# CARBONATION INDUCED CORROSION ANALYSIS OF REINFORCED CONCRETE STRUCTURES BASED ON FULL PROBABILISTIC APPROACH – AN INDONESIAN CASE STUDY

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## ABSTRACT

*The assessment of the service life of concrete structures using the durability design approach is widely accepted nowadays. It is really encouraged that a simulation model can resemble the real performance of concrete during the service life. This paper investigates the concrete carbonation through probabilistic analysis. Data regarding Indonesian construction practice were taken from Indonesian National Standard (SNI). Meanwhile, data related to Indonesian weather condition for instance humidity and temperature are taken from local Meteorological, Climatological, and Geophysical Agency from 2004 until 2016. Hopefully the results can be a starting point for durability of concrete research in Indonesia.*



**Keywords**: *Carbonation, Full Probabilistic Approach, Reinforced Concrete Structures, Indonesian Climate*

# 1.0 INTRODUCTION

The adoption of American Concrete Institute (ACI) 318-11 regarding "Building Code Requirements for Structural Concrete" (ACI, 2011) as a reference for Indonesian Standard SNI 2487:2013 (SNI, 2013) opens a great opportunity for Indonesian concrete construction community to become accustomed to durability issues in material and structural concrete design. SNI 2847:2013, in chapter 4, explicitly mentioned the categories and class of environmental exposure. It also explains the requirements of concrete materials for every exposure class. Exposure class S regulates the requirements of concrete materials in the environment susceptible to sulfate. Concrete structures directly in contact with water are required to refer to exposure class P. And last but not least, Exposure class C controls the requirements related to rebar corrosion protection of reinforced concrete structures (Prabowo, 2017).

It is common in Indonesian concrete design practice that the structural engineering aspect mainly focused on the feature of the material strength (e.g. fc' and fy). Next step, the dimensions of structural elements are determined based on design loads. It is certainly quiet important, but it cannot be assured that the structures can still be used during their design service lives. The reinforced concrete structures are frequently forced to stop functioning before their service lives achieved. It is not caused by the worse anticipated design loads but rather due to material deteriorations of the structural components. They can be in a form of concrete cover cracks or spalls and rebar corrosion related to environmental exposure.

Durability issues become more and more important. It is true for infrastructures that generally have a long design service life. It must take into account safety factor, serviceability, durability, and ease of repair in its structural design process (FIB, 2012). The repair and maintenance scenario should be determined in the early stage of design. It should be set that the structures can be guaranteed to achieve their design service lives (Verma, Bhadauria, & Akhtar, 2014). The process of cumulative deterioration of concrete structures can be found in (Binder, 2013) where durability approach design can be seen in (Altmann & Mechtcherine, 2013).

Degradation mechanisms affecting the performance of concrete have a lot of types. Carbonation is one of them. Carbonation is physicochemical process causing corrosion of reinforced concrete structures' rebar. Abundant researchers have attempted to obtain carbonation model which is uncomplicated and can be easily implemented. The well-known model for durability design is the DuraCrete approach (DuraCrete, 2000). Further, in order to utilize its practical usage for real situation, "Model Code for Service life Design of Concrete Structures" detailed the DuraCrete model (FIB, 2006).

FIB bulletin 34 stress the point on a full probabilistic method (Gulikers & I.S. Oslakovic, 2014). It is essential for Indonesian user to become acquainted with the mathematical model used for reinforced concrete structures durability design. Proper knowledge of the fundamental physics is also necessary. It is also important to investigate whether the model resulting in the suitable condition for Indonesian tropical climate after some related parameters were inserted.

Model Code 2010 is the successor of Model Code for Service life Design of Concrete Structures 2006 (FIB, 2012). In this Code, the structural design should take into account the functional, environmental, and economic aspects. ISO 16204 recognized concepts developed by Federation Internationale du Beton (FIB) in 2012. This standard is the combination of ISO 2394, ISO 13823, and Model Code 2010 (ISO, 2012).

