Effects of climate change on structures; analysis of carbonation-induced corrosion in Reinforced Concrete Structures in Malta

Bernice Mizzi¹, Ying Wang¹ and Ruben Paul Borg²

¹ Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, United Kingdom
² Faculty for the Built Environment, University of Malta, Malta

E-mail: mizzibernice@gmail.com, ying.wang@surrey.ac.uk, ruben.p.borg@um.edu.mt

Abstract. The various elements that are affecting the Earth’s climate have brought climate change to the top of the priority list amongst scientists and policy-makers. Expected changes to local climatic conditions impact directly on the surrounding environment and potentially lead to changes in the degradation processes of building materials, affecting the durability and service life of infrastructures. The aim of this paper is to investigate the effects of future climate projections on concrete structures in Malta, in particular on carbonation-induced corrosion resulting from increasing temperatures and CO₂ concentrations. Thirteen reinforced concrete structures in Malta were chosen for a retrospective analysis in order to validate two carbonation depth prediction models. The validated prediction models were subsequently used to evaluate the varying climate change scenarios in order to determine the effects on concrete carbonation depth for several concrete grades. The age of the structures used for the retrospective analysis ranged from 10 to 60 years. The field data verified the validity of both prediction models for structures with carbonation depths less than 50mm. Although both models proved valid for the retrospective analysis, a difference was noted between the models with regards to the predicted carbonation depth in relation to different climatic scenarios. An increase in carbonation depth of up to 40% is being predicted, by 2070, when considering the worst case climatic scenario. The findings prove that climate change plays a major role on the carbonation depth of concrete, which in turn reduces the service life of concrete structures.

Keywords: reinforced concrete structures, climate change, carbonation-induced corrosion

1. Introduction

Reinforced concrete forms an essential part of our world’s built environment and its durability issues have been widely researched. The main deterioration process which highly degrades the durability of reinforced concrete is corrosion [1]. Reactions between atmospheric Carbon Dioxide (CO₂) and the hydrated phases of concrete lead to a decrease in the concrete potential hydrogen (pH) level, which in turn causes de-passivation of the embedded rebar and results in corrosion. This phenomenon is referred to as carbonation-induced corrosion of concrete [1,2]. Variations in concrete mixes and exposure to different environments result in different carbonation rates [3]. Climate change, has a direct impact on the surrounding environment. Therefore variations in precipitation amounts and
Climate change is a major international problem which humankind is currently enduring. Greenhouse gas (GHG) emissions, including CO$_2$ generated by anthropogenic activities are affecting the Earth’s climate [5,6]. In 2014, the Intergovernmental panel on climate change (IPCC) 5th assessment report (AR5), declared that anthropogenic GHG emissions were the highest in history from 2000 to 2010 [7]. Furthermore, the Mediterranean region has been identified as a ‘hot spot’ region for climate change [8–10]. In consequence to Malta’s strategic location within this region, the Maltese archipelago is experiencing pronounced effects due to change in climate. From 1951 till 2010, the maximum and minimum temperatures have increased by +1.2°C and +1.1°C respectively [11].

Albeit the common consensus amongst researchers with regards to the changing climate, it is only till recently that the effects of climate change on structures is being studied. A simplified model proposed by Yoon et al [12], was one of the first researches which confirmed that carbonation depths shall increase due to the effect of CO$_2$ concentrations resulting from a changing climate.

Subsequent studies of Stewart et al [13–15] built up on the work of Yoon et al [12] where the effect of temperature on the CO$_2$ diffusion coefficient was being taken into consideration. Furthermore, advanced probabilistic and reliability-based methods were developed which considered time to crack initiation, crack propagation and failure due to reinforcement corrosion. These studies found that in particular regions and depending on different scenarios of Australian cities, the risk due to carbonation-induced corrosion can increase by 400% by the year 2100. However, the model used in these researches is an approximation, as it does not consider the time-dependent effect of CO$_2$ concentration and other parameters such as temperature and humidity.

The numerical model presented in Zhou [16], which is based on Fib Bulletin 34 [17], has been evaluated using the special report on emissions scenarios (SRES) climate change prediction data. A comparison between other predicted carbonation models and the new model was investigated where it resulted that the variations in predictions escalate as the exposure time and extent of climate change increase.

