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Determination of Carbonation Depth of Structures in Intramuros using Artificial Neural Network

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Abstract: Corrosion in reinforced concrete structures is among the most serious concern that engineers and building owners encounter since it is an indication that the structure will soon deteriorate. The typical cause of corrosion is through steel in concrete reacting chemically with chloride or carbon dioxide. This study aims to predict the rate of carbon dioxide penetration in reinforced concrete structures using Artificial Neural Network (ANN). Old structures in Intramuros, Manila were chosen to provide data for training and testing the prediction model developed through ANN. Non-destructive drilling procedure were performed on old structures to determine actual carbonation penetration. Penetration of carbon dioxide in reinforced concrete structures, or simply carbonation, may be caused by several factors and its interaction. Five (5) holes will be drilled per elevation of a structure. Concrete powder will be retrieved from the holes drilled and will be tested using phenolphthalein solution. In this study, researchers focused on factors like age, relative humidity, temperature, mean sea level elevation, moisture content and CO_2 concentration in the atmosphere. Knowing the rate of carbonation penetration in reinforced concrete structures will benefit engineers and owners as it can now provide a gage for timely maintenance of structures.ANN requires a set of data for training the model and another set for testing. This study will use the results of field works for testing while data from previous study, that of Bata, et al (2013), for training. Predicted carbonation depth by ANN is compared with the carbonation depth measured on site. Carbonation prediction results through ANN, in this study, are consistent with theory of diffusion that depth is related to the square root of time. Based on early results, the researchers concluded that utilizing ANN is an effective tool in predicting carbonation depth considering age, relative humidity, temperature, mean sea level elevation, moisture content and CO_2 concentration as factors.

Keywords: carbonation; artificial neural network; concrete degradation

1. INTRODUCTION

As a developing country, the Philippines is undergoing modernization as with the rest of the world, and with this, several developments have been taking place in the country. Aggressive companies, a promising government together with our rising economy have been spearheading the country's rapid growth. With modernization comes development, and with development comes carbon dioxide. Carbonation is caused by carbon dioxide (CO_2) that is massively produced by technology as they undergo processes. Vehicles are among the several culprits of the rise of carbon dioxide emission. According to the Philippine Statistics Authority-National Statistics Coordination Board, there was a 25% increase in the registration of motor vehicles from 2007 to 2012, totalling to 7,463,393 vehicles in the country. By the end of 2013, the level of carbon dioxide in the Philippines has reached 90.78 million metric tons, when back in 1965 it was only at 12.88 million metric tons. Figure 1.1 shows the increasing trend of carbon dioxide levels in the Philippines with carbon dioxide amount units of Million Metric Tons.

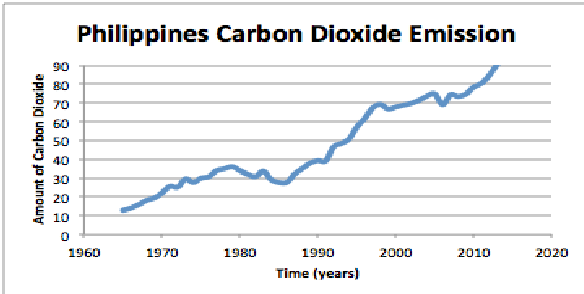

Figure 1.1: Amount of carbon dioxide in the Philippines from 1965 to 2013 (Source: Ycharts)

Studies have recognized that carbon dioxide can penetrate into our concrete structures, react with cement hydration elements, and eventually with the right pH level, set the environment for the reinforcing steel to corrode. Carbonation is the process wherein carbon dioxide in the atmosphere diffuses in gaseous form to the concrete pores that dissolves and forms acid with the cement paste (Pham, 2013). Further explanation from (Monkman, 2012) states that carbon dioxide particles penetrate into the concrete surface through the pores and react with pore water (H_2O) inside the reinforced concrete (RC). This reaction produces carbonic acid (H_2CO_3), which in turn reacts with hydration products namely, Calcium Hydroxide $Ca(OH)_2$ and C-S-H that produce $CaCO_3$. This chemical process depletes the concrete of $Ca(OH)_2$, and when this happens the pH of the concrete drops from 13 upto around 8. Through this, the protective passive layer of the ferrous reinforcing steel bars deteriorate as they require a higher pH to be stable. With a pH of below 13 the reinforcing steel bars affected by carbonation will be susceptible to harmful corrosion.

