Predicted carbonation of existing concrete building based on the Indonesian tropical micro-climate

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Predicted carbonation of existing concrete building based on the Indonesian tropical micro-climate

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Abstract. This paper is aimed to predict the carbonation progress based on the previous mathematical model. It shortly explains the nature of carbonation including the processes and effects. Environmental humidity and temperature of the existing concrete building are measured and compared to data from local Meteorological, Climatological, and Geophysical Agency. The data gained are expressed in the form of annual hygrothermal values which will use as the input parameter in carbonation model. The physical properties of the observed building such as its location, dimensions, and structural material used are quantified. These data then utilized as an important input parameter for carbonation coefficients. The relationships between relative humidity and the rate of carbonation established. The results can provide a basis for repair and maintenance of existing concrete buildings and the sake of service life analysis of them.

1. Introduction

Carbonation of concrete is a physicochemical reaction between chemical constituents in water-air-frontier of concrete’s pores and carbon dioxide in the air [1]. It takes place just below the water surface. Carbonation is well-known phenomenon causing steel rebar in reinforced concrete structures to corrode. It is therefore quite an important aspect to observe in ensuring the durability of structures[2]. The corrosion risk generated by carbonation comes from two mechanisms in a row. First, carbonation of concrete lowers the pH. This related to the thickness and composition of concrete. Second, the low pH level will make the steel is no longer passivated and then active corrosion of steel is occurring[3].

Knowing its importance, many researchers developed methods to obtain universal carbonation models incorporating its changes in time and various variables. The following simplest formula for predicting the progress of carbonation widely used in practice (equation (1)). Where, $x = \text{carbonation depth}$, $b = \text{coefficient of carbonation rate}$, and $t = \text{time of exposure}$. This formula relates to an average constant relative humidity (RH) and carbon dioxide in the environment[4]. It is necessary to have a model that is simple but not simplistic, practically executable, and able to utilize readily available data with ease[5].

\[ x = b \cdot t^{1/2} \] (1)
2. Overview of Numerical Models Describing Carbonation Depth as Compressive Strength Function

Concrete compressive strength is one of the frequently used parameters for estimating durability since it reflects the quality and content of the concrete which is the criterion in design[6]. The following are several formulas using compressive strength to predict carbonation depth in time, namely Brown, Duval, Bob, Parrott, and De Fontenay.

Brown [7] proposed a model that describes the approximate course of carbonation with time t as inversely proportional to the concrete compressive strength (equation (2)). where, \( x \) = carbonation depth (mm), \( K_c \) = carbonation rate (mm/years\(^{1/2}\)), \( f_c \) = compressive strength (MPa), \( t \) = exposition time (years).

\[
x = \frac{K_c \cdot t^{1/2}}{f_c}
\]  

(2)

Duval [8] described the relation between carbonation depth and concrete strength as following (equation (3)). Where, \( x \) = carbonation depth (mm), \( f_{c28} \) = compressive strength after 28 days (MPa), \( t \) = exposition time (years).

\[
x = \sqrt{365 \cdot t} \left( \frac{1}{2.1 \cdot \sqrt{f_{c28}}} - 0.06 \right)
\]  

(3)

Bob[9], similar to Brown’s \( K_c \)[7], used several coefficients to express the carbonation depth and concrete strength relation (equation (4)). Where, \( x \) = carbonation depth (mm), \( f_{c28} \) = compressive strength after 28 days (MPa), \( t \) = exposition time (years), \( c \) = binding capacity coefficient of type of cement, \( k \) = environmental condition coefficient, \( d \) = surface concentration coefficient.

\[
x = \frac{150 \cdot c \cdot k \cdot d}{f_{c28}} \left( 1 + \frac{\sqrt{t-1}}{1.766} \right)
\]  

(4)

Parrott [10] states the carbonation depth and concrete’s strength correlation as the exponential function with the power of -0.05 (equation (5)).

\[
x = \sqrt{521} \cdot t \cdot \exp(-0.05 \cdot f_{c28})
\]  

(5)

Another formulation of carbonation depth was proposed by De Fontenay[11],[12]. The formula also used compressive strength after 28 days (equation (6)). Where, \( x \) = carbonation depth (mm), \( f_{c28} \) = compressive strength after 28 days (MPa).

\[
x = 6800 \cdot \left( f_{c28} + 2.5 \right)^{-2.5} - 0.06
\]  

