# Impact of Climate Change on Corroded Reinforced Concrete Structure in Indonesia Using Web Information Systems and Technology-Probability Approach

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Abstract: The deterioration of concrete over time, which is influenced by environmental circumstances, is a crucial factor in determining its durability. This environment may be altered by climate change, accelerating the deterioration process and affecting the safety, durability, and serviceability of concrete infrastructure, especially in Indonesia. The concrete deterioration evaluated by the environmental parameter using integrated web information system provided by the meteorological, climatological, and geophysical agency (BMKG) website data set using monte Carlo analysis. This approach is used in general to adapt models and investigate the changing of environment. Climate change connected with the frequency of reinforcing corrosion initiation and corrosion-induced damage in concrete structures from 2000 to 2023. Since $CO_2$ concentration and temperature are the primary causes of increased concrete deterioration, the damage risks will increase. Change's effect on deterioration cannot be ignored, but it can be countered through innovative design approaches. Existing concrete structures whose design did not take into account the effects of a changing climate may deteriorate more quickly than anticipated.

## 1 INTRODUCTION

In the coming years, infrastructure demand will increase exponentially. Both developed and developing countries are investing heavily in their infrastructure systems to improve quality of life and economic growth. To accommodate growing populations and economic growth, developing countries are investing more in infrastructure planning and construction. To meet infrastructure demands, rising Asian countries will need to invest 776 billion dollars every year between 2010 and 2025. (Bhattacharyay, 2012). With 12 billion metric tonnes used worldwide, concrete is the most widely used construction material (Ranade, 2014; Yildirim, Şahmaran and Anil, 2017). It is suited for use in both developed and developing countries due to the fact that it is composed of inexpensive and abundant raw materials. In addition, concrete is a versatile building material since it can be moulded in a variety of ways and its mechanical properties may be utilised in a vast array of structural situations (Taylor and Sæther, 2011).

As a direct result of the widespread usage of concrete in construction, the material properties and performance of concrete have a substantial impact on the global infrastructure's overall health. Concrete is sadly one of the most fragile materials, despite being the most commonly used building material. Due to its brittleness, concrete is susceptible to cracking, which reduces the durability and sustainability of concrete

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structures. Both newly restored and previously existing concrete structures exhibit deterioration, corrosion, and faults. The cost retrofitting under corrosion is estimated to be between 3 and 4 percent of their gross domestic product (Stewart, Wang and Nguyen, 2011; Damme, 2018).

In addition, the most significant performance requirements for the design, building, and maintenance of concrete structures are safety, serviceability, and durability (Ding *et al.*, 2018; Hájková *et al.*, 2018); In spite of this, all three of these characteristics will worsen as time passes. The rate at which concrete structures deteriorate is determined not only by the environment in which they are placed, but also by the methods and materials used in their construction. There is a chance that climate change will drastically impact this environment, especially over the long term (Kim, McCarter and Suryanto, 2018; Strategy, Carbon and Resilience, 2021). As a result, concrete deteriorates differently, affecting its safety, usage, and lifetime. Climate change can accelerate corrosion by a few percent, resulting in hundreds of billions of dollars in yearly maintenance and repair expenses. Corrosion directly and indirectly costs a lot (Mattei, 2017).

Several research inform climate change as a long-term environmental effect on building. Humans' greenhouse gas emissions are blamed for the planet's climate. The worldwide bank and meteorological, climatological, and geophysical agency's annual reports showed a large increase in atmospheric carbon dioxide ($CO_2$) from 280 ppm in 1850 to 490 ppm in 2023, with an accelerating trend (Wang *et al.*, 2010).

The most conservative estimate of the increase in global temperatures since industrialization due to greenhouse gas concentrations in the atmosphere is 2.1 degrees Celsius at 450 parts per million (ppm) of CO2-equivalent, 2.9 degrees at 550 ppm, 3.6 ppm at 650 ppm, 4.3 ppm at 750 ppm, and 5.5 ppm at 1000 ppm (Intergovernmental panel on climate Change, 2000). Over the past century, thermal expansion and water transfer between oceans and other reservoirs like glaciers have caused the global mean temperature and sea level to rise (Asian Development Bank, 2016).