The study will only consider structures in Intramuros, Manila. RC structural members are the main concern of the researchers to investigate its carbonation depth. Furthermore the study will be focused on the depth of carbonation and the time for it to propagate. Since carbonation plays a significant impact in the deterioration of structures, it is essential to predict the initiation and propagation of carbonation in concrete. Knowing this would allow timely maintenance and rehabilitation that could extend the service life of structures. The aim of the study is to predict the carbonation depth of old reinforced concrete structures in Intramuros using artificial neural network (ANN).

2. LITERATURE REVIEW

2.1 Carbonation Process

Carbonation has been one of the major problems in concrete corrosion because it deteriorates the structure internally. Before you know it, carbon have already corroded the reinforcement steel if not monitored properly. Carbonation reduces the hydroxide ions in the pore solution, destroying the passivity of the reinforcement bars (Chang and Chen, 2006). A two-phased model was illustrated by (Köliö, Pakkala, Lahdensivu, and Kiviste, 2014) for the corrosion in the reinforcement of concrete in Fig. 2.1 wherein there would be the initiation then the propagation stage of concrete corrosion. The initiation stage is where the carbon dioxide penetrates into the concrete cover and goes through a chemical processes. This chemical process involves the reaction of carbon dioxide with cement hydration elements, which are calcium hydroxide $Ca(OH)_2$ and calcium-silicate-hydrates C-S-H, that forms calcium carbonate $CaCO_3$ and water. The propagation stage is where the reinforcement steel starts to corrode over time because $CaCO_3$ will lower the pH level of the concrete environment and later on with levels lower than 9, the reinforcement steel will start to corrode. The corrosion would only begin if the reinforcement steel reaches

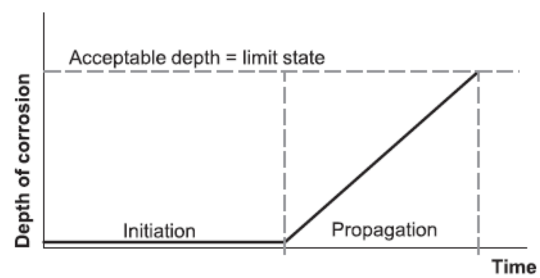

Fig. 2.1: Two-phased model of carbonation corrosion (Köliö, Pakkala, Lahdensivu, and Kiviste, 2014)

a significant electrical potential difference with sufficient amount of oxygen and moisture. The electrochemical process have two layers (Köliö et al., 2014; Marques and Costa, 2010) namely the anode wherein the passive elements release positively charged hydrated ions in oxidation reaction into the pore water acting as an electrolyte and the cathode wherein the hydroxide ions are formed due to oxygen, water and electrons coming from the anode. For the electrochemical corrosion to happen, (Köliö et al., 2014) stated that it requires: a reactive metal where the anodic oxidation can take place, a reducible substance which can act as a cathodic reactant, an electrolyte that will allow the movement of ions, and an electron conduction between anodic and cathodic areas. To simplify the explanation on carbonation process, a chemical equation developed in Equation 2.1.1 showing the reaction between $Ca(OH)_2$ and carbon dioxide, forming $CaCO_3$. This equation clearly states that when carbon dioxide and calcium hydroxide are reacted with an enough amount of water, it would form calcium carbonate with water and eventually lowering the pH level of the concrete environment.

$$CO_2 + Ca(OH)_2 \;\; Ca \rightarrow CO_3 + H_2O \qquad \text{(Eq. 1)}$$

However, (Burkan Isgor and Razaqpur, 2004) have further detailed this chemical equation. They further explained that in the process of carbonation, it involves the dissolution of carbon dioxide gas with water in the pores of concrete to form carbonic acid before reacting with $Ca(OH)_2$. Eqn. 2.1.2 illustrates the detailed chemical equation. Where Ca^{2+}(aq) + 2OH (aq) represent the calcium hydroxide, $2H^+$ (aq) + CO_3^2 (aq) represents the carbonic acid which in turn forms calcium carbonate, $CaCO_3$.

$$Ca^{2+}\,(aq) + 2OH\,(aq) + 2H^+\,(aq) + CO_3^2\,(aq) \rightarrow CaCO_3 \qquad \text{(Eq. 2)}$$

