Evaluation of carbonation depth evolution tendencies of reinforced concrete buildings located in coastal and inland areas of North Cyprus

Q Al Haj Houseen and P Akpınar*
Near East University, Civil Engineering Department, Lefkosa, Mersin 10, Turkey

*pinar.akpinar@neu.edu.tr

Abstract. Carbonation is a critical concrete durability problem that is known to have potential adverse effects both on the concrete cover and steel reinforcing bars. This study involves detailed experimental investigations on the carbonation progress status of 149 samples from 39 existing buildings in North Cyprus that are located in coastal and inland areas. It is known that the varying exposure conditions in coastal and inland areas are likely to affect the durability performance of concrete buildings in different manners. Concrete core samples that were originally extracted from structures for compressive strength determination, were later tested by using Phenolphthalein indicator in order to determine the extent of carbonation occurred throughout their service duration. Besides studying their current carbonation states, the expected carbonation depth at the end of a 50-years of service life, as well as time needed to carbonate 30 mm-depth concrete cover were also investigated by using the Fick’s law. Results showed that 41% of the inland samples have been exhibiting satisfactory carbonation resistance performance according to Eurocodes, where this rate was as high as 71% for the samples obtained from coastal areas of North Cyprus.

1. Introduction
Concrete is one of the most commonly used and dependable construction material all around the world [1], due to its high compressive strength in hardened state and other advantages such its ability to be casted into any desired form while it is in fresh state, its fire resistance and it’s affordability in the aspects of the costs of constituents materials as well as the technology required for its manufacture [2,3]. However, concrete’s durability is a critical issue to be considered in order to ensure its performance throughout its designed service life. The service lives of structures are defined by codes and regulations to vary between 50 to 100 years according to their designed service functions [4].

Corrosion of steel bars is known as one of the most critical durability threats faced by reinforced concrete structures. Reinforcement corrosion is known to yield damages both on the steel bars and the concrete surrounding them. Hence, in the case of reinforcement corrosion occurrence, costly and elaborated repairing activities or demolition of the structure might become inevitable [5-6]. Carbonation of concrete is a durability problem that is known to be likely to facilitate the initiation of reinforcement corrosion. During carbonation, CO₂ gas from the atmosphere permeates into concrete through its pores and is converted into a weak carbonic acid. Later on, this carbonic acid is known to further permeate in concrete and yield a reduction in the overall pH in the concrete microstructure. In an undamaged concrete, pH is known to be as high as 12 or more, and this state is known to provide a natural protection.
to embedded steel bars Once the carbonation problem occurs, the naturally high pH value of concrete may drop drastically even below the value of 10, and in this case, steel corrosion may also start besides the ongoing changes in concrete due to continuing carbonation [2,3]. The initial quality of concrete is expected to play a critical role on the rate of carbonation progress in concrete during its lifetime. Concrete having high compressive strength values are known to have higher density and hence lower permeability [2], yielding a lower rate of carbonation progress in concrete. Characteristic compressive strength of concrete is known to be mainly dependent on the mix design; the types and quantities of constituents materials used in the manufacture of concrete [7, 8]. Beside the compressive strength and the initial quality of concrete, environmental conditions such as external CO₂ concentration, relative humidity, and temperature are all known to affect the extent of carbonation problem in concrete [9, 10].

This study aims to evaluate carbonation progress tendency in reinforced concrete structures located in coastal and inland areas of North Cyprus. Coastal and inland areas of Cyprus are expected to yield differences in the carbonation progress tendencies of concrete buildings, mainly due to the varying relative humidity and temperature exposure conditions. The methodology for handling and testing the samples and the obtained results and discussions are presented in the following sections.

2. Methodology

2.1. Acquisition and preparation of concrete samples
The concrete samples used in this study were originally extracted from the buildings by the Cyprus Turkish Chamber of Civil Engineers in North Cyprus, in order to be tested to verify their current compressive strength performance according to EN ??????. These extracted core samples were delivered to Civil Engineering Department Laboratory of Near East University, for additional investigations on their current level and the further tendency of carbonation. Carbonation depth of a total of 149 concrete samples obtained from 39 existing structures have been determined experimentally and the results have been analysed. These 149 samples were taken from buildings located in Nicosia (inland area) and in coastal cities such as Kyrenia and Famagusta. Their ages were reported by the Cyprus Turkish Chamber of Civil Engineers to be varying between 3-50 years.

