5
6	20	24.9	50	18.0
7	22	33.9	55	21.8
8	22	28.2	40	26.3
9	4	26.1	60	30.9
10	15	38.3	50	36.1
11	19	39.3	50	41.9
12	10	50	50	48.3

Table 5. Carbonation Depths (w/c=0.65)

Week	Crack Area (mm^2)	Carbonation Depth (mm)	Max Crack Depth (mm)	Predicted Carbonation Depth (mm)
1	18	6.4	10	2.3
2	22	14.2	30	4.4
3	27	19.5	10	7.0
4	12	8.1	10	9.5
5	80	40.4	65	12.5
6	15	14.5	10	15.4
7	23	18.8	55	19.1
8	35	26.9	10	22.7
9	8	15.1	40	26.9
10	25	17.1	45	31.6
11	16	13.4	45	36.8
12	13	20.4	15	42.0

In all cases, the depth of carbonation on the cracked side was significantly greater than on the uncracked sides. This clearly shows that carbonation progresses faster through a damaged interface than through a sound interface. Therefore, when measuring the average crack depth, measurements were taken on the cracked side only. Taking measurements on the uncracked sides would provide unrepresentative results for a cracked interface. The Carbonation Depth provided in Tables 4 and 5 is the average depth of carbonation on the cracked side, at the three sawcut locations for each specimen.

The Predicted Carbonation Depths presented in Tables 4 and 5 are calculated using the Effective Diffusion Coefficient from Equation 2. Theoretically, the upper limit on the value of β in Equation 2 is 1.0, as the purpose of this factor is to account for diffusion retardation due to tortuosity, connectivity and constrictivity. The actual value should be less than 1.0. However, initially a value of 1.0 was used, and it was expected that the factor could then be adjusted to < 1.0 based on the actual crack depths.

Results indicate that the presence of cracks severely affects the carbonation depth, causing it to vary significantly from specimen to specimen, depending on the actual cracks. Based on these findings, the effective diffusion coefficient concept cannot be used to accurately predict carbonation depths in concrete containing discretized structural cracks. Rather, it is postulated that the presence, of deep, wide structural cracks allows for rapid penetration through the crack, followed by diffusion orthogonally through the concrete (Figure 5 + 6). This can be verified, as it was found that usually, for early stages of carbonation, wherever crack depths exceeded the predicted carbonation depth, the actual measured depth would also exceed the predicted depth (Tables 4 + 5). Therefore, the presence of a deep structural crack in a concrete specimen greatly increased the initial rate of carbonation, and may lead to premature, localized corrosion within the specimen.

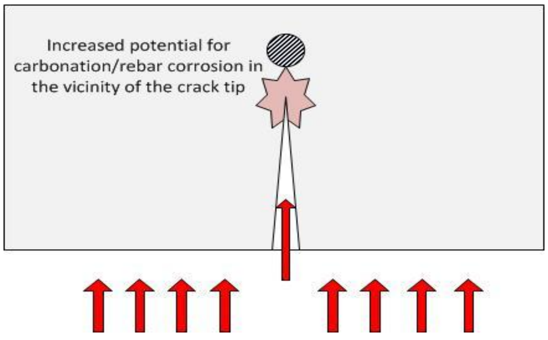

Figure 5. CO_2 diffusion into Cracked Concrete.

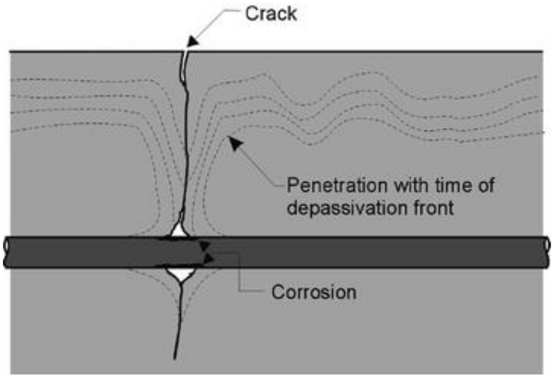

Figure 6. Depassivation Front in Cracked Concrete (Pacheco and Polder, 2010).

While the effective diffusion concept may be valid for non-structural microcracks, it is no longer valid when larger structural cracks are present. In such circumstances, a two-dimensional numerical model should be developed in order to predict the propagation of the carbonation front in the vicinity of the crack. A 2D numerical model, such as the one proposed by Meier et al (2007), may be useful in such circumstances. Moreover, Zhang et al (2011) reported that carbonation depth penetration into a sample increases rapidly when the crack width increases from 0-0.1 mm, with 0.1 mm being a threshold beyond which carbonation depths increase only marginally. Therefore, the presence of a structural crack which extends to the depth of rebar may be considered sufficient to induce localized depassivation at it surface.