To further explain the process and diffusion of carbon dioxide, an illustration in Fig 2.2 shows the sequence of flow when carbonation occurs. The contact between concrete and CO_2 occurs in [1]. The dissolution process has already taken place in [2]. The carbon then penetrates into the concrete structure [3,4] and slowly propagating until the cover depth and eventually corroding the reinforcement steel. As the carbon have penetrated in the structure, it would react with cement hydration products, $Ca(OH)_2$ and C-S-H, to form $CaCO_3$. This in turn would reduce the pH level (usually below 9) of the inside of the concrete and thus corroding the reinforcement steel. However, studies from (Park, 2008) have stated that only 50% of CO_2 would react with $Ca(OH)_2$ and the other half would react with C-S-H. Further research from (Talukdar, et al., 2012; Yoon, et al., 2007) have stated that carbonation would not continue at a constant rate. With elapsed time, cement particles continue to hydrate, and CO_2 also continue to react with $Ca(OH)_2$ to form $CaCO_3$. These two processes would tend to decrease the diffusion coefficient of carbon because carbon dioxide with $Ca(OH)_2$ involves an expansion of solid volume inside the concrete thereby densifying the microstructure inside thus diffusion of carbon slows down.

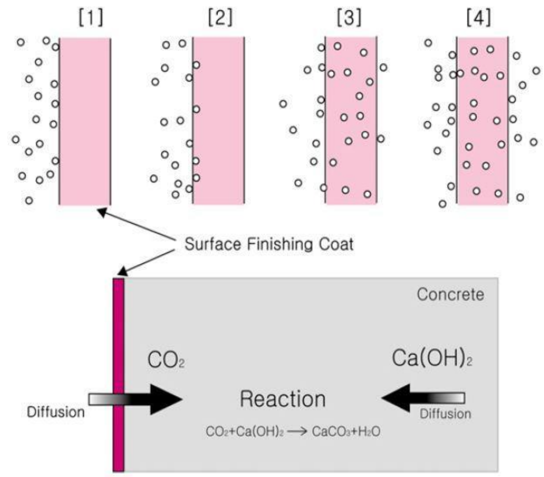

Fig 2.2: Diffusion of Carbon Dioxide and Concrete Carbonation (Park, 2008)

2.2 Factors Affecting Carbonation

There are many factors that can influence the rate of carbonation. The important ones were enumerated (Houst and Wittmann, 2002) as follows: water to cement ratio, degree of hydration, CO_2 concentration of the surrounding air, moisture content, temperature, alkali content, and presence of damaged zones and cracks. These factors should be considered when predicting the carbonation depth of concrete since these are the parameters that lead to the problem. Researchers will focus on factors that are relevant and manageable to measure. Temperature, relative humidity, degree of concentration of CO_2, moisture content, elevation, and age are the factors considered for this study.

2.2.1 Temperature

As temperature increases, the diffusivity of gaseous CO_2 also increases (Talukdar et al., 2012). The diffusivity of carbon is the rate of CO_2 to react and fully blend in with the cement hydrating elements. If temperature is higher, the higher the diffusivity is due to the increased molecular activity. (Köliö et al., 2014) also added that the rise in temperature translates to a higher solubility of chemical compounds thereby also increasing the rate of corrosion of the reinforcement steel.

2.2.2 Relative Humidity

Relative humidity dependence also plays a major role in determining the diffusivity of CO_2. CO_2 penetration tends to slow down in concrete because CO_2 has a low rate of diffusivity in water. Hence carbonation reaction also slows down if the concrete is too wet, although CO_2 diffuses into the capillary pores, it still cannot dissolve into the thin layer of water covering the pores. Therefore the higher the humidity, the slower the CO_2 diffusion in carbon due to the water present in the pores.

2.2.3 Elevation

Elevation have a major role in concrete carbonation. Studies from Castro, et al. (2000), the temperature remains constant while the humidity changes with respect to its elevations. It will decrease with respect to the height of a building thus lower parts of the building will be more humid. This tends to have less access of carbon dioxide due to partial water saturation that blocks and prevent the reactions than higher elevations. But the study also cited that there are instances that these situation does not apply.

3. METHODOLOGY

3.1 Samples Collected

In extracting samples, the researchers will consider five (5) drill holes labeled as DH. Figure 3.1.1 is a diagram on where the drilling of the concrete will be done. Table 3.1.1 is a summary of the things to be done in the extracted concrete powder.

