Qosai Mohammad Galeb Al Haj Houseen

Evaluation of Carbonation Depth Progress and Compressive Strength Evolution of Existing RC Structures in Coastal and Inland Areas of N. Cyprus

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EVALUATION OF CARBONATION DEPTH PROGRESS AND COMPRESSIVE STRENGTH EVOLUTION OF EXISTING RC STRUCTURES IN COASTAL AND INLAND AREAS OF N. CYPRUS

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES

OF

NEAR EAST UNIVERSITY

By

Qosai Mohammad Galeb Al Haj Houseen

In Partial Fulfilment of the Requirements for

the Degree of Master of Science

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Civil Engineering

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Approval of Director of Graduate School of Applied Sciences

Prof. Dr. Nadire ÇAVUŞ

We certify this thesis is satisfactory for the award of the degree of Master of Science in Civil Engineering

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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To my family…

ABSTRACT

Carbonation is one of the most severe concrete problems that can potentially affect both concrete cover and steel reinforcing bars. This investigation involves experimental studies on carbonation depth progress and calculations on compressive strength evolution estimations on 149 samples from 39 existing building in North Cyprus.

Phenolphthalein indicator test had been used on the concrete samples in order to determine the depth of carbonation. Fick's law method was used to determine the predicted carbonation after 50 years as well as the time needed to reach 30 mm depth. British Standards BS EN1992-1-1 were used to predict the compressive strength at 28 days in order to determine the evolution of the compressive strength and its relationship with carbonation in concrete.

It was observed that 41% of the inland samples are conforming the Eurocodes in the aspect of carbonation depth, while 71% of the coastal samples were conforming the standard and that could be due to the differences of the surrounding environment. Moreover, the relationship between compressive strength and carbonation is observed to be inversely proportional for the majority of samples, as the compressive strength increases the carbonation rate reduces in concrete.

Keywords: Carbonation depth; phenolphthalein indicator test; carbonation exposure conditions; Fick's law method; compressive strength evolution

ÖZET

Karbonatlaşma; hem beton paspayı bölgesini hem de çelik donatıları olumsuz yönde etkileyebilen en ciddi beton problemlerindem biridir. Bu çalışma Kuzey Kıbrıs'ta 39 mevcut betonarme binadan alınan 149 numune üzerinde yürütülen deneysel karbonatlaşma derinliği ile basınç dayanımı, gelişimi hesaplamalarım içermektedir.

Fenolftalein çözeltisi kullanılarak beton numunelerindeki karbonatlaşma tespit edilmistir. Fick Kanunu yöntemi, aynı numunelerin bilgileriyle kullanılarak 50 yıl sonraki karbonatlaşma derinliği ve 30 mm pas payını aşan karbonatlaşma derinliğini için gereken süreler hesaplanmıştır. Sonrasında, BS EN 1992-1-1 kullanılarak, güncel basınç dayanımları bilinen bu numunelerin 28 günlük karakteristik basınç dayanımları hesaplanmış ve bu değerler karbonatlaşmanın ilerleme eğilimi ile kıyaslanmıştır.

Çalışmalar sonucunda, adanın iç kesimlerindeki binaların %41'inin, kıyı kesimlenindeki binaların ise %71'inin standartlardaki kriterleri karşıladığı gözlemlenmiştir. Bu performans farklılığının iki kesimdeki binaların maruz kaldığı farklı koşullardan dolayı olması beklenmekterdir. Buna ilaveten, numunelerin büyük bir kısmında basınç dayanımının yüksek olduğu hallerde karbonatlaşma seviyesinin düşük olduğu gözlemlenmiştir.

Anahtar Kelimeler: Karbonatlaşma derinliği; fenolftalein çözeltisi; karbonatlaşmaya neden olen etkenler; Fick kanunu metodu; basınç dayanımı gelişimi

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LIST OF ABBREVIATIONS

ASTM: American Society for Testing and Materials

USGS: United States Geological Survey

BS: British Standard

CH: Calcium Hydrate

C_3S: Tricalcium Silicate

C_2S: Dicalcium Silicate

CHAPTER 1
INTRODUCTION

Concrete is the most depended material for construction (Moreno, 2013; Papadakis et al., 1989). Concrete's shapeability into any desired form in its fresh state, it's excellent ability to withstand water, availability of concrete and it's cheap and affordable price is what makes it popular around the world (Monteiro & Mehta, 2005). Cement production in 2017 worldwide increased up to 4.1 billion tons according to USGS ("USGS - Minerals Information: Cement," 2018).