## 2.0 LITERATURE REVIEW

European Union funded two projects that develop Full Probabilistic Approach. Firstly, DuraCrete has generated a full probabilistic design method for the modelling of carbonation induced corrosion of uncracked concrete. Then, research project Durable and Reliable Tunnel Structures (DARTS) slightly customized the method (FIB, 2006). Limit-state equation is the basis for the approach. The equation can be seen as follows (equation (1)).

$$x_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot \left(k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t\right) \cdot C_S} \cdot \sqrt{t} \cdot W(t) \tag{1}$$

With: xc(t) = carbonation depth at the time t [mm], ke = environmental function [-], kc = execution transfer parameter [-], kt = regression parameter

[-], $R_{ACC,0}^{-1}$ = inverse effective carbonation resistance of concrete [(mm2/years)/(kg/m3)], εt = a normal distributed error term [-], Cs = CO2 concentration [kg/m3], t = time [years], W(t) = weather condition [kg/m3].

**Table 1: Variable quantification in the carbonation model**

| Parameter | Description | Unit | Source for quantification |
|---|---|---|---|
| $RH_{real}$ | Relative humidity of the carbonated layer | [%] | BMKG Supadio Airport (weather station) |
| $RH_{ref}$ | Reference relative humidity | [%] | Predefined, $RH_{ref}$ = 65 |
| $f_e$ | Exponent | [-] | Predefined, $f_e$ = 5.0 |
| $g_e$ | Exponent | [-] | Predefined, $g_e$ = 2.5 |
| $t_c$ | Period of curing | [days] | Indonesian Standard (SNI) |
| $b_c$ | Exponent of regression | [-] | Predefined<br>$\mu$ = -0.567; $\sigma$ = 0.024 |
| $k_t$ | Regression parameter | [-] | Predefined<br>$\mu$ = 1.25; $\sigma$ = 0.35 |
| $R_{ACC,0}^{-1}$ | Inverse effective carbonation resistance of concrete | [(m²/s)/(kg/m³)] | SNI and FIB Bulletin 34 |
| $\varepsilon_t$ | Error term | [(mm²/years)/(kg/m³)] | Predefined<br>$\mu$ = 315.5; $\sigma$ = 48 |
| $C_s$ | $CO_2$ concentration | [kg/m³] | Predefined, Normal Distribution (ND)<br>$\mu$ = 0.00082; $\sigma$ = 0.0001 |
| t | Time | [years] | Design service life, SNI |
| $t_o$ | Time of reference | [years] | Predefined; $t_o$ = 0.0767 |
| $p_{SR}$ | Probability of driving rain | [-] | BMKG Supadio Airport (weather station)<br>for interior, $p_{SR}$ = 0 |
| ToW | Time of Wetness | [-] | BMKG Supadio Airport (weather station) |
| $b_w$ | Exponent of regression | [-] | Predefined, ND<br>$\mu$ = 0.446; $\sigma$ = 0.163 |

(Source (FIB, 2006))

The sources of parameter quantification can be seen in Table 1. Most of them come from FIB Bulletin 34 (FIB, 2006). Several parameters also give chance to Indonesian climate as input values. Each parameter in Table 1 will be explained below.

Relative humidity of the carbonated layer (RHreal) data can be supplied from the nearest weather station. The weather station data which were daily mean value has to be evaluated. This variable should apply restricted distribution with an upper limit. This is due to the fact that the relative humidity varies by definition utmost in a range of 0 % < RH ≤ 100 %. A right-skewed distribution is in general appropriate to describe RHreal, especially in European climate conditions. The lower limit of RH might significantly different from zero. It depends on the area. It is likely reasonable in such a case to describe the data set by means of a distribution function with an upper and a lower limit using Beta-distribution or Weibull(max)-distribution for instance.

Reference relative humidity (RHref) has to be selected in relation to the test condition for determining the carbonation resistance of the concrete. The reference climate for the recommended ACC-test method is T=+20°C/65%RH. Therefore, RHref is quantified as RHref [%]: constant parameter, value: 65.