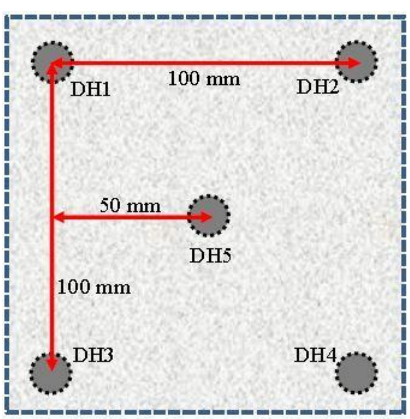

Fig 3.1.1: Proposed drill holes (Bata, et al., 2013)

Table 3.1.1: Summary of tests to be done in each drill hole (Bata, et al., 2013)

Test	Drill Hole #
Moisture Content	1
Phenolphthalein Solution Test	2
Phenolphthalein Solution Test	3
Moisture Content	4
Phenolphthalein Solution Test	5

To further test the accuracy of the ANN model, the group will include at least two hundred (200) samples for the experiment. This amount of sample will not only help the ANN to get its accuracy but also generate a better relationship between the carbonation depth between the parameters considered by the group.

In conducting the experiment, it will follow a specific time frame of 3:00 to 5:00pm in the afternoon. This was so because one of the parameters included are temperature, relative humidity, degree of concentration carbon dioxide which vary throughout the day. The time frame considered by Bata et al. (2013) were at these times therefore it will also adopt the same time for it to conform with the ANN model.

3.2 Procedure in Sample Extraction

Factors should be considered in obtaining samples. Since the parameters include temperature and relative humidity as major contributions in carbonation depth, the value will vary at any time of the day. Therefore the team decided to extract samples between 3:00pm to 5:00pm for temperature and relative humidity. The group will test the structure at one (1) meter intervals up to the top most part of the structure. Next step is to locate and determine the rebar using the Profoscope Proceq Rebar Detector. After locating the rebar, CO_2 concentration, relative humidity, and the temperature are to be measured using Telaire 7001 and a hygrometer from ASHRAE respectively. After recording all preliminary parameters, drilling activity will commence. The powder collected from the sample will then be tested in the lab for determination of the moisture content. The three (3) other samples will be tested on-the-spot through the phenolphthalein test to obtain onsite depth of carbonation.

3.3 Artificial Neural Network Modeling

In modelling the ANN, the group considered four (4) input nodes as they represent the parameters considered by Bata, et al., (2013), which are age, elevation, temperature, and relative humidity. The hidden layer will contain three transfer functions to process the input data. Finally, the output will contain one output node to process for the carbonation depth. In training the model, the group would utilize data from Bata et. al. After training, it will then test the trained model by putting in random samples from Bata's data. Proving the model trained and tested, researchers will test their data and compare the results from the carbonation depth obtained onsite.

4. RESULTS AND DISCUSSIONS

4.1 Trained ANN Model

Based from Bata et al (2013) data, the group have collected a total of thirty nine (39) data. On the 39, researchers have divided it into two cases. One is 29 were trained and the other 10 were tested. Second was 34 were trained and 5 were tested. Table 4.1 illustrates a comparison of actual and tested for Case 1. Figure 4.1 shows a summary of training for Case 1 using MATLAB 2011. Figure 4.2 on the other hand displays the R-value from the training of Figure 4.1.

Table 4.1: Case 1: Ten data points used for testing

Actual Carb Depth, Bata (2013)	ANN tested	% difference
12.80	11.0096	15.04
35.03	140.92	120.36
55.00	137.7212	85.85
146.58	53.9176	92.43
62.32	44.7084	32.90
59.00	59.332	0.56
14.00	14.7521	5.23
26.96	20.3624	27.87
29.19	57.5094	65.34
67.03	81.7351	19.76