Awareness for concrete's durability problems reached a significant level, especially among developed nations in the last decades (Domone & Illston, 2010; Papadakis et al., 1989). Codes and regulation prescribe specifications to ensure a lifetime of a structure from a minimum of 50 years reaching 100 years of service (Domone & Illston, 2010).

Steel bars' corrosion is the main threat faced by reinforced concrete structures. As a result of reinforcement corrosion, both the concrete and the steel bars are damaged. Consequently, high repairing cost or demolition becomes inevitable (Elmoaty, 2018; Moreno, 2013; Zhao et al., 2017).

Carbonation is one of the main reasons that yields the initiation of corrosion process by its influence on the reduction of pH level to a level below 10; at this point the protective layer protecting the reinforcement is destroyed (Elmoaty, 2018; Moreno, 2013; Papadakis et al., 1989).Carbonation in concrete is a complex problem: concrete parameters like concrete permeability, alkalinity, concrete strength, and thickness of concrete cover, as well as external conditions like CO_2 concentration, relative humidity, the exposure condition, and temperature are all known to affect the progress of carbonation in concrete.

This study covers the evaluation of carbonation progress in reinforced concrete structures in coastal and inland areas of North Cyprus, as well as the evolution of compressive strength of the same selected existing structures in N. Cyprus in details.

1.1 Definition of the Problem

Reinforced concrete structures in Cyprus Island are subjected to different climate conditions within its inland and coastal areas. These different climate conditions are expected to influence progress of concrete carbonation to different extents. The carbonation resistance performance of inland and coastal structures in North Cyprus considering their compressive strength evolution tendencies had not been studied in details previous literatures, making it an interesting point to focus on.

1.2 Objectives and Scope of the Study

The objectives and the scope of this thesis study are:

- To carry out experimental and theoretical studies for the investigation of the carbonation progress tendencies of existing structures in North Cyprus considering the exposure differences in coastal and inland areas.
- To study the evolution of compressive strength evolution in time of selected existing structures in North Cyprus by estimating the characteristics of compressive strength values at a 28-days age according to BS EN1992-1-1 and comparing the strength evolutions in coastal and inland areas.
- To evaluate carbonation progress and strength evolution tendencies for inland and coastal areas.

1.3 Significance of the Study

An insight on the carbonation progress tendency of existing structures in coastal and inland areas of Northern Cyprus will be provided. In this way; better strategies can be defined for rehabilitation of existing old structures and also for the planning of new construction.

1.4 Limitations of the study

Certain limitations had been faced throughout the studies carried out for this thesis. The lack of information on initial concrete grade, the exact cement type used, the exact month of construction completion within the specified year and additional historical information incidence that might have affected the structures' durability, lead to the need of reading certain assumption for the calculations carried out in this study, which are explained in detail in the following section in the thesis.

CHAPTER 2
LITERATURE REVIEW ON CONCRETE CARBONATION

The reaction identified as carbonation occurs between carbon dioxide (CO_2) from the atmosphere and cement hydration products, in the presence of moisture, producing calcium carbonate ($CaCO_3$) causing concrete alkalinity reduction in concrete (Bertolini et al., 2014; Dyer, 2014; Richardson, 2002).

Normal atmospheric concentration of CO_2 is about 0.03% in rural areas, 0.1% in unventilated laboratory, and in large cities their volume may go up to 0.3% (Brooks, 2014; Neville & Brooks, 2010).

Carbonation can penetrate from concrete surface through in, but it’s considered extremely slow (Neville & Brooks, 2010).