The anticipated increase in both the intensity and frequency of severe storms may have a substantial impact on the loading activities that must be considered when designing concrete structures. This must be taken into account (Wang, 2009; Stewart, Wang and Nguyen, 2011). Consequently, infrastructure will become more vulnerable as a result of future increases in loads, deterioration, and capacity loss. This subject will not be discussed within the scope of this study, which focuses on the effects of climate change on the deterioration of concrete (Bastidas-arteaga *et al.*, no date).

As demonstrated in Figure 1, climate change—variations in $CO_2$, temperature, and relative humidity—can directly or indirectly cause concrete structures to deteriorate. Environmental pollutants cause most climate change-related concrete degradation. Carbon dioxide and chloride cause reinforcing steel corrosion. Due to increased diffusivity, steel corrodes, and hazardous compounds enter faster at higher temperatures. For every 2 degrees Celsius temperature increase, corrosion may increase by 15%. Elevated CO2 levels, moderate temperatures, and high humidity promote concrete deterioration, affecting Indonesia's and all concrete infrastructure worldwide. This study focuses on concrete infrastructure, although temperature and humidity can affect steel structures (Asian Development Bank, 2016).

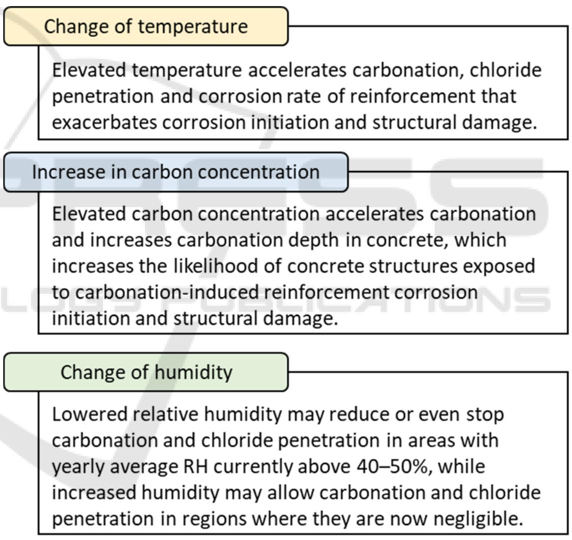


Figure 1: The effects of climate change on reinforced concrete constructions (Asian Development Bank, 2016).

Buildings and infrastructure have a 30-200-year lifespan; thus, their design, upkeep, and replacement must reflect the future environment. Despite the unpredictability of the climate, an event-based Monte Carlo simulation can be used to assist in the analysis of potential implications in this decision-making process (Stewart, 2010; Stewart, Wang and Nguyen, 2011). This system could inform us of the amount of design and maintenance modifications required to ensure safety, serviceability, and durability under any of the known climate change scenarios (Stewart, 2010). 5–10% more CO2 is found in urban air than in rural air. Carbonation depths of Reinforced Concrete (RC) structures with 100-year service lives were evaluated assuming a climate change scenario involving up to 450 parts per million of carbon dioxide (Wales and Carolina, 1998).

This study employs a probabilistic and reliability-based method to predict corrosion start and severe cracking for Indonesian concrete infrastructure exposed to carbonation and chloride-induced corrosion due to increased CO2 levels and temperatures using web information approach. The approach is dissected into its component elements in great detail in this study. This study examines how various climate change scenarios may affect Indonesian concrete constructions' longevity and damage risk. In turn, these realisations would have equivalent implications for a number of other nations.

# 2 SIMULATION AND PROBABILISTIC MODELLING USING WEB INFORMATION SYSTEM

Figure 2 shows that a probabilistic simulation was used to model carbonation and chloride penetration-driven concrete degradation. The concept using analytical approach followed by web-based illustration technology. Probabilistic modelling of material property, dimension, model error, ambient conditions, and uncertainties is used. $CO_2$ concentration, annual mean temperature, and relative humidity. Climate influence under reinforced concrete—corrosion assessment Calculating climate risk for typical Portland cement–concrete structures above ground using Life 365 v2.2.

The modelling and simulation approach the research conducted by Stewart et al. (Stewart, 2010) and Wang et al.'s study (Wang, 2009). Multiple models are simulated to comply the comparison criteria. Time dependant also created as parameter, followed by environmental parameter. The results show penetration depth distributions, means, and the risk of corrosion and damage.