(6)

Provided that adequate field and weather data are sufficient, the theoretical carbonation depth expressed in the formulation proposed by Niu (equation (7))[13]. Where, \( x \) = carbonation depth (mm), \( f_{cu} \) = compressive strength of cube concrete (MPa), \( k_{mc} \) = Uncertainty coefficient, \( k_l \) = Coefficient of structural member position, \( k_{co2} \) = CO2 concentration coefficient, \( k_p \) = surface finishing condition, \( k_s \) = condition of axial loading, \( T \) = environmental temperature (K), \( RH \) = relative humidity, \( mc \) = ratio of concrete compressive strength.
As can be seen, the formulations from Duval, Parrott and De Fontenay offered direct relation between carbonation depth and concrete compressive strength. It gave the advantage for practicing engineers in predicting carbonation depth rapidly. Besides that, those formulations also have a shortcoming. It cannot illustrate the influence of local micro-climate.

The formulation from Brown, Bob and Niu seem more promising in incorporating local condition parameter in predicted carbonation depth. Above all, Niu’s model gave somewhat various factors while maintaining its simplicity. The formula also took micro-climate data (temperature and relative humidity) into account. These hygro-thermal variables, $T$ and $RH$, can be used to predict the carbonation progress in the existing local concrete building.

3. Methodology
The methods employed for the hygro-thermal assessment of the local concrete building includes the data collection and statistical analysis of two types of data, namely primary and secondary. Primary data gained from the field measurements of temperature and humidity parameters of the existing concrete buildings. Then, the obtained data statistically analyzed by using several parametric tests. The secondary data, in this case, were in the form of micro-climate data (humidity and temperature) obtained from local Meteorological, Climatological, and Geophysical Agency (BMKG). These data analyzed by using descriptive statistics.

3.1. The hygro-thermal Measurements of the Existing Concrete Building
The building selected for this study is one of the campus buildings in Politeknik Negeri Pontianak, West Kalimantan Province, Indonesia. It is a three-story building with 4 m floor to floor height. The geometry of the building takes a rectangular shape with representative building plan dimension 22 m x 25 m. The front view and the typical story plan are as follows (figure 1).

![Building front-view and typical building plan with north direction](image-url)
The main structural elements of the studied structure made of reinforced concrete. It is a common practice in Indonesian construction practice that the minimum quality of the reinforced concrete for the structural application is the compressive strength of 20 MPa ($f'_c = 20$ MPa)\cite{14, 15}. It equals to C20/25 in Eurocode and BS\cite{16}. Cementitious material used based on ASTM C150M\cite{14, 15} which is equivalent to CEM I in Eurocode and BS\cite{16}. The hygro-thermal analyses conducted at structural columns in all three stories of the existing building. The column chosen for the measurements were located in the center of the building and also those on the right side of the building. The purpose of the gauges is to identify any differences regarding relative humidity between the exterior and interior column and any differences among stories. The measurements were carried out according to ASTM F2420-05\cite{17}. The measurements performed by using the humidity-temperature digital instrument (YK-2001TM type, Lutron, Taiwan) (figure 2).

**Figure 2.** (a) The measurement of RH and T (b) RH and T digital instrument

3.2. *The Statistical Analysis of the Field Measurements*

The measurements conducted in July 2017 in the morning (9 am till 11 am), noon (1 pm till 2.30 pm), and in the afternoon (4 pm till 6 pm). The data gained were then statistically analyzed using statistical parametric analysis\cite{18}. In this case, three independent time parameters observed (morning, noon and afternoon). It is appropriate to use analysis of variance (ANOVA) to find out any differences during the time of measurements\cite{19}. It obtained that the measuring time in the morning and the afternoon were representatives used in the next analysis. The results as shown in table 1a till table 1d.