2.1 Mechanism of Carbonation Reaction in Concrete:

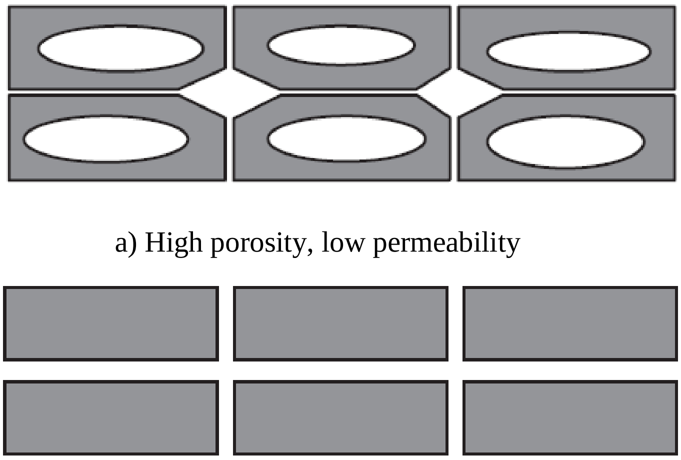
2.1.1 Factors affecting carbonation:

2.1.1.1 Internal factors affecting carbonation process:

a. *Concrete permeability:*

Permeability refers to the ability of fluids and gases to move freely through the concrete. Permeability is the major concern in case of structures exposed to chemical attack or in case of water-tightness of liquid-retaining structures (Neville & Brooks, 2010) (Aïtcin & Flatt, 2016).

Water/Cement (W/C) ratio and the effectiveness of curing concrete have the major effect on permeability especially at early ages. Therefore, higher water/cement ratio in concrete with simultaneous inefficient curing lead to higher chance of carbonation, i.e., deeper carbonation will occur (Domone & Illston, 2010).



a) High porosity, low permeability

b) Low porosity, high permeability

Figure 2.1: Illustration of the difference between porosity and permeability (Domone & Illston, 2010)

The connections between porosity is the most important than its quantity and volume. However, as shown in Figure 2.1 (a), the amount of porosity is high but the connected parts of it is less which means that the effective part of it is the connected ones. On the other hand, the porosity in Figure 2.1 (b) is less but it is connected to each other due to that the concrete bears higher permeability.

b. Alkalinity reverse:

Carbonation resistance of concrete is directly related to CH presence in concrete which provides higher and healthier pH level. CH is considered as the most important compound against carbonation providing high pH level that keeps concrete healthy. The more CH occurred, the higher carbonations resistance there is. CH is a product of hydration of calcium silicates C_3S and C_2S from cement, thus, the higher content of these clinker compounds results higher CH quantity, and the higher alkalinity in concrete (Richardson, 2002).

c. Concrete strength:

Strength is related to many factors such as concrete permeability and alkalinity reserve and so this implies that the carbonation rate should be inversely proportional to strength. The rate of carbonation in high quality concretes may be so low that the carbonation depth tends to a limit of a millimeter or less (Domone & Illston, 2010).

d. Thickness of concrete cover:

Concrete cover thickness considered as a shield for reinforcement, non-efficient cover lead to carbonation reach reinforcement faster (Bertolini et al., 2014).

2.1.1.2 External factors:

a. Carbon dioxide concentration:

Higher carbon dioxide concentrations lead to higher carbonation rate. Also carbonation rate increases even more in industrial structures (Monteiro & Mehta, 2005; Richardson, 2002). Richardson (2002) mentioned that coastal areas shows minimum level of carbon dioxide in the atmosphere, while urban areas shows more. Interior of buildings typically has the highest levels carbon dioxide (Figure 2.2).