Samples were first grouped according to their origin (i.e. coming from coastal or inland areas) and then they were split vertically into two halves carefully, regarding to minimize any excess damage causing unacceptable irregularity on the inner surface where the phenolphthalein solution was to be applied for carbonation depth measurements.

2.2. Carbonation depth measurements by phenolphthalein indicator solution
Phenolphthalein solution is an pH indicator solution widely used in concrete carbonation depth determination studies. Phenolphthalein solution used in this study was prepared by following the RILEM recommendations that are described in the related literature [11] where 1 g of phenolphthalein powder was added into and dissolved in 70 ml of Ethyl alcohol, and then the solution was completed to 100 ml by addition of distilled water.

As a next step, phenolphthalein solution was sprayed evenly on the inner surface of split concrete core samples. When phenolphthalein is applied, the areas with high pH, as in the natural state of concrete, turn in to pink color; where the areas that have pH lower than 10 show no color change, indicating the occurrence of carbonation in concrete [12], as can be seen in Figure 1.
After the color changes could be observed within few seconds, the carbonated area’s (i.e. remaining in grey color) depth was measured to the possible highest precision with the aid of a calliper, by taking average of three measurement for the sample of concern, as indicated in equation 1 given below:

$$d = \frac{x_1 + x_2 + x_3}{3}$$ (1)

2.3. Carbonation tendency calculations for studied structures

Carbonation is a time-dependent durability of concrete, whose progress in concrete could be expressed by Fick’s Law as indicated in the below Equation 2 [13]:

$$k = \frac{D_{\text{carbonation}}}{t^{0.5}}$$ (2)

Where;
- $D_{\text{carbonation}}$ = depth of carbonation from the surface of concrete
- $k$ = coefficient of carbonation
- $t$ = exposure duration

Initially, the coefficient of carbonation ($k$) is individually calculated for each concrete element provided that its actual age and corresponding carbonation depth is known. Once the coefficient of carbonation ($k$) is known, then calculation the depth of carbonation at a certain concrete age (i.e. carbonation exposure duration) as shown in equation 3, or calculating the time required for reaching a critical concrete carbonation depth, as shown in equation 4, becomes possible.

$$D_{(\text{carbonation})} = k \times t^{0.5}$$ (3)

$$t = \left(\frac{D_{\text{carbonation}}}{k}\right)^2$$ (4)

Using equations 3 and 4, the depth of concrete carbonation at the end of 50 years of service life, as well as the time required to reach 30mm of carbonation (i.e. conventional concrete cover thickness in which the steel bars are embedded) have been calculated for each studied structure.
2.4. Carbonation Depth Performance Satisfaction According to Eurocode EN1992-1-1
General Rules and Rules for Buildings specified in EN1992-1-1 [14], defines the safe limit of carbonation as maximum 30mm at the end of a 50-years of service life period for a concrete building. If the carbonation depth progresses up to only this level at the end of the service life of the building, it is expected that the embedded steel bars would not be affected of the resultant reduced alkalinity and therefore, corrosion would not be initiated. Performance of the structures studied in this work has been evaluated considering this criterion of EN1992-1-1 [14].

3. Results and Discussions
149 extracted core samples coming from 39 different existing structures from inland and coastal areas of North Cyprus have been examined by using phenolphthalein indicator solution and based on the observed results, Fick’s law equation was employed to study the carbonation depth progress tendencies of the studied structures.

The concrete samples which were observed to have less than 1 mm carbonation, as well as the samples which were observed to be carbonated throughout the entire studied surface were eliminated, since these two findings indicate potential local anomaly regarding the individual specific sample of concern. Figure 2. a, b, and c represent the location distribution of structures, and the ratio of employed and eliminated structures at coastal and inland areas.

Table 1 and 2 provide detailed results on the carbonation status and progress tendencies of studied structures located in inland and coastal areas of North Cyprus, respectively. The eliminated results for inland and four coastal structures have been reported in Tables 1 and 2 as grey-highlighted.