Talukdar et al [16–18] argued that there is the need for a model which predicts reliably the depth of carbonation as a function of time. A numerical model which includes the effects of changing variables such as humidity, porosity, temperature and atmospheric CO$_2$ concentrations was developed [16–18]. The model involves simultaneous solutions of chemical reaction equations of CO$_2$ and Calcium hydroxides (Ca(OH)$_2$) based on past research studies [21,22]. Talukdar et al [19], refined the one-dimensional numerical diffusion equation, which is used to forecast the diffusion coefficient of CO$_2$ in concrete as a continuation to the work described in Talukdar et al [16–18]. The refined model together with the latest climate forecasts obtained from the AR5 of the IPCC were used to forecast carbonation depths for a series of urban environments in the United States. The results confirmed that climate change will affect carbonation depth and the magnitude of increase of such carbonation depth is dependent on the Representative Concentration Pathways (RCP) scenario and geographic location. Furthermore, such an increase in depth will also have a bearing on the concrete cover proposed by the current building codes.

Likewise, the latest RCP emission scenarios were used in the recent study of Peng et al [23], in order to investigate the carbonation-induced deterioration in three typical Chinese cities. In 2100, the mean carbonation depths of reinforced concrete structures in China are expected to increase up to 45% as a result of changing parameters of atmospheric CO$_2$, temperature and relative humidity. Considering that climate change is a global phenomenon, similar implications on concrete infrastructure is expected for other countries. This study therefore explored the predicted effects of climate change on structures in Malta up until 2070. Being the first study of its kind to be conducted in the Maltese Islands, the salient points earmarked in this paper may be considered as a tool for local structural designers and construction enterprises to embrace the right adaptation measures to rectify the effects of future climate change on local structures.
2. Carbonation models and climate scenarios

2.1. Carbonation Models
Carbonation, having a direct bearing on the service life of reinforced concrete structures, has brought about the need to develop a model for estimation of the depth of carbonation as a function of different variables in order to quantify this phenomenon. Despite the broad knowledge on this subject, a numerical model which accurately predicts carbonation depth is still not available [24,25]. This is due to the fact that integrating all the various factors affecting the carbonation process into a prediction model results in a complex process [24,25].

Following extensive research on the various available existing models, an empirical-mathematical model based on Fick’s first law and a statistical model, developed from multiple regression of various parameters, were chosen for this research study. Potential practical applicability and unequivocal functionality were the two main criteria used for choosing these models. Both of the carbonation models do not include corrosion propagation time to cracking and therefore determine only the time to steel de-passivation.

2.1.1. Statistical model of carbonation – Model 01. The statistical model of carbonation proposed by Silva et al [26] was selected for this research. Being a rudimental model, it combines both CO₂ concentrations and compressive strength of concrete. Albeit its simplicity, the model was developed from a sample comprising 964 case studies through multiple linear regression analysis. Furthermore, this statistical technique is an innovative approach in the field of carbonation modelling. The carbonation coefficient, which is defined as the dependent variable, varies according to concrete characteristics, curing conditions and environmental exposure, and is given as:

\[ h = k_w \cdot t^{0.5} \] for RH > 70% \hspace{1cm} (1)

and

\[ k_w = 3.355c - 0.019C - 0.042f_c + 10.83 \] \hspace{1cm} (2)

Where:
- \( h \) – carbonation depth [mm]
- \( k_w \) – carbonation coefficients [mm/year\(^{0.5}\)]
- \( t \) – CO₂ exposure time [years]
- \( c \) – CO₂ content [%]
- \( f_c \) – concrete compressive strength [MPa]
- \( C \) – clinker content [kg/m³]

2.1.2. Square root of time model of carbonation – Model 02. The proposed abridged second carbonation model used in this study is based on Fick’s first and second law of diffusion. Proposed in CEB [27] and modified further in Yoon et al [12], Equation 03 expresses carbonation depth as a function of the CO₂ diffusion coefficient and CO₂ binding capacity. The CO₂ diffusion coefficient (\( D_{CO₂} \)) is based on the empirical equation proposed by Papadakis [22] and further modified in order to cater for both temperature effects and relative humidity.

\[ X_c = \left[ \frac{2D_{CO₂}C_{CO₂}t}{a} \right]^{1/2} \] \hspace{1cm} (3)