## 2.1 Corrosion Modelling

Steel reinforcement corrosion can be caused by carbonation of the concrete cover and chloride concentrations in excess of a critical threshold. This cycles parameter is the more common cause of corrosion. In every circumstance, the expanding corrosion products cause tensile pressures to be exerted on the concrete, which ultimately results in spalling, cover cracking, and a loss of structural strength. This type of corrosion-related damage is not only costly but also disruptive to society.

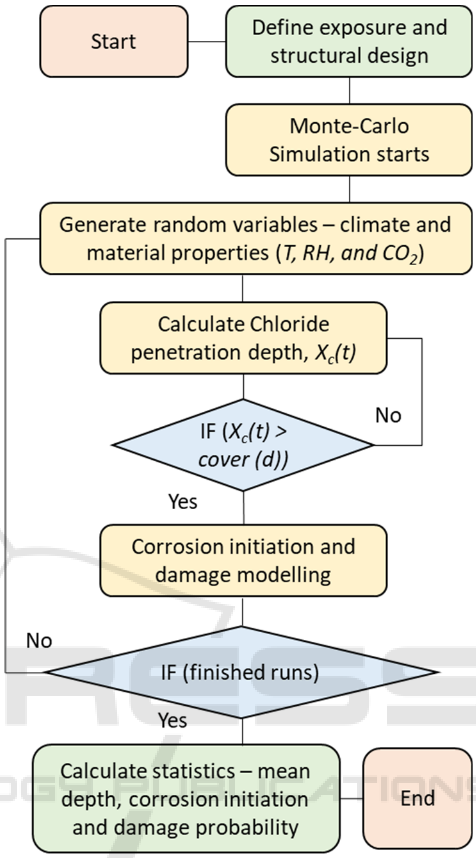


Figure 2: Simulation of reinforced concrete deterioration under climate change (Al-ostaz *et al.*, 2010).

To account for time-dependent variations in $CO_2$ concentration, temperature, and relative humidity, numerous deterioration models need to be adjusted.

### 2.1.1 Carbonation Penetration Models

The DuraCrete model is considered to be adapted on which the carbonation depth is assisted (DuraCrete, 1998). It includes time-dependent $CO_2(t)$ and temperature $f_T$ modifications. Those criteria are distinguished by the carbonation depth model, based on the model proposed by DuraCrete, with time-dependent $CO_2(t)$ and temperature $f_T$ corrections ($t$), which characterized by several equations as follow:

$$x_c(t') \approx \sqrt{\frac{2 f_T(t') D_{CO_2}(t' - 2000)}{a} k_{urban}} \qquad (1)$$

$$\sqrt{\int_{2000}^{t'} C_{CO_2}(t')dt'} \left(\frac{1}{t'-2000}\right)^{n_m}$$

where:

$$D_{CO_2}(t) = D_1 t^{-nd} \quad (2)$$

$$a = 0.75 C_e C_a O_{\propto H} \frac{M_{CO_2}}{M_{CaO}} \quad (3)$$

$$f_T(t') \approx e^{\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273 + T_{av}(t')}\right)} \quad (4)$$

$$T_{av}(t') \approx \frac{\sum_{t_0'=2000}^{t'} T(t')}{t' - 2000} \quad (5)$$

*CCO₂(t)* is the illustrated time-dependent considering mass of atmospheric concentration a molecule of carbon dioxide in $10^{-3}$ kg/m$^2$ where *t* is time in years and *t'* is the year commencing in the first investigated in this case a year of 2000. *DCO₂(t)* is a carbon dioxide diffusion coefficient inside concrete, $D_1$ is the carbon dioxide diffusion coefficient after one year, and $n_d$ is the age factor for the carbon diaxoide diffusion coefficient. CaO represents the ratio of calcium oxide concentration in cement; *H* represents the degree of hydration; MCaO represents the weight of molar mass of calcium oxide; and $MCO_2$ represents the molar mass of carbon dioxide. $f_T(t')$ is the temperature (nm) associated with the frequency of wetting and drying cycles (assuming nm = 0 for factor of the diffusion coefficient compared to one at 20°C, *E* is the diffusion activation energy in kJ/mol, and R is the constant gas. Carbonation occurs at *RH* 40–75% or 50–70% (Bouzoubaâ *et al.*, 2010; Stewart, Wang and Nguyen, 2011). Another research state that where the RH below 30% there is little or no carbonation (Kaewunruen *et al.*, 2018), However, carbonation processes cannot occur below 50% RH (Atiş, 2003).