The parameters ke, kc, and W(t) can be described by means of the following equations (Equation (2) until (4)).

$$k_e = \left( \frac{1 - \left( \frac{RH_{real}}{100} \right)^{fe}}{1 - \left( \frac{RH_{ref}}{100} \right)^{fe}} \right)^{ge} \qquad (2)$$

$$k_c = \left( \frac{t_c}{7} \right)^{b_c} \qquad (3)$$

$$W(t) = \left( \frac{t_o}{t} \right)^{\frac{(p_{SR} \cdot ToW)^{bw}}{2}} \qquad (4)$$

A curve fitting procedure of the actual data test is used to determine the parameters fe and ge. The best values for those parameters are 2.5 and

5.0 respectively.

The variables tc and bc have been quantified as follows. Parameter tc is a constant parameter represent the period of curing. It is chosen based on Indonesian Standard SNI 03-2847-2002 (SNI, 2002) and common construction practice in Indonesia. For instance, the period of curing is 7 days for normal concrete. Parameter bc is an exponent of regression following a normal distribution. It has a mean value of -0.567 and standard deviation of 0.024.

The variable (kt) is a regression parameter which considers the influence of test method on the ACC-test. It follows a normal distribution with a mean value of 1.25 and standard deviation of 0.35.

The inverse carbonation resistance (RACC,0-1) is a parameter following a normal distribution. This parameter is quantified based on test data. If in a certain condition where data is not available, the following table can be used for orientation purposes (Table 2).

**Table 2: RACC parameter quantification (FIB Bulletin 34, 2006)**

| $D_{RCM,0}$ [m$^2$/s] | $w/c_{eqv.}$ [1] | | | | | |
|---|---|---|---|---|---|---|
| cement type | 0.35 | 0.40 | 0.45 | 0.50 | 0.55 | 0.60 |
| CEM I 42.5 R | n.d.[2] | $8.9.10^{-12}$ | $10.0.10^{-12}$ | $15.8.10^{-12}$ | $19.7.10^{-12}$ | $25.0.10^{-12}$ |
| CEM I 42.5 R +FA (k=0.5) | n.d.[2] | $5.6.10^{-12}$ | $6.9.10^{-12}$ | $9.0.10^{-12}$ | $10.9.10^{-12}$ | $14.9.10^{-12}$ |
| CEM I 42.5 R +FA (k=2.0) | | $4.8.10^{-12}$ | n.d.[2] | n.d.[2] | $5.3.10^{-12}$ | n.d.[2] |
| CEM III/B 42.5 | n.d.[2] | $1.4.10^{-12}$ | $1.9.10^{-12}$ | $2.8.10^{-12}$ | $3.0.10^{-12}$ | $3.4.10^{-12}$ |

1 equivalent water-cement ratio, hereby considering FA (fly ash) or SF (silica fume) with the respective k-value (efficiency factor). The considered contents were: 22 wt.-%/cement; SF: 5 wt.-%/cement.

2 n.d. – chloride migration coefficient RACC,0-1 has not been determined for these concrete mixes.

(Source: Fib Bulletin 34, 2006)

Te value of RACC,0-1 in table 2 is determined by the unit [10-11. (m2/s)/(kg/m2)]. Converting RACC,0-1 into the respective unit for the deterioration model [(mm2/years)/(kg/m2)], a multiplication factor has to be applied.
The error term (εt) is parameter considering inaccuracies which occur conditionally when using the ACC test method [(mm2/years)/(kg/m2)]. It follows a normal distribution which has the mean value of 315.5 and standard deviation of 48.

Parameters kt and εt fulfill all the differences between specimens tested at ACC conditions and the structure tested under natural carbonation conditions. Differences in compaction and water movements due to vibration between test specimen and structure are not quantified so far since compared specimen tested at ACC condition and natural condition were compacted identically.