Where:
- \( X_c \) – carbonation depth (cm)
- \( D_{CO₂} \) – CO₂ effective diffusion coefficient [cm²s⁻¹]
- \( t \) – time [s]
- \( C_{CO₂} \) – atmospheric CO₂ concentration [gcm⁻³]
- \( a \) – an amount of CO₂ for complete carbonation [kgm⁻³]
2.2. Climate Scenarios
RCPs are emission scenarios, based on GHG concentration trajectories which span until the year 2100 [28]. Though four different scenarios are available, the stringent mitigation scenario (RCP 2.6) and the worst GHG emissions scenario (RCP 8.5) were considered in this paper. Apart from representing two divergent scenarios, these opposing scenarios were chosen because no equivalent scenario similar to RCP 2.6 has been used in previous assessments such as SRES.

The CO₂ concentrations in parts per million (ppm) were converted into mass concentrations in metric units by using the ideal gas law behaviour and considering ambient temperatures [12]. Based on a 30-year climatic period, the monthly mean relative atmospheric humidity over the Maltese Islands was in the range of 70% and 80% [29].

3. Experimental Work

The initial part of the work performed was to verify the validity of two carbonation deterioration models through field data. For the purpose of carbonation model application, the field data was obtained from already-conducted site investigations. Durability assessment was done on thirteen (13) ageing concrete structures of 10 to 60 years consisting of major bridges and buildings in Malta as listed in Table 1. The data was obtained from a local accredited independent materials laboratory. The buildings selected to inspect carbonation and concrete strength included both public and private buildings, tallying to circa 300 cores. The destructive site investigation tests, through which the real values of the depth of carbonation and compressive strengths were obtained, were executed during the period from 2005 till 2017.

| Building code | Date of Construction | Building Use               |
|---------------|----------------------|----------------------------|
| 01            | 1970                 | Commercial                 |
| 02            | 1990                 | Industrial                 |
| 03            | 1980                 | Commercial                 |
| 04            | 1960                 | Industrial                 |
| 05            | 1970                 | Industrial                 |
| 06            | 1980                 | Water Retaining Structure  |
| 07            | 1960                 | Residential                |
| 08            | 2005                 | Commercial                 |
| 09            | 1960                 | Commercial                 |
| 10            | 1994                 | Commercial                 |
| 11            | 1970                 | Commercial                 |
| 12            | 1986                 | Industrial                 |
| 13            | 1970                 | Infrastructure             |

The data was grouped according to date of construction, location related to exposure and building element. Following which, the statistical variability for durability design parameters, including compressive strength, carbonation depth and carbonation rate, was established and compared to published literature. The accuracy and suitability of the two chosen carbonation models was examined by verifying whether the models can reliably replicate the carbonation depths of the structures determined from the field carbonation results. The predicted calculations from the carbonation depth models were subsequently compared with actual carbonation depths, by plotting a line of equality.

Following validation of the carbonation models, based on the parameters included in equations 1, 2 and 3, the projected CO₂ concentrations together with the relative humidity and varying temperatures
corresponding to the coming years were inserted in the carbonation models. Predicted carbonation depths were calculated and plotted for different structures having varying concrete grades, assuming that 2017 was the build year of the structures. The concrete grades together with their constituent material quantities were retained identical to those used for the retrospective analysis for the validation of the two carbonation depth prediction models.

4. Results and discussion

The coefficient of variation for compressive strength and carbonation depth of the field results that were used for the retrospective analysis were found to be 0.15 and 0.38 respectively, which resulted in being compliant with other values used in published literatures [30,31]. For both carbonation depth models, it was observed that there is a deficient correlation between the predicted values of carbonation depths for buildings that had an actual carbonation depth in the range of 50mm or more. Contrarily, with a mean difference of circa +/- 7mm between the actual and predicted results, a strong correlation was attained for both the statistical model and the numerical model of carbonation for structures with actual carbonation depths less than 50mm. Despite minor discrepancies between the predicted and the actual carbonation depths were present, both models gave realistic predictions and therefore both carbonation models were used for the prediction of carbonation depths of buildings in future years under varying conditions of climate change.