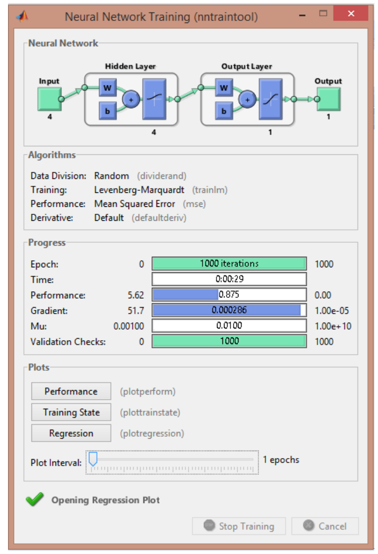

Figure 4.1: Training for Case 1

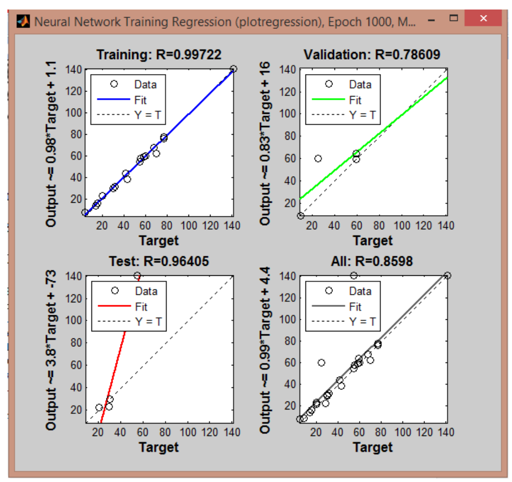

Figure 4.2: R-value for Case 1

Case 2 on the other hand shows an R-value closer to 1.0. Table 4.2 is a summary of actual and tested data with five (5) data points tested on the trained model.

Table 4.2: Case 2: Five data points for testing

Actual Carb Depth, Bata (2013)	ANN tested	% difference
59.00	58.6251	0.64
14.00	19.8131	34.38
26.96	10.2702	89.65

29.19	10.6485	93.07
67.03	50.6783	27.79

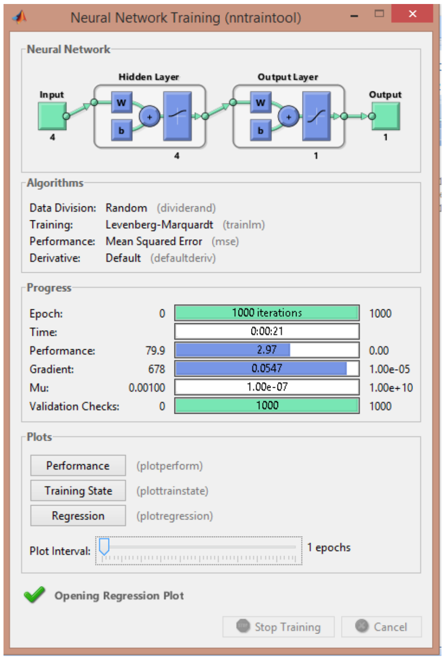

Figure 4.3: Training for Case 2

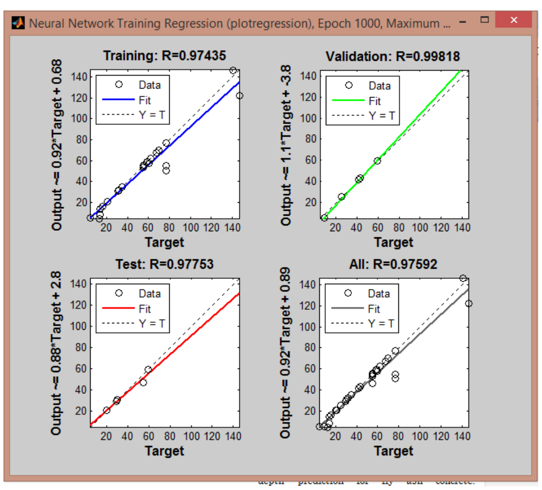

Figure 4.4: R-value for Case 2

The results from the trained ANN model for Case 1 and 2 got an R-value of 0.8598 and 0.9759. The two values states that the more data trained using ANN, the model becomes more accurate or close to 1.0. However data tested in the trained model is still far from the actual carbonation depth based on Table 4.1 and 4.2. There are percent differences ranged from 0.56 to as much as more than 100. Researchers thought that the model should be retrained and recalibrated from its raw data. It also thought that the cause for this big discrepancy might be due to insufficient data topped with some data errors encountered form site.

5. CONCLUSIONS

Result show that more data trained yields a better ANN model but it does not mean that the ANN model can accurately predict the actual carbonation depth obtained. The group thought that the model should be rechecked and retrained, add more data points for it to yield better values. Obtaining actual carbonation depth should be carefully extracted for it to obtain better results. Other factors such as porosity and water to cement ratio of a concrete member can also be some of the reason for the big discrepancy of the data. Furthermore, the group suggests that the ANN model should be rechecked and apply necessary changes.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Bata, K.J., Beltran, B., and Sacaguing, A. (2013). Carbonation profile of old and new reinforced concrete structures in Intramuros, Manila. De La Salle University. Taft, Manila.