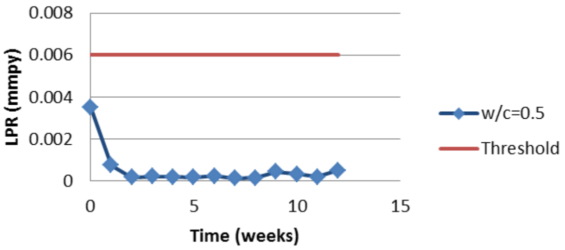

Figure 7. Corrosion Rate vs Time based on LPR testing (w/c=0.5).

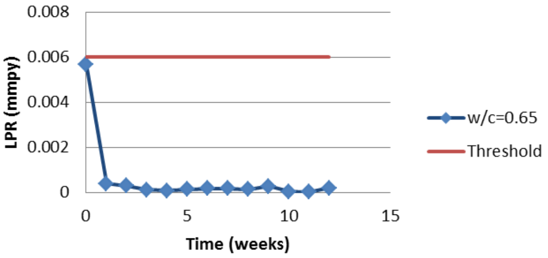

Figure 8. Corrosion Rate vs Time based on LPR testing (w/c=0.65).

The results of the LPR tests are noteworthy (Figures 7 + 8). A number of researchers, including Malhotra and Carino (2000) have established that the corrosion current corresponding to a low level of corrosion is 0.1 μA/cm^2, to a moderate level is 0.5 μA/cm^2 and to a high level as to 1 μA/cm^2. Therefore, we define the corrosion threshold as 0.5 μA/cm^2. Using Faraday's Law, for the dimensions of rebar in question, we can convert this current density to a corrosion rate equivalent to 0.006 mm/yr.

With time, it was found that the corrosion density for all specimens was extremely low, generally <0.006 mm/yr. Even more astonishing was that while the initial LPR-derived corrosion rates were sometimes close to 0.006 mm/yr, as carbonation depth increased to well beyond the depth of the rebar, the corrosion rate decreased. This was completely contrary to expectations. Yoon et al (2007) reported that carbonation induced corrosion typically initiated when carbonation depths reached to within 5mm of the expected rebar. However, no such increase in corrosion rate was noticed at such carbonation depths, and in fact, it seems that corrosion rates actually decreased with an increase in carbonation depth.

A review of literature regarding corrosion current showed that corrosion current is heavily dependent on ambient relative humidity. Jung et al (2003) state that little corrosion is able to occur when the relative humidity is less than 60% in concrete. Enevoldsen et al (1994) contend that the minimum relative humidity required is even higher (>80%). Specimens subjected to LPR testing were tested immediately after being removed from the carbonation chamber, in which the ambient relative humidity had been held constant at 60%. Therefore, when the specimens were being tested, the relative humidity in the vicinity of the rebar was not high enough for a significant corrosion current to have developed. To test this hypothesis, a number of specimens which had initially shown low levels of corrosion as per LPR results, were left outside, exposed to natural atmospheric conditions where they would be subjected to fluctuating levels of relative humidity, often in excess of 80%. Under such conditions, within a matter of weeks, it was visually apparent that corrosion product had developed (Figure 9). Therefore, while LPR can still be used as a valuable tool to assess corrosion progression within a specimen, it was not appropriate to assess corrosion rates in this study, as relative humidity values in the accelerated tests were far too low to allow for a current to even develop. Rather, before running LPR tests, the specimens should be allowed to come to equilibrium with a higher ambient humidity before testing for the corrosion current. Looking at the LPR results at face value immediately after removal from the testing chamber would lead to the erroneous conclusion that the carbonated specimens were not susceptible to corrosion.

Figure 9. Formation of Corrosion Product on corroded rebar.

In general, throughout North America, the state of infrastructure is considered to be quite poor. The average service life of a building in Canada is expected to be 37 years (Vanier, 2001). This indicates that even before considering the effects of climate change, infrastructure is not being designed and maintained properly, and is generally not able to achieve design life prescribed by building codes. The findings from this paper suggest that the rate of carbonation in the presence of cracks caused by improper maintenance or overloading are far higher than in concrete which is properly maintained, but subject to climate change. The effects of carbonation due to climate change are not expected to be noticeable until around the year 2030 (Talukdar et al, 2012b), and by then the structure would have already have significantly degraded. Therefore, for the short term, it is recommended that focus be placed on designing and maintaining durable infrastructure (incorporating durability into the design criteria). By doing so, we will be helping to mitigate climate change by increasing longevity and promoting sustainability of infrastructure. If we manage to extend the lifespan of infrastructure as such, then we will have to consider designing for the effects of climate change as a secondary issue.