### 2.1.2 Chloride Penetration Models

Diffusion equations form the chloride penetration model can be seen in Equation (3) followed the popular model (DuraCrete, 1998). C(x,t) describes the chloride concentration across depth x at time t or a calendar year *t', t* = *t*+2000.

$$C(x,t) = C_o\left[1 - erf\left(\frac{x}{2\sqrt{k_e k_t k_c f_T(t'-2000)}}\right)\right] \left[\left(\frac{x}{D_c\left(\frac{1}{t'-2000}\right)^n (t'-2000)}\right)\right] \quad (6)$$

Table 1: Corrosion parameter, material properties and dimension adapted from Stewart (Stewart, 2010).

| Parameter | Mean | COV | Distribution |
|---|---|---|---|
| $f_c$ (28) | 1.03f'$_c$ | 0.18 | Normal |
| $CO_2$ diffusion coeff. ($D_1$) | 0.47 – 2.22 × $10^{-4}$ cm$^2$ s$^{-1}$ | σ = 0.15 | Normal |
| Age factor – Carbonation ($n_d$) | 0.19 – 0.240 | 0.12 | Normal |
| Age factor – Chloride (n) | 0.37 – 0.65 | σ = 0.07 | Normal |
| Environmental factor ($k_e$) | 0.265 – 0.924 | σ = 0.05 – 0.16 | Normal |
| Diffusion coefficient ($D_c$) | 7 – 15 ×$10^{-12}$ cm$^2$ s$^{-1}$ | 0.285 | Normal |
| Model Error for crack propagation | 1.04 | 0.09 | Normal |
| $k_{urban}$ | 1.15 | 0.10 | Normal[1] |
| Cover | $C_{nom}$+ 6 mm | σ =11.5 mm | Normal[2] |
| Surface chloride concentration | 1.15 – 7.35 kg/m$^3$ | 0.5 – 0.7 | Normal |
| Critical chloride concentration | 3.35 kg/m$^3$ | 0.375 | Normal[3] |
| Corrosion rate ($i_{corr-20}$) – Carbonation | 0.17 – 0.43 µA/cm$^2$ | σ = 0.086 – 0.259 µA/cm$^2$ | Lognormal |
| Corrosion rate ($i_{corr-20}$) – Chloride | 2.586 – 6.035 µA/cm$^2$ | σ = 1.724 – 3.448 µA/cm$^2$ | Lognormal |
| $f_t$ | 0.53($f_c$)$^{0.5}$ | 0.13 | Normal |
| $E_c$ | 4600($f_c$)$^{0.5}$ | 0.12 | Normal |

Table 2: Concrete design class category in accordance with SNI 2847 – 2019.

| Exp. class | Maximum w/cm[1] | Minimum f'c, Mpa | Cementitious materials[2] - types | | | Calcium chloride admixture |
|---|---|---|---|---|---|---|
| | | | ASTM C150 | ASTM C595 | ASTM C1157 | |
| S0 | T/A | 17 | No type of restriction | | | |
| S1 | 0.50 | 28 | II[3,4] | Type IP, IS or IT with (MS) designation | MS | Not restriction |
| S2 | 0.45 | 31 | V[4] | Type IP, IS or IT with (HS) designation | HS | Not restriction |
| S3 | 0.45 | 31 | V plus pozzolan or slag cement[5] | Type IP, IS or IT with (HS) designation plus pozzolan or slag cement[5] | HS plus pozzolan or slag cement[5] | Not permitted |
| | | | | | | |
| W0 | N/A | 17 | None | | | |
| W1 | 0.50 | 28 | None | | | |
| | | | Maximum water-soluble chloride ion (Cl–) content in concrete, percent by weight of cement[6] | | Additional provisions | |
| | | | No prestressed concrete | Prestressed concrete | | |
| C0 | N/A | 17 | 1.00 | 0.06 | None | |
| C1 | N/A | 17 | 0.30 | 0.06 | | |
| C2 | 0.40 | 35 | 0.15 | 0.06 | Concrete cover[7] | |