Burkan Isgor, O., and Razaqpur, A. G. (2004). Finite element modeling of coupled heat transfer, moisture transport and carbonation processes in concrete structures. *Cement and Concrete Composites*, *26*(1), 57–73. doi:10.1016/S0958-9465(02)00125-7

Chang, C.-F., and Chen, J.-W. (2006). The experimental investigation of concrete carbonation depth. *Cement and Concrete Research*, *36*(9), 1760–1767. doi:10.1016/j.cemconres.2004.07.025

Han, S. H., Park, W. S., and Yang, E. I. (2013). Evaluation of concrete durability due to carbonation in harbor concrete structures. *Construction and Building Materials*, *48*, 1045–1049. doi:10.1016/j.conbuildmat.2013.07.057

Houst, Y. F., and Wittmann, F. H. (2002). Depth profiles of carbonates formed during natural carbonation. *Cement and Concrete Research*, *32*(12), 1923–1930. doi:10.1016/S0008-8846(02)00908-0

Kasperkiewicz, J. (2000). The applications of ANNs in certain materials-analysis problems. *Journal of Materials Processing Technology*, *106*(1-3), 74–79. doi:10.1016/S0924-0136(00)00641-5

Khunthongkeaw, J., Tangtermsirikul, S., and Leelawat, T. (2006). A study on carbonation depth prediction for fly ash concrete. *Construction and Building Materials*, *20*(9), 744–753. doi:10.1016/j.conbuildmat.2005.01.052

Köliö, A., Pakkala, T. a., Lahdensivu, J., and Kiviste, M. (2014). Durability demands related to carbonation induced corrosion for Finnish concrete buildings in changing climate. *Engineering Structures*, *62-63*, 42–52. doi:10.1016/j.engstruct.2014.01.032

Lu, C., and Liu, R. (2009). Predicting Carbonation Depth of Prestressed Concrete under Different Stress States Using Artificial Neural Network. *Advances in Artificial Neural Systems*, *2009*, 1–8. doi:10.1155/2009/193139

Marques, P. F., and Costa, a. (2010). Service life of RC structures: Carbonation induced corrosion. Prescriptive vs. performance-based methodologies. *Construction and Building Materials*, *24*(3), 258–265. doi:10.1016/j.conbuildmat.2009.08.039

Monkman, S. (2012). Concrete Carbonation – A Guide to the Different Types. Retrieved August 8, 2014, from http://carboncure.com/2012/06/concrete-carbonation/

Oreta, A. W. C. (2004). Simulating size effect on shear strength of RC beams without stirrups using neural networks. *Engineering Structures*, *26*(5), 681–691. doi:10.1016/j.engstruct.2004.01.009

Papadakis, V. G. (2000). Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress. *Cement and Concrete Research*, *30*(2), 291–299. doi:10.1016/S0008-8846(99)00249-5

Park, D. C. (2008). Carbonation of concrete in relation to CO2 permeability and degradation of coatings. *Construction and Building Materials*, *22*(11), 2260–2268. doi:10.1016/j.conbuildmat.2007.07.032

Rebar Detector and Covermeter - Profoscope. (n.d.). Proceq. Retrieved in August 9, 2014., from http://www.proceq.com/products/concrete-testing/ cover-meter-rebar-detector/profoscope.html

Steffens, A., Dinkler, D., and Ahrens, H. (2002). Modeling carbonation for corrosion risk prediction of concrete structures. *Cement and Concrete Research*, *32*(6), 935–941.

Talukdar, S., Banthia, N., and Grace, J. R. (2012). 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. doi:10.1016/j.cemconcomp.2012.04.011

YCharts. (2013). *Philippine Carbon Dioxide Emissions: 1965 to 2013*. Retrieved from http://ycharts.com/indicators/philippines_carbon_dioxide_emissions

Yoon, I. S., Çopuroğlu, O., and Park, K. B. (2007). Effect of global climatic change on carbonation progress of concrete. *Atmospheric Environment*, *41*(34), 7274–7285. doi:10.1016/j.atmosenv.2007.05.028