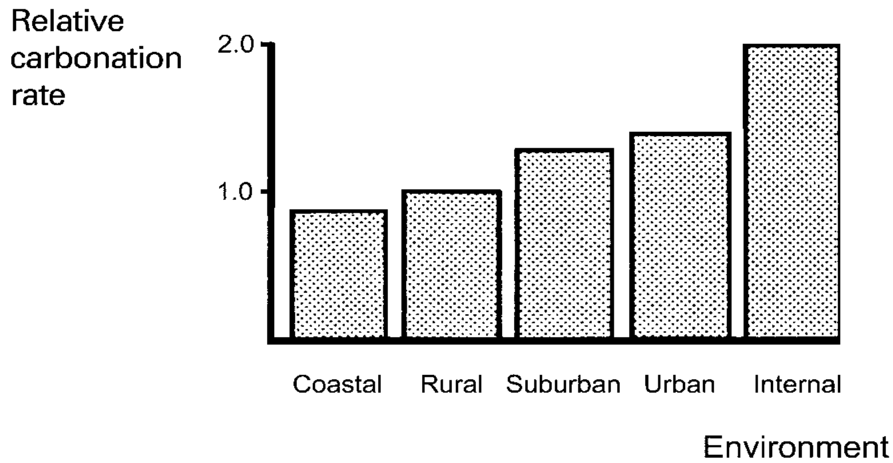


Figure 2.2: Influence of environment on the rate of carbonation (Richardson, 2002)

b. Relative Humidity (RH) of the Ambient Medium:

Carbonation rate have two causes of variation according to humidity. First, carbon dioxide diffusion is facilitated within air-filled pores in concrete, but when the pores are filled with water the penetration of carbon dioxide becomes very slow. Carbon dioxide diffusion rate is inversely proportional with humidity of the concrete rate converses to zero in case of water-saturated concrete. This means that when the concrete is fully saturated, CO_2 will not be able to diffuse. However, in dry concretes the initiation of carbonation reaction is negligible due to the absence of water. Rate of carbonation, thus, the value of K, will change on passing from a wet or humid climate to a dry one. Under equilibrium conditions, environments with constant relative humidity will initiate carbonation at 50-70% humidity (Aïtcin & Flatt, 2016; Bertolini et al., 2014; Domone & Illston, 2010; Poursaee, 2016), that is a value similar to the annual averages of the relative humidity of the atmosphere in Northern Cyprus, Nevertheless, rate of carbonation decreases in cases where structures are subjected to periodic wetting. Frequency and duration of wetting–drying cycles are important parameters. As long as the frequency of wetting and drying duration lessen, the carbonation depth decreases (Bertolini et al., 2014). Carbonation rate may vary among parts of a structure (e.g., if one part of the structure is permanently sheltered, the rate of penetration will be considerably higher than in other parts exposed to rain), or moving from the outer layers of concrete member to the inner ones (the outer layers will be drier during the phase of drying, while they will be wetter during periods of wetting). Carbonation of concrete can thus be very variable along different parts of a single structure (Bertolini et al., 2014).

In the case of Cyprus, the humidity level ranges between 53.5 % during the summer and rises to 74 % during winter in inland areas, giving an annual average humidity of 63.7 %. On the other hand, the humidity level in coastal areas ranges between 66 % during summer and 71 % during winter with an annual average humidity of 69.3 % (Malami, 2014). Generally, N. Cyprus consider as an appropriate environment for concrete carbonation according to its relative humidity. For monthly relative humidity values, see Table 2.1 and 2.2.

Table 2.1: Average relative humidity of inland areas (Malami, 2014)

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Annual
73.3	72.0	69.1	62.7	56.9	53.5	54.4	57.8	59.4	62.5	68.7	74.0	63.7

Table 2.2: Average relative humidity of inland areas (Malami, 2014)

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Annual
71.3	71.0	71.4	70.8	69.6	67.1	66.0	66.3	67.1	68.8	70.1	71.6	69.3

c. The Exposure Conditions:

Degree of exposure has significant effect on carbonation just as degree of moisture does in the permeable pore structure. Carbonation still occurs in all environments and at different concrete strength which proves how the degree of exposure is of great significance. Moisture content has diffusion coefficient on pore structure, that’s way it appears that moisture has a considerable effect on carbonation rate (Baker, 1991). By analyzing data from an Irish study ,categorization will be as following:

- external, exposed to rain;
- external, sheltered from rain;
- internal.

Results are shown in Figure 2.3. These trends corresponds to studies in warm countries using same categories (Richardson, 2002). As it can be observed from the Figure (2.3), the structural elements present in the external part of the structure and exposed to rain have the lowest rate of carbonation while the parts that were not exposed to rain had a higher carbonation rate. On the other hand, the internal elements of the structure show the highest carbonation rate (Richardson, 2002).

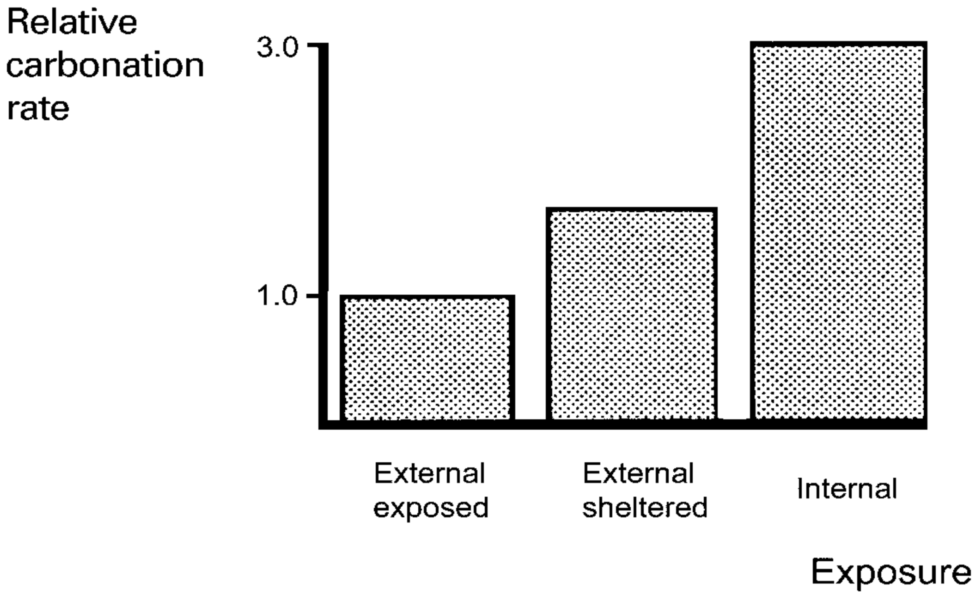


Figure 2.3: Influence of exposure condition on the rate of carbonation (Richardson, 2002)

BS 8500 (British Standards Institution, 2015) provides quality requirements of concrete and steel bars cover for various exposure classes or conditions; minimum values are summarized in Table 2.3.

Table 2.3: Minimum recommendations for 50-years design life for carbonation-induced corrosion of concrete reinforcement (British Standards Institution, 2015)

<table>
<tr><th colspan="2">Exposure class and description</th><th>Minimum strength class</th><th>Maximum w:c</th><th>Minimum cement content (kg/m^3)</th><th>Minimum cover to steel (mm)</th><th>Cement type</th></tr>
<tr><td>XC1</td><td>Dry or permanently wet</td><td>C20/25</td><td>0.7</td><td>240</td><td>15</td><td rowspan="4">CEM I, CEM II, CEM III (with max 80 % ggbs) CEM IV, SRPC</td></tr>
<tr><td>XC2</td><td>Wet, rarely dry</td><td>C25/30</td><td>0.65</td><td>260</td><td>25</td></tr>
<tr><td>XC3</td><td>Moderate humidity</td><td rowspan="2">C40/50</td><td rowspan="2">0.45</td><td rowspan="2">340</td><td rowspan="2">20</td></tr>
<tr><td>XC4</td><td>Cyclic wet and dry</td></tr>
</table>

d. Temperature

Carbonation is influenced by temperature and thus it can be seen that the chemical reaction rate constant shown in Equation 2.1 has a different Arrhenius equation form. Thus, reaction's rate increase Commensurate with temperature increase (Dyer, 2014).

$$k = Ae^{-E_a/RT} \quad (2.1)$$

where

k = the rate constant

A = pre-exponential factor

E_a = the activation energy

R = the ideal-gas constant

T = the temperature in K

The temperature level in inland areas during winter ranges between a minimum of 5.4 ^oC and a maximum of 15.7 ^oC, with a minimum of 21.9 ^oC and a maximum of 36.7 ^oC during summer. The annual average temperature