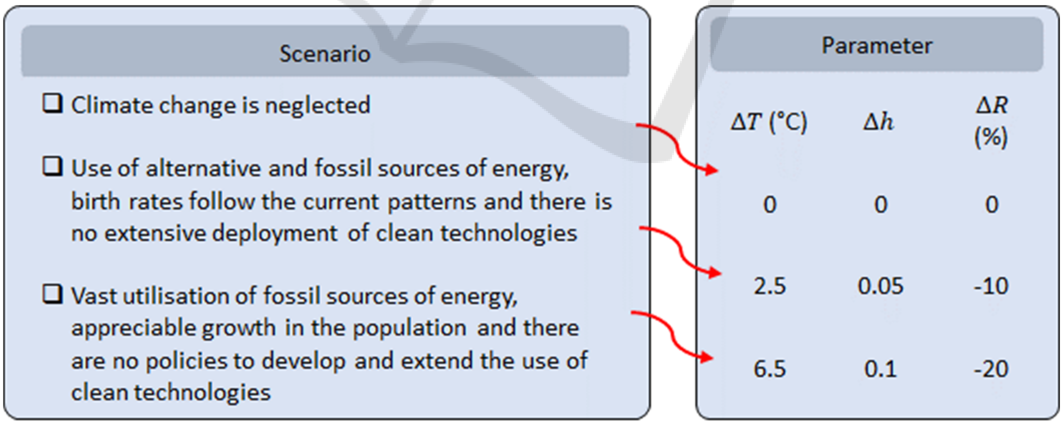


Figure 3: Climate change scenarios for period 100 years (Al-ostaz *et al.*, 2010).

The concentration of surface chloride is denoted by $C_0$, the coefficient of diffusion is denoted by $D_c$, the age factor is denoted by $n$, and the environmental component of concrete is denoted by $k_e$. $k_c$ and $k_t$ refer to the curing factor and the test technique, respectively. This study does not take into account the influence that relative humidity has on chloride absorption. Because of the reduction in relative humidity caused by climate change, equation (6) does not include chloride penetration.

In fact, the characterization of first evaluation is employed by using Equation (6), which can be

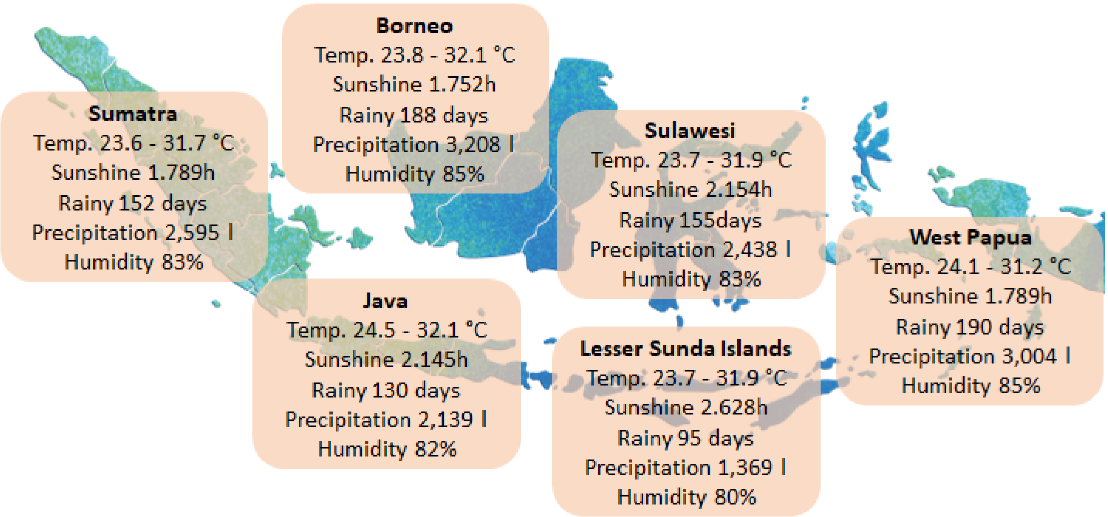


Figure 4: Result summary using web-based information category in Indonesia (Meteorological, climatological, and geophysical agency, 2023).

accessed to identify the current condition and the expected model criteria. Where, the corroded condition parameter in accordance with the actual corrosion value of Equation (7).

$$i_{corr}(t) = i_{corr-20}[1 + K(T(t) - 20)] \quad (7)$$

where $i_{corr}20$ is the corrosion rate at 20°C and $K$ = 0.025, at least for temperature below 20°C but may be conservative for $T_{(t)}$>20°C. DuraCrete researched both values. Equation (7) states that a 2°C temperature increase increases corrosion by 15% (Bamforth, 1997; DuraCrete, 2000; Alexander and Beushausen, 2019).