The CO2 concentration parameter (Cs) of the ambient air represents the direct impact on the concrete structure. The following equation describes this impact (Equation (5)).

$$C_S = C_{S,\mathrm{atm}} + C_{S,emi} \qquad (5)$$

Where: Cs = CO2 concentration [kg/m3], Cs,atm = CO2 concentration of the atmosphere [kg/m3], and Cs,emi = additional CO2 concentration due to emission sources [kg/m3]. Increased CO2 concentration can be applied e.g. to road tunnels or when combustion engines are used. For usual structures, Equation (5) can be reduced to following equation (Equation (6)).

$$C_S = C_{S,\mathrm{atm}} \qquad (6)$$

The actual CO2 content in the atmosphere has been identified to be in a range of 350 – 380 ppm. This related to the concentration of 0.00057 to 0.00062 kg/m3 respectively. Its standard deviation is almost flat with a maximum value of 10 ppm. Cs,atm parameter follows a normal distribution with a mean value of 0.00082 and standard deviation of 0.0001.

The weather parameter (W) in equation (4) considers the meso-climatic conditions due to wetting events of the concrete surface. The weather functions compose of two model variables. The first is the exponent of regression (bw) and the other is the time of reference parameter (to). The quantification of these variables is as follows. Parameter exponent of regression (bw) is following a normal distribution which has a mean value of 0.446 and standard deviation of 0.163. Meanwhile, parameter time of reference (to) is a constant parameter which value is 0.0767.

The parameters time of wetness (ToW) and the probability of driving rain (pSR) are parameters related to the effect of rain events on the concrete with respect to its carbonation resistance depends on the orientation and the geometrical characteristics of the structures. These two variables are quantified as follows. Parameter time of wetness (ToW) is the average value of rainy days every year. A rainy day is quantified by a minimum amount of precipitation water of hND = 2.5 mm every day. The nearest weather station data will be valuable for the quantification of ToW. The parameter probability of driving rain (pSR) is the average wind direction distribution during rain events. Based on the data from the nearest weather station, wind direction during rain events can be determined by carried out an evaluation. The quantification of the pSR parameter can be given in the following table (Table 3).

**Table 3: pSR parameter quantification**

| Parameter distribution | Value | Description |
|---|---|---|
| constant | Based on data | If vertical elements are treated $p_{SR}$ has to be evaluated from weather station data |
| constant | 1 | If horizontal elements are treated |
| constant | 0 | If interior structural elements are treated |

(Source: (FIB, 2006))

The design service life parameter (tSL) determine the carbonation depth and almost every variable related to it. Indicative values for the design of service life are given as follows (Table 4).

**Table 4: Indicative values for the design service life**

| Design service life $t_{SL}$ [years] | Examples |
|---|---|
| 10 | Temporary structures (structures or parts of structures that can be dismantled with a view to being re-used should not be considered as temporary) |
| 10 - 25 | Replaceable structural parts, e.g. gantry girders, bearings |
| 15 – 30 | Agricultural and similar structures |
| 50 | Building structures and other common structures |
| 100 | Monumental building structures, bridges, and other civil engineering structures |

*(Source: (FIB, 2006))*

## 3.0 METHODOLOGY

The method utilized for carbonation depth prediction incorporates the data collections and statistical analysis of secondary data. These data mainly derivate from Indonesian Standard (SNI) for aspect related to concrete properties and taken from local Meteorological, Climatological, and Geophysical Agency (BMKG) in Pontianak, Supadio International Airport (IATA: PNK, ICAO: WIOO), West Kalimantan Province, Indonesia (BPS, 2017).

Data coming from BMKG were Relative Humidity (RH) and Temperature (T) taken every month during the year 2004 until 2016. These data were average values of relative humidity and temperature of each month during the observation years. The RH and T data were processed by using descriptive statistical analysis. Using bar chart, the processed data can be seen as follows (Figure 1 and Figure 2).