When the carbonation coefficient (k) values estimated by Fick’s law for inland structures that are shown in Table 1 are studied, it is observed that the k values are varying between 1.16 and 14.67 mm/year^{0.5}. When the values of k reported in Table 1 was further observed, it can be seen that these significantly varying k values do not necessarily follow any structure age relation neither. For instance, the youngest inland structure, which is represented with structure no-2 that is only four years old was observed to have the highest reported carbonation coefficient, where other inland structures 19 and 20 that are both forty-two years-old are observed to have very varying k values of 1.77 ad 7.10 mm/year^{0.5}, respectively. This finding may potentially be due to the variance of initial concrete quality and characteristic strength of each structure that could not be measured or reported in this study, due to the limitations in acquiring satisfactory information on the exact initial state of buildings. It is expected that if the characteristic strength of concrete was low and initial quality of concrete was relatively poor in the sense of having higher permeability, such a building would experience faster progress of carbonation even though its age could be young.
### Table 1. Carbonation depth and compressive strength information for inland structures.

| Structure No. | Age of Sample (years) | Carbonation Depth (mm) | Carbonation Coefficient; K (mm/year^{0.5}) | Estimated Carbonation Depth at 50 Years Age (mm) | Estimated Carbonation Time for 30 mm Cover (years) |
|---------------|-----------------------|------------------------|------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1             | 44                    | 42.00                  | 6.33                                     | 44.77*                                        | 22.45                                         |
| 2             | 4                     | 29.33                  | 14.67                                    | 103.71*                                      | 4.18                                          |
| 3             | 46                    | 45.50                  | 6.71                                     | 47.44*                                        | 20.00                                         |
| 4             | 28                    | 31.50                  | 5.95                                     | 42.09*                                        | 25.40                                         |
| 5*            | 16                    | -                      | -                                       | -                                             | -                                             |
| 6             | 44                    | 26.20                  | 3.95                                     | 27.93                                         | 57.69                                         |
| 7             | 44                    | 26.13                  | 3.94                                     | 27.86                                         | 57.98                                         |
| 8             | 8                     | 5.23                   | 1.85                                     | 13.08                                         | 262.89                                        |
| 9             | 33                    | 41.23                  | 7.18                                     | 50.75*                                        | 17.47                                         |
| 10            | 50                    | 22.27                  | 3.15                                     | 22.27                                         | 90.71                                         |
| 11            | 10                    | 38.60                  | 12.21                                    | 86.31*                                        | 6.04                                          |
| 12*           | 44                    | -                      | -                                       | -                                             | -                                             |
| 13            | 18                    | 41.47                  | 9.77                                     | 69.11 b                                       | 9.42                                          |
| 14*           | 28                    | -                      | -                                       | -                                             | -                                             |
| 15            | 49                    | 65.43                  | 9.35                                     | 66.09*                                        | 10.30                                         |
| 16            | 8                     | 3.28                   | 1.16                                     | 8.21                                          | 667.89                                        |
| 17            | 37                    | 19.40                  | 3.19                                     | 22.55                                         | 88.48                                         |
| 18            | 11                    | 16.73                  | 5.05                                     | 35.68*                                        | 35.36                                         |
| 19            | 42                    | 11.46                  | 1.77                                     | 12.50                                         | 287.96                                        |
| 20            | 42                    | 46.03                  | 7.10                                     | 50.23*                                        | 17.84                                         |
| 21*           | 43                    | -                      | -                                       | -                                             | -                                             |

*Grey-highlighting refers to the case of eliminated structures due to local anomalous measurements.
*Asterisks refers to the case of samples that do not satisfy the carbonation criterion in EN1992-1-1.

Besides the carbonation coefficient, the depth of carbonation expected to be experienced at the end of 50 years, as well as the time to carbonate 30 mm concrete cover thickness were also determined and presented in Tables 1 and 2. It was observed that 41% of samples obtained from inland structures would not exceed 30 mm in 50 years of service life; therefore, these could be classified as conforming the acceptable carbonation level criterion defined in the related European Norms.

When the carbonation coefficient values determined for coastal structures that are presented in Table 2 are studied, it was observed that k values are varying between 0.69 and 6.97 mm/year^{0.5}. Similar, to what is observed in Table 1 for inland structures, the k value showed no detectable relation with respect to the age of the coastal structures, as it could be clearly seen in the cases of structures 22-26 that are all four years old but having varying k values. Similarly, this finding is expected to be due to the differences in the initial qualities of concrete buildings. Since exact data regarding the initial states of the structures could not be obtained in this study, further experimental investigations that could also control such missing parameters, are necessary in order to be able draw more solid conclusions on this matter.
Table 2. Carbonation depth and compressive strength information for coastal structures.