## 2.2 Probability of Corrosion Initiation and Corrosion Damage

When carbonation depth reaches the reinforcing bar's surface or chloride concentration above the critical chloride concentration, corrosion ensues. Corrosion requires these two conditions (Stewart, 2010). The following equations show the cumulative likelihood of corrosion starting at time t or calendar year *t'*:

$$p_i(t') = \begin{cases} \Pr[h - x_c(t') < 0] \\ \Pr[C(h,t') - Cr < 0] \end{cases} \quad (8)$$

In accordance to Equation above, *h* symbolises the concrete cover, $x_c$ $(t)$ illustrate as the carbonation depth, C(*h,t*) alternate as the chloride concentration, and $C_r$ the critical chloride concentration. Thus, $t = t'$ - 2000.

The RC corrosion normally causes by damaged of the cover or the concrete can easily absorb the water from outside which interact with the reinforcement bars. When a crack is wider than one millimetre, corrosion damage may develop. Then, when the cracks are in extreme condition, it will lead to delaminated stage, where all the concrete cover spalling. This cracks parameter was determined through simulation using fracture initiation and propagation models. These models computed the duration of severe cracking and spalling considering some past research created by some researches (Komara *et al.*, 2019, 2020, 2021; Mooy *et al.*, 2020; Susanti *et al.*, 2021) and are primarily impacted by cover, concrete strength, and corrosion rate. The likelihood of corrosion damage is then calculated as follows:

$$p_s(t) = Pr[t \geq T_{sp}] \quad (9)$$

# 3 STUDY OF PROBABILITY ANALYSIS OF CORRODED RC

Deterioration of concrete, particularly in RC structures, is caused by environmental exposures that can be categorised using a variety of criteria. Past researchers (Alexander, Dehn and Moyo, 2008) classifies exposure in regard to the type of deterioration. In comparison AS3600 (Australian Standard, 2009) is used to assesses exposure based on the concrete structure's distance from the coast or sea, climate (arid, temperate, and tropical), and industrial zones. Since Indonesian and Australian environments are similar. In fact, Indonesia exposure classified by SNI 2847-2019 (Badan Standardisasi Nasional, 2019) where in detail it is divided into three categories, S0, S1, S2, S3 (sulphate group), W0 – W1 (in contact with water) and C0 – C2 (corrosion protection of reinforcement), more information can be seen in Table 2 this standard also related with ACI 318-14 (American concrete Institute, 2014).

Figure 4 approximates the environmental exposure of concrete structures in Indonesia, which depends on temperature, relative humidity, and K-index. Figure 4 illustrates all Indonesian archipelagos. which encompasses Borneo, Java, the Lesser Sunda Islands, Sulawesi, Sumatra, and West Papua. Each place has its own condition. This webpage links global demographic statistics confirm the actual situation cited by annual database https://www.worlddata.info/asia/indonesia/index.php (WorldData, 2023) and BMKG (Meteorological, climatological, and geophysical agency, 2023) provide records from the previous seventy-three years which can be accessed through the website processing by https://www.bmkg.go.id/iklim/?p=tren-suhu. This data is inputted to conduct the probability analysis.

As a type of additional analysis, inputted distance exposure also included as design parameter (see Table 3). This parameter is derived from an equivalent geographical location to the one being compared. The combination criterion as a category for exposure in relation to the minimum cement concentration and *w/c* ratio is presented in Table 4. These two categories are also considered for inclusion in the evaluation criteria.