4. CONCLUSIONS

1. The numerical model developed by Talukdar et al (2012a) was able to forecast carbonation depths in non-pozzolanic, unloaded, uncracked concrete specimens under conditions of multiple, simultaneous, time-varying concentrations of CO_2, temperature and humidity. This makes it ideal to be able to predict carbonation depths under conditions of climate change.

2. The effective diffusion coefficient based on a model for homogenously dispersed microcracks is not applicable to sections showing large structural cracks. Carbonation rates in the vicinity of these cracks are much higher due to localized penetration. One-dimensional models are unable to account for the effect of large cracks. A two-dimensional model is needed to account for this situation.

3. While instances of overloading or weathering due to more frequent extreme weather events may cause a concrete structure to deteriorate more quickly, increasing the probability of crack formation, the presence of significant cracks is more serious than the effects of climate change. In the presence of a structural crack, the carbonation front progresses extremely quickly, spreading outwards from the crack, and the effect of a small increase in temperature or ambient CO_2 concentration is secondary.

4. LPR testing must be performed cautiously and only under conditions where the ambient relative humidity is high enough to allow for corrosion current to flow in the rebar.

REFERENCES

Alahmad, S., Toumi, A., Verdier, J., Francois, R., (2009). “Effect of crack opening on carbon dioxide penetration in cracked mortar samples”. Materials and Structures, 42(5):559-566.

Enevoldsen, J.N., Hansson, C.M., Hope, B.B., (1994). “The influence of internal relative humidity on the corrosion of steel embedded in concrete and mortar”. Cement and Concrete Research, 24(7):1373-1382.

Gerard, B., Marchand, J., (2000). “Influence of cracking on the diffusion properties of cement-based materials, Part I: Influence of continuous cracks on the steady-state regime”. Cement and Concrete Research 30(1):37-43.

Jang, S.Y., Kim, B.O., Oh, B.H., (2011). “Effect of crack width on chloride diffusion coefficients of concrete by steady-state migration tests”. Cement and Concrete Research, 41(1):9-19.

Jung, W.Y., Yoon, Y.S., Sohn, Y.M., (2003). “Predicting the remaining service life of land concrete by steel corrosion”. Cement and Concrete Research 33(5):663-677.

Malhotra, V.M., Carino, N.J., “Handbook on Nondestructive Testing of Concrete”, 2004, ASTM International, West Conshohoken, USA.

Marrero, T.R., and Mason, M.A., (1972). “Gaseous diffusion coefficients”. Journal of Physical and Chemical Reference Data. 1:3-118.

Meier, S.A., Peter, M.A., Muntean, A., Bohm, M., (2007). “Dynamics of the internal reaction layer arising during carbonation of concrete.” Chemical Engineering Science. 62(4):1125-1137.

Odeh, A.M., Abu-El-Shar, W., Al-Ruzouq, R., (2006). “Gas transport through concrete slabs”. Building and Environment, 41(4):492-500.

Pacheco, J., Polder, R., (2010). “Corrosion initiation and propagation in cracked concrete – a literature review”. Proceedings of the 4th International RILEM PhD Workshop, Madrid, Spain.

Sappakittipakorn, M., (2010). “Microstructural Refinements in Concrete due to Fiber

Reinforcement and its Influence on Corrosion Inititiation of Reinforcing Steel". PhD Thesis. University of British Columbia.

Song, H.W., Kwon, S.J., Byun, K.J., Park, C.K., (2006). "Predicting carbonation in early-aged cracked concrete". Cement and Concrete Research, 36(5):979-989.

Talukdar, S., Banthia, N., Grace, J., (2012a). "Carbonation in concrete infrastructure in the context of global climate change: Part 1, experimental results and model development". Cement and Concrete Composites, 34(8):924-930

Talukdar, S., Banthia, N., Grace, J., Cohen, S., (2012b). "Carbonation in concrete infrastructure in the context of global climate change: Part 2, Canadian urban simulations". Cement and Concrete Composites, 34(8):931-935

Vanier, D.J., (2001). "Why industry needs asset management tools". Journal of Computing in Civil Engineering, 15(1):35-43.

Wilke, C.R., (1950). "Diffusional properties of multicomponent gases". Chemical Engineering Progress, 46:95-104.

Yoon, I.S., Copuroglu, O., Park, K.B., (2007). "Effect of global climatic change on carbonation progress of concrete". Atmospheric Environment, 41(34):7274-7285.

Zhang, S., Zong, L, Dong, L., Zhang, W., (2011). "Influence of Cracking on Carbonation of Cement-based Materials". Advanced Materials Research, 261-263:84-88.