| Structure No. | Age of Sample (years) | Carbonation Depth (mm) | Carbonation Coefficient; K (mm/year) | Estimated Carbonation Depth at 50 Years Age (mm) | Estimated Carbonation Time for 30 mm Cover (years) |
|---------------|-----------------------|------------------------|--------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 22            | 4                     | 3.50                   | 1.75                                 | 12.37                                         | 293.88                                        |
| 23            | 4                     | 7.37                   | 3.68                                 | 26.05                                         | 66.34                                         |
| 24            | 4                     | 1.38                   | 0.69                                 | 4.88                                          | 1890.36                                       |
| 25            | 4                     | 2.25                   | 1.13                                 | 7.95                                          | 711.11                                        |
| 26            | 4                     | 6.17                   | 3.08                                 | 21.80                                         | 94.67                                         |
| 27            | 44                    | 33.83                  | 5.10                                 | 36.07*                                        | 34.59                                         |
| 28            | 44                    | 46.27                  | 6.97                                 | 49.32*                                        | 18.50                                         |
| 29            | 3                     | 10.58                  | 6.11                                 | 43.19*                                        | 24.12                                         |
| 30            | 14                    | 8.47                   | 2.26                                 | 16.00                                         | 175.77                                        |
| 31            | 22                    | 25.53                  | 5.44                                 | 38.49*                                        | 30.37                                         |
| 32            | 4                     | 1.73                   | 0.87                                 | 6.13                                          | 1198.22                                       |
| 33*           | 46                    | 72.70                  | -                                   | -                                             | -                                             |
| 34*           | 23                    | 73.00                  | -                                   | -                                             | -                                             |
| 35            | 44                    | 18.57                  | 2.80                                 | 19.79                                         | 114.88                                        |
| 36*           | 3                     | 0.00                   | -                                   | -                                             | -                                             |
| 37*           | 26                    | 0.00                   | -                                   | -                                             | -                                             |
| 38            | 44                    | 25.32                  | 3.82                                 | 26.99                                         | 61.78                                         |
| 39            | 44                    | 6.92                   | 1.04                                 | 7.38                                          | 826.96                                        |

* Grey-highlighting refers to the case of eliminated structures due to local anomalous measurements.
* Asterisks refers to the case of samples that do not satisfy the carbonation criterion in EN1992-1-1.

When the values for the depth of carbonation expected to be experienced at the end of 50 years for coastal structures that are presented in Table 2 were examined, it was observed that 71% of studied coastal samples would not exceed 30 mm in 50 years of service life; hence, these samples are conforming the acceptable carbonation level criterion defined in the related European Norms.[14]

Figure 3. Number of inland and coastal structures conforming and non-conforming EN1992-1-1[14]. criterion for acceptable concrete carbonation level.

The exact number of structures located in inland and coastal areas of North Cyprus that conform EN1992-1-1 criterion for carbonation are illustrated in Figure 3.
Figure 4. Carbonation depth for inland structures at current age, at 50 age years and the time required to reach 30 mm of carbonation depth.
Figure 5. Carbonation depth for coastal structures at current age, at 50 years age and the time required to reach 30 mm of carbonation depth
Figures 4 and 5 illustrate collectively the estimations presented in Tables 1 and 2 for inland and coastal structures. The numbers given in the legends of figures 4 and 5 represent the structure numbers that were previously defined for inland and coastal structures. For an individual structure; the first point indicates its current age and corresponding carbonation depth; where the following points are the time to reach to a 30 mm carbonation depth and the total carbonation depth to be experienced at the end of 50 years of service life. The carbonation progress tendency lines connecting these three points for each building was observed to be of a different characteristics (e.g. linear or parabolic) according to the determined coefficient of carbonation in both graphs.

Figures 4 and 5 serve to illustrate more clearly the differences in the actual carbonation depths observed for the current ages of the structures (i.e. the first data point for each structure) in the cases where the structures of same age located in similar conditions (e.g. all coastal or all inland). Besides the possible variations in the initial concrete quality being a potential reason for this observed carbonation progress performance difference, it should be kept in mind that in some cases the exact location of the concrete element from which the test cores were extracted could be influential. It is known that even within a specific building, the carbonation progress observed could vary if the element to be tested is an internal or an external element. Also, for external concrete elements, their state of being sheltered or unsheltered is known to yield different levels of carbonation progress in concrete [2]. Lack of these specific information on the samples acquired is observed to cause difficulties in clear interpretation of the observed carbonation progress tendencies of the structures.

Nevertheless, the fact that the carbonation coefficient values for coastal structures are significantly lower in general than the values of inland structures, as well as the fact that 71% of the coastal structures meet the acceptable concrete carbonation level in European Norms, where only 41% of inland structures could meet the same criteria, indicate that coastal structures are less prone to carbonation attack than inland structures in North Cyprus. Similar findings indicating that the coastal structures experience less severe carbonation occurrence are also reported by Alexander et al. [15], in which the carbonation depth progress of different localities of South Africa was investigated. This finding might be due to the effect of relatively higher relative humidity in the coastal areas that could fill the concrete porosity yielding a slower progress of carbonation [2]. However, the exact factors affecting the ultimately observed carbonation depths in studied structures should be further verified with additional experimental studies.