Table 3: Exposure class classification varied by nominal concrete strength.

| Exposure classification | Nominal concrete cover divided by characteristics strength | | | | |
|---|---|---|---|---|---|
| unit [MPa] | 20 | 25 | 32 | 40 | ≥ 50 |
| ≥ 50 km | 20-50 | 20-30 | 20-25 | 20 | 20 |
| 1 – 50 km | | 60 | 40-65 | 30-45 | 25-50 |
| ≤ 1 km | | | | 70 | 50-65 |

Table 4: exposure classification to w/c ratio.

| Exposure classification | Minimum cement content (kg/m3) | Maximum water / cement ratio |
|---|---|---|
| ≥ 50 km | 320 | 0.56 |
| 1 – 50 km | 320 - 370 | 0.50 – 0.46 |
| ≤ 1 km | 420 | 0.4 |

The record earlier data created by BMKG, which is based on a multi-model dataset by the program for climate model diagnostics (see Figure 4), are also evaluated for climate change projections. (Meteorological, climatological, and geophysical agency, 2023).

As illustrated in Figure 4-5, temperature (T) and relative humidity (RH) in 2023 based on BMKG, respectively, $T_{min}$ 8, $T_{max}$ 12 and $RH_{min}$ 5.3%, $RH_{max}$ 100%. The T and RH in the range of 8% and 70% increase from 1999. It should be indicated that the environmental change my be provided by BKMG models, but they appear mostly to provide similar trends for all environmental conditions, including wheatear i.e., rain and wind. Within such range, change in carbonation and chloride penetration induced corrosion may not be small enough to be ignored.

# 4 DISUCSSION

Simulations suggest that as a result of climate change, concrete buildings may become both more fragile and more resistant to damage. The threat posed by climate change cannot be disregarded in Indonesia or anywhere else given the fact that increases in $CO_2$ and temperatures will have an effect on most, if not all, of the world's places.

The evaluation of the impact places more of an emphasis on the relative change in corrosion start and damage risks as a result of higher $CO_2$ levels and temperature compared to values in the year 2000 than it does on absolute risk forecasts. This is because higher temperatures and higher $CO_2$ levels both increase the likelihood of corrosion starting. This is due to the fact that both the temperature and the levels of $CO_2$ are forecasted to keep climbing over the next few years. On the other hand, these models are based on the assumption that the surrounding environment would not change. Determining the extent to which environmental factors that are dependent in both time and space may play a role in the deterioration of concrete is currently one of the most pressing questions facing the scientific community. If it turns out that other models of deterioration are more applicable, including them into the stochastic and reliability framework that has been given in this research won't be a difficult task at all. Even though different models of deterioration will each generate their own one-of-a-kind estimates of absolute risk, the choice of deterioration model ought to have less of an impact on comparative risks. This is the case despite the fact that there are multiple models of deterioration.