However, though both models of carbonation have been validated as being accurate and suitable to predict carbonation depth, it is evident that that model 01 does not simulate the influence of varying future climatic factors, as illustrated in table 2 and 3. No major difference in the ultimate carbonation depth was visible when comparing the controlled climatic scenario (RCP 2.6) carbonation depth against the worst scenario (RCP 8.5) carbonation depth for the different grades in question. The subtle percentage difference between the two climatic scenarios for the different concrete grades was between 1.48% and 6.6%. This observation highlights the fact that apart from CO₂ concentration, which is a major climatic variable, temperature (which is a varying parameter not included in model 01) also has a direct bearing on the process of carbonation as indicated by model 02. This is also in agreement with published literature, where an increase in temperature resulted in additional risks of carbonation-induced damage by 2100 [13,14].

| Concrete Grade | Projected Carbonation Depth as per MODEL 01 and RCP 2.6 [mm] | Projected Carbonation Depth as per MODEL 01 and RCP 8.5 [mm] |
|----------------|---------------------------------------------------------------|---------------------------------------------------------------|
|                | 2050 | 2070 | 2050 | 2070 |
| C15            | 38.72 | 49.05 | 38.92 | 49.78 |
| C20            | 34.41 | 43.58 | 34.60 | 44.31 |
| C25            | 27.50 | 34.82 | 27.69 | 35.56 |
| C30            | 22.14 | 28.04 | 22.34 | 28.77 |
| C35            | 14.72 | 18.63 | 14.91 | 19.36 |
| C40            | 12.99 | 16.44 | 13.18 | 17.17 |
| C45            | 8.67  | 10.97 | 8.87  | 11.70 |
Table 3. Model 02: Predicted carbonation depths for different scenarios

| Concrete Grade | Projected Carbonation Depth as per MODEL 02 and RCP 2.6 [mm] | Projected Carbonation Depth as per MODEL 02 and RCP 8.5 [mm] |
|----------------|---------------------------------------------------------------|---------------------------------------------------------------|
|                | 2050  | 2070  | 2050  | 2070  | 
| C15            | 39.17 | 49.10 | 44.20 | 67.59 |
| C20            | 35.29 | 44.23 | 39.82 | 60.88 |
| C25            | 29.73 | 37.26 | 33.54 | 51.29 |
| C30            | 26.85 | 33.65 | 30.29 | 46.32 |
| C35            | 23.22 | 29.11 | 26.21 | 40.07 |
| C40            | 23.06 | 28.91 | 26.02 | 39.79 |
| C45            | 19.69 | 24.68 | 22.22 | 33.97 |

Concrete structures in 2070, which are constructed from C25, are expected to have a carbonation depth of circa 50mm for the worst case climatic scenario as illustrated in figure 1. Therefore, the cover thickness chosen for such structures should ensure that the carbonation front does not reach the reinforcement during the designed service life of the structure. Environmental exposures in Malta are classified by the Maltese Codes for Design of concrete structures that are based on Eurocode 2 [32]. The Code in general specifies a concrete cover that ranges between 10 to 65mm, depending on for example concrete grade, maximum aggregate size, fire performance and exposure classes. For normal grades of concrete exposed to ordinary environments, a typical value of 25mm (+/-10mm) is generally adopted locally as concrete cover. Therefore, in this paper it is being shown that due to varying climatic variables, carbonation-induced corrosion would begin as early as year 2050 for a structure that is constructed today with a 25mm cover. This is clearly indicated in the predicted carbonation depth results obtained for model 02 that are in the range of or more than 25mm for all concrete grades. This is further highlighted in year 2070 where higher carbonation depths are projected.
5. Conclusions

This research shows that climate change could play a role on the carbonation depth of concrete that will in turn reduce the service life of the structures. It is shown that circa 40% increase in the carbonation depth is expected when comparing the worst case climatic scenario RCP 8.5 to the controlled climatic scenario RCP 2.6. Although the models used in this research are an approximation due to their simplicity, the findings from this research should act as a basis for development of climate adaptation through the improved design of concrete structures locally. A thorough sensitivity analysis could be conducted in order to investigate the effects of random variables (such as varying concrete cover) on the results obtained. Such an analysis can further confirm which concrete parameters could effectively diminish the climate change effects on degradation of concrete structures. This can be extended further by conducting an economic valuation of adaptation with numerous variables being taken into consideration, including increased concrete mix durability, galvanised reinforcement and surface treatments.

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