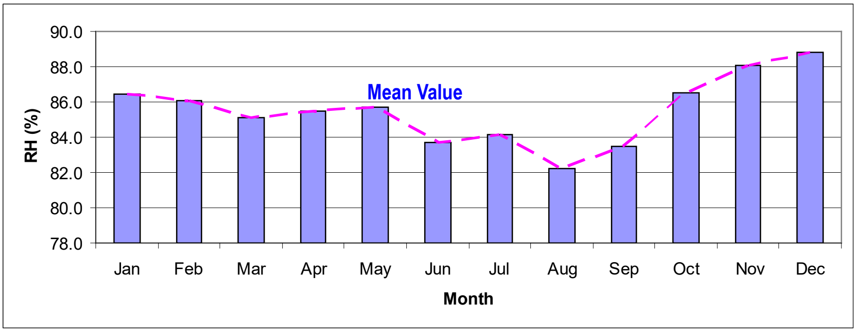


**Figure 1: Average monthly relative humidity during years 2004 – 2016**

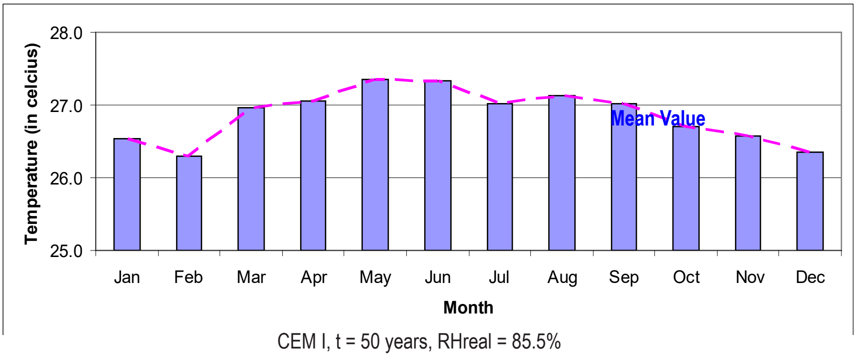


**Figure 2: Average monthly temperature during years 2004 – 2016**

Data in relation with SNI among others: tc, cement type and w/c ratio for the determination of $R^{-1}_{ACC,0}$ values, and t for design service life. SNI 03-2847-2002 regulates that the period of curing is 7 days for normal concrete and 3 days for concrete with high early compressive strength (SNI, 2002). According to SNI 7394:2008, the average value for w/c ratio is 0.55 for low rise building and housing (SNI, 2008). Then, $R^{-1}_{ACC,0}$ values can be obtained by using Table B1-2 in fib bulletin 34 (FIB, 2006). It is common in Indonesian building practice to assume that buildings will last for 50 years. These values will be chosen as design service life for predicting carbonation depth. The calculation of concrete carbonation depth can be summarized in the following flowchart (Figure 3).