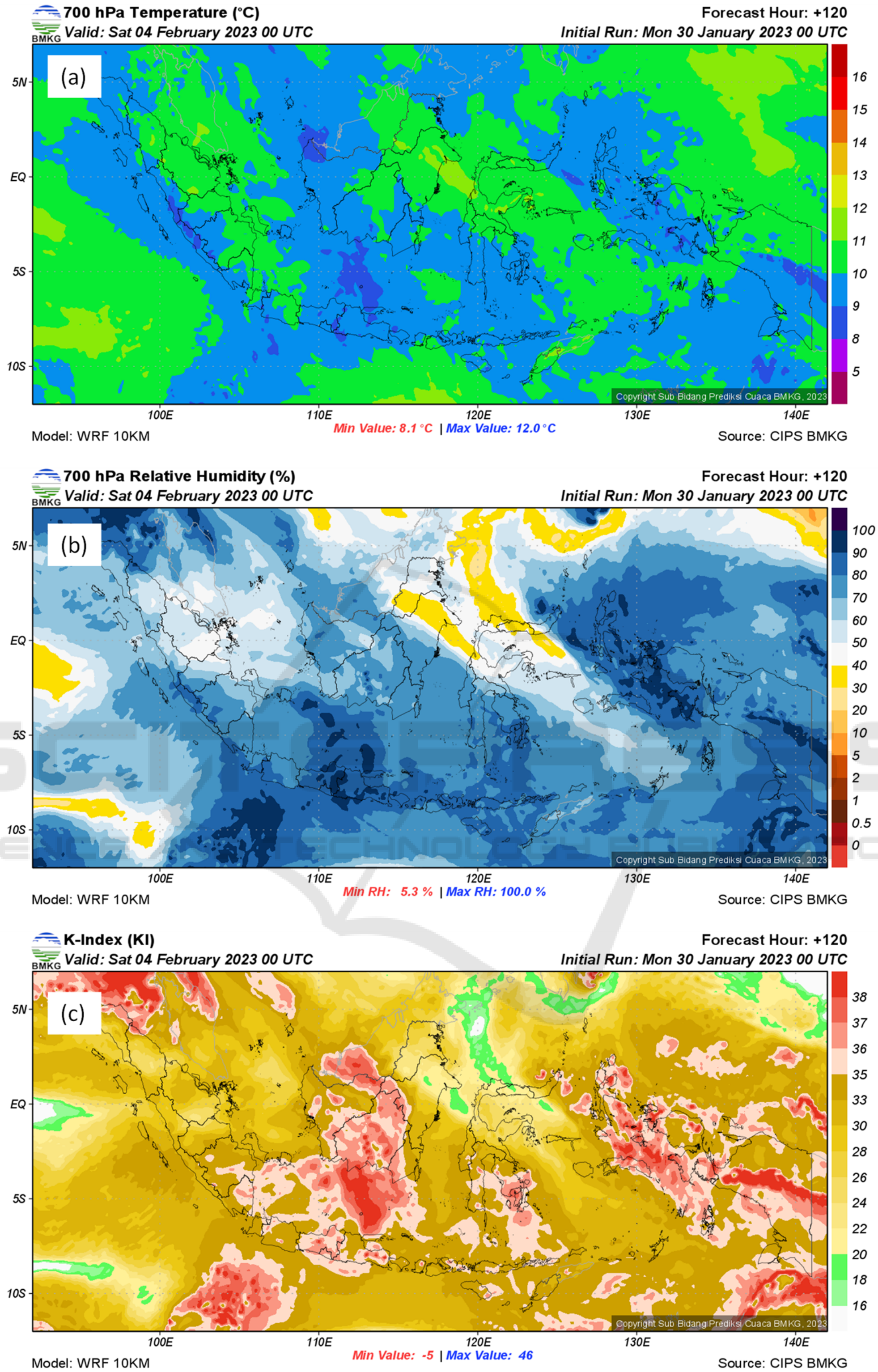


Figure 5: Environment exposure in Indonesia due to (a) Temperature, (b) Relative humidity and (c) K-index (Meteorological, climatological, and geophysical agency, 2023).

Responses to this change in risk will be new procedures and materials can reduce corrosion risk in unbuilt structures. Existing concrete structures can be made more durable to reduce climate change. Cover design, cement and mix selection, surface coating barriers, extraction, and cathodic protection are examples. A new design might reduce environmental exposure by enhancing cover and strength grade and lowering material diffusion coefficient without harming concrete durability and serviceability. Our research will highlight the design improvements needed to maintain concrete structure durability.

Climate change is projected to accelerate the decay of many existing concrete structures that did not account for environmental changes. A little increase in damage hazards could cost hundreds of billions or trillions of dollars in maintenance and repair. A cautious approach would propose enhanced monitoring and maintenance of concrete structures because this risk varies widely based on location, environmental exposure, and material design, making it impossible to predict for each structure. This research shows that site-specific costs and benefits will be critical for successful adoption.

# 5 CONCLUSIONS

In order to evaluate the probabilities of corrosion initiation and corrosion damage for existing concrete infrastructure in Indonesia that is subject to climate change in the current year, which shows future change, a time-dependent probability study has been carried out. Compared to the previous figure, forecasts of atmospheric $CO_2$ concentration, local temperature, and humidity changes across the Indonesian continent for the next 100 years will increase. The probabilistic study factored in the unpredictability of $CO_2$ concentration, degradation processes, material characteristics, dimensions, and predictive models. Carbonation-induced damage risks have been found to rise similarly to the environment during the past year. The risk of corrosion due to chloride increases by less than 10 percent, as indicated by the larger figure. The results were especially sensitive to fluctuations in atmospheric $CO_2$ levels. Since $CO_2$ concentration and temperature are the key drivers of accelerated concrete deterioration, the elevated infrastructure damage risks in Indonesia are anticipated to be observed in many other concrete infrastructures across the world. Existing concrete structures whose design does not account for the effects of climate change may deteriorate more quickly than expected.

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