**Table 1a.** Descriptive analysis of the measured data

| Time    | N  | Mean     | Std. Deviation | Std. Error | 95% Confidence Interval for Mean | Min    | Max    |
|---------|----|----------|----------------|------------|---------------------------------|--------|--------|
|         |    |          |                |            | Lower Bound                      |        |        |
| Morning | 18 | 64.8111  | 8.54923        | 2.01507    | 60.5597 to 69.0625               | 44.80  | 74.80  |
| Noon   | 18 | 41.5000  | 0.0000         | 0.0000     | 41.5000 to 41.5000               | 41.50  | 41.50  |
| Afternoon | 18 | 63.4833  | 8.19550        | 1.93170    | 59.4078 to 67.5589               | 48.80  | 76.30  |
| Total  | 18 | 56.5981  | 12.70490       | 1.72892    | 53.1304 to 60.0659               | 41.50  | 76.30  |
Table 1b. Test of homogeneity of variance

| Levene Statistic | df1 | df2 | Sig. |
|------------------|-----|-----|------|
| 12.931           | 2   | 2   | .000 |

Table 1c. Analysis of variance (ANOVA)

| Levene Statistic | Sum of Squares | df | Mean Square | F     | Sig.  |
|------------------|----------------|----|-------------|-------|-------|
| Between Groups   | 6170.627       | 2  | 3085.314    | 65.993| .000  |
| Within Groups    | 2384.343       | 51 | 46.752      |       |       |
| Total            | 8554.970       | 53 |             |       |       |

Table 1d. Homogeneous subsets

| Waktu  | N  | Subset for alpha = 0.05 |
|--------|----|------------------------|
|        | 1  |                        |
| Noon   | 18 |                        |
| Afternoon | 18 | 41.5000                |
| Morning| 18 | 63.4833                |
|        | 2  |                        |
|        | 18 | 64.8111                |

3.3. Micro-climate Secondary Data and Descriptive Statistics Analysis

The micro-climate data (humidity and temperature) shown here based on records obtained from Meteorological, Climatological, and Geophysical Agency (BMKG) in Pontianak Supadio International Airport (IATA: PNK, ICAO: WIOO), West Kalimantan Province, Indonesia[20]. The data were taken on July during the year 2004 until 2015. The data provided by using descriptive statistics as follows (figure 3 and figure 4).

Figure 3. Relative humidity on July during 2004 - 2015
4. Numerical Calculation and Discussion

Essential data used as input parameters in carbonation models among others: concrete compressive strength, relative humidity, and temperature. Concrete compressive stress simulated from 20 MPa until 40 MPa. Relative humidity is taken by averaging the highest value between data gained from field measurements and those from BMKG (RH = 80%). The temperature obtained from the mean value of BMKG’s data ($T = 27^\circ C = 301 \text{ K}$).

Numerical calculation results have been conducted to examine the influence of concrete strength on carbonation depth of concrete. To do so, the formulations from Brown (equation 2), Duval (equation 3), Bob (equation 4), Parrott (equation 5), De Fontenay (equation 6), and Niu (equation 7) have compared. The concrete strength was simulated from 20 MPa until 40 MPa to find the related value of concrete’s carbonation depth in mm (Figure 5). It attained that all six models used showing the similar trends. The highest values of carbonation depth gained from Parrott equation. Meanwhile, Brown model showed the lowest carbonation depth among the models. It has to notice that Niu’s formulation using RH and T as its inputs. It is then interesting to find out how these micro-climate parameters influence the carbonation depth.

![Figure 4. Temperature on July during 2004 - 2015](image)

![Figure 5. Concrete strength vs. Carbonation depth](image)
Figure six and seven are simulating carbonation depth incorporating relative humidity (RH) and temperature (T) variables. Firstly, the carbonation depths evaluated for varied concrete strength (20 until 40 MPa) with constant RH = 80% and T = 301 K. The plot confirm similar trend to that from Figure 6. Next, RH = 80% and fc28 = 20 MPa are chosen as constant input parameters to gain the influence of the raised temperature to carbonation depth. As the temperatures elevate, carbonation depths proportionally rise.

5. Conclusion
The numerical calculation of concrete’s carbonation depth based on the Indonesian tropical microclimate is quite demanding. It is due to the practical need of a simple formulation that can quickly predict the carbonation depth based on concrete strength based on the Indonesian tropical microclimate.

Based on the calculation results, the following conclusion obtained:
1. All the formulas are incorporating the compressive strength parameters, including Niu’s model, are showing relatively similar trends in simulating carbonation depth.
2. Niu’s formulation enables micro-climate parameters included in the simulation. It opens the opportunity to incorporate various weather conditions in the carbonation depth predictions.
3. Certain parameters in Niu’s formulation have adjusted to Indonesian environment. These parameters especially are uncertainty coefficient (kmc) and CO2 concentration (kco2). Therefore, further studies are required.

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