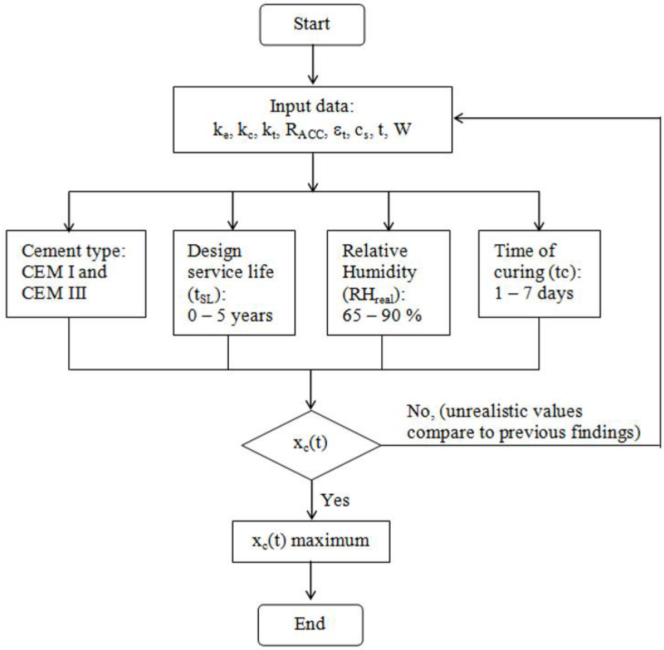


**Figure 3: Flowchart for concrete carbonation depth calculation**

## 4.0 RESULTS AND DISCUSSIONS

Time of curing, design service life, and RHreal were the essential parameters in carbonation models. Time of curing modeled from 1 days until 7 days. Design service life was chosen from 0 to 50 years where RHreal were simulated from 65% to 90%. The first model (Figure 4) was the time of curing vs. carbonation depth. Parameters such as Cement type I (CEM I), time of service life, and RHreal were kept constant. Second simulation (Figure 5) was design service life vs. carbonation depth. Cement type I (CEM I), RHreal, and time of curing were kept constant in this simulation. Third simulation (Figure 6) was RACC vs. carbonation depth. This simulation kept RHreal, time of curing, and time of service life remain steady. Last simulation (Figure 7) was RHreal vs. carbonation depth. This simulation kept Cement type I (CEM I), time of curing, and time of service life remain unchanged.

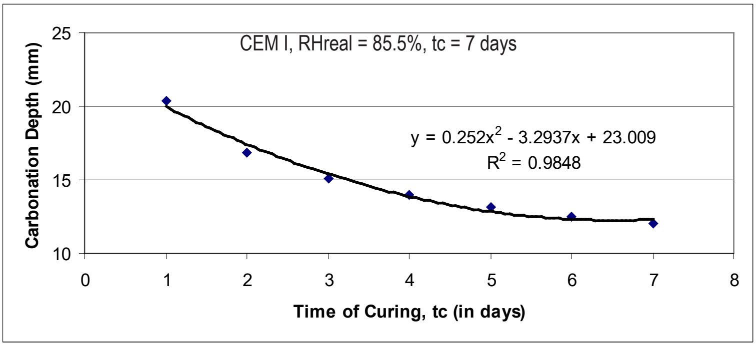


**Figure 4: Time of curing vs. Carbonation depth**

Figure 4 simulated relation between time of curing and carbonation depth. As can be seen, carbonation depth significantly declined as the time of curing rose. For common Indonesian practice of 7 days curing, carbonation depth read at around 12 mm. The curve fitting shows that the quadratic equation gives the best fit for the model with a coefficient of correlation ($R^{2)}$ equals to 0.9848. In accordance with the time of curing, carbonation depth can be expressed as:

$$x_c(t) = 0.252t_c^{\ 2} - 3.2937t_c + 23.009 \quad (7)$$

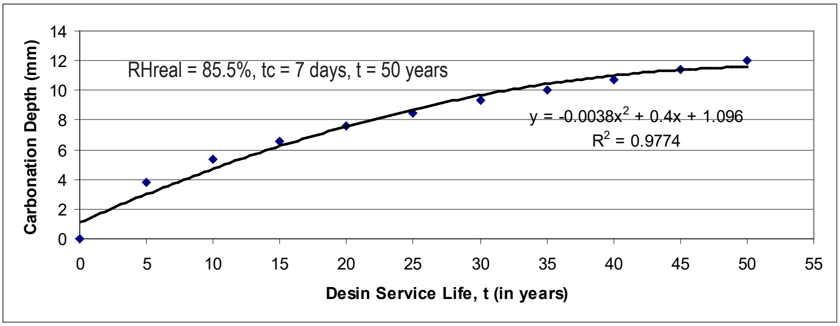


**Figure 5: Design service life vs. Carbonation depth**

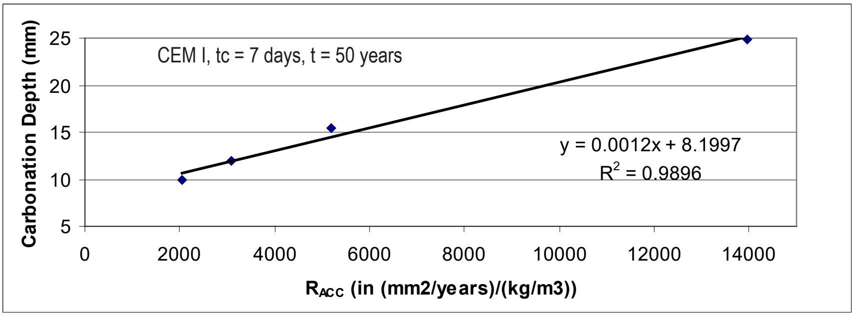


**Figure 6: RACC vs. Carbonation depth**

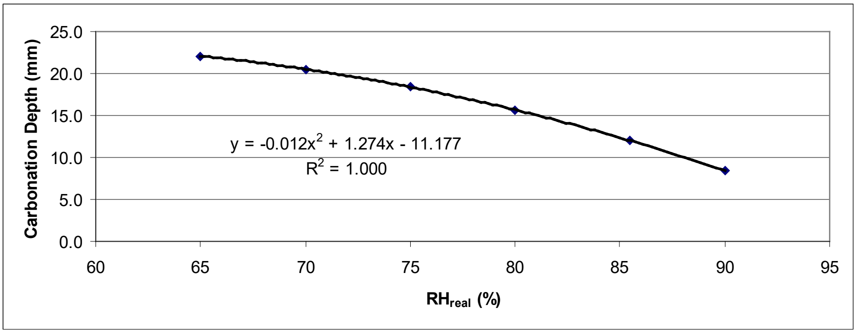


**Figure 7: RHreal vs. Carbonation depth**

The relation between design service life and carbonation depth can be observed in Figure 5. The carbonation depth increased considerably as the design service life became longer. It reached the highest value at around 12 mm for 50 years service life. The procedure of curve fitting confirms that the quadratic formulation offers the best fit for the simulation with a coefficient of correlation (R2) equals to 0.9774. The carbonation depth can be formulated as design service life dependence as follows.

$$x_c\left(t\right) = -0.0038{t_{SL}}^2 + 0.4t_{SL} + 1.096 \tag{8}$$

Figure 6 simulated relation between RACC and carbonation depth. As can be seen, carbonation depth significantly is proportionally rose as RACC developed. For common Indonesian practice of CEM I, carbonation depth read at around 12 mm. The curve fitting demonstrates that the linear equation gives the best fit for the model with a coefficient of correlation (R2) equals to 0.9896. In accordance to RACC, carbonation depth can be expressed as:

$$x_c\left(t\right) = 0.0012R_{ACC} + 8.1997 \qquad (9)$$

It is also interesting to examine Figure 7. It relates the RHreal and carbonation depth. The carbonation depth decreases at the same time as the RHreal climb up. Relative humidity from BMKG (RHreal = 85.5%) related to carbonation depth at around 12 mm. The procedure of curve fitting confirms that the quadratic formulation offers the best fit for the simulation with a coefficient of correlation (R2) equals to 1.000. The carbonation depth can be formulated as design service life dependence as follows.

$$x_c\left(t\right) = -0.012RH_{real}{}^2 + 1.274RH_{real} - 11.177 \qquad (10)$$

All parameters including time of curing, design service life, RACC and RHreal which were simulated against carbonation depth showed similar values at around 12 mm. It should be noticed that the simulations were predicting the carbonation depth for the interior structural elements. This implied that weather exponent parameter is set to 1. This weather exponent opens a good opportunity to incorporate the other Indonesian climate-related variables, for instance, the probability of driving rain and time of wetness.

## 5.0 CONCLUSION

Numerical carbonation depth simulations based on the full probabilistic design approach have been carried out. Some Indonesian tropical climate parameters and concrete material properties from the Indonesian standard (SNI) have been provided during the simulations.
Based on the results, the following conclusions attained:

Input variables such as time of curing, design service life, and RHreal which were set to Indonesian conditions showed convergence results.

The curve fitting procedure shows that quadratic equation best fit the results from input parameters such as time of curing, design service life, and

RHreal. For RACC parameter, a linear equation is adequate.

There are still chances to incorporate the other Indonesian climate-related variables, such as the probability of driving rain and time of wetness in further researches.

It is also essential to examine the predefined values in the formulation especially its compatibility aspects with Indonesian construction practice and the Indonesian climate condition in general.

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