4. Conclusive remarks
The carbonation progress tendency of concrete structures located in inland and coastal areas of coastal structures were evaluated by carrying out studies on 149 concrete samples acquired from 39 existing reinforced concrete structures of varying ages. The conclusive remarks attained are as the following:

I. Concrete carbonation coefficient values determined by Fick’s law for structures in coastal areas of North Cyprus are observed to be generally lower than the values determined for inland structures; indicating a slower progress of carbonation for coastal structures.

II. 71% of the coastal structures are estimated to yield less than 30 mm of concrete carbonation at the end of a 50 years of service life indicating conformity to EN1992-1-1 criterion; where this value is only 41% for inland structures of North Cyprus. When the results obtained for the studied 39 structures are taken into consideration, it is observed that coastal structures are less prone to concrete carbonation.

III. The observed cases of structures having the same age and being located in the same type of areas yielding varying carbonation depths and carbonation coefficient values are expected to be due to varying initial qualities of concretes, as well as potentially varying localized status of concrete elements tested. Further specific information and further experimental studies are required to verify the exact influencing factors yielding different carbonation tendencies for the buildings located in same areas with similar ages.
Acknowledgments
Authors would like to acknowledge Cyprus Turkish Chamber of Civil Engineers for their support and collaboration throughout this study.

References
[1] Moreno E I 2013 Carbonation Coefficients from Concrete Made with High-Absorption Limestone Aggregate Advances in Materials Science and Engineering 2013 1–4 https://doi.org/10.1155/2013/734031
[2] Neville AM 2005 Properties of Concrete (New York: John Wiley & Sons)
[3] Monteiro P J M and Mehta P K 2005 Concrete: Microstructure, Properties, and Materials-3rd ed. (USA: McGraw-Hill Professional)
[4] Domone P L J and Illston J M 2010 Construction materials: their nature and behaviour -4th ed. (Milton Park, Abingdon, Oxon ; New York: Spon Press)
[5] Zhao H, Sun W, Wu X and Gao B 2017 The effect of the material factors on the concrete resistance against carbonation KSCE Journal of Civil Engineering 22(4) 1265–74 https://doi.org/10.1007/s12205-017-0988-9
[6] Elmoaty A E M A 2018 Four-years carbonation and chloride induced steel corrosion of sulfate-contaminated aggregates concrete Construction and Building Materials 163 539–56 https://doi.org/10.1016/j.conbuildmat.2017.12.128
[7] Akpinar P and Khashman A 2017 Intelligent classification system for concrete compressive strength Procedia Computer Science 120 712-8 https://doi.org/10.1016/j.procs.2017.11.300
[8] Khashman A and Akpinar P 2017 Non-destructive prediction of concrete compressive strength using neural networks Procedia Computer Science 108 2358-62 https://doi.org/10.1016/j.procs.2017.05.039
[9] Akpinar P and Uwanuakwa I D 2016 Intelligent prediction of concrete carboration depth using neural networks Bull Transilv Univ Brasov, Ser III Math Informatics, Phys 9(2) 99–108
[10] Malami S I, Akpinar P and Lawan M M 2018 Preliminary investigation of carbonation problem progress in concrete buildings of north Cyprus MATEC Web Conf. 20306007 https://doi.org/10.1051/matecconf/201820306007
[11] Neville A M 2006 Concrete: Neville’s Insights and Issues (Thomas Telford)
[12] Houf Y F and Wittmann F H 2002 Depth profiles of carbonates formed during natural carbonation Cement and Concrete Research 32 (12) 1923-30
[13] Monteiro I, Branco F A, Brito J d and Neves R 2012 Statistical analysis of the carbonation coefficient in open air concrete structures Construction and Building Materials 29 263–9 https://doi.org/10.1016/j.conbuildmat.2011.10.028
[14] EN 1992-1-1 2014 Eurocode 2: Design of concrete structures - Part 1-1 : General rules and rules for buildings (London: BSI Standards)
[15] Alexander M G, Mackechnie J R and Yam W 2007 Carbonation of concrete bridge structures in three South African localities Cement and Concrete Composites 29(10) 750–9. https://doi.org/10.1016/j.cemconcomp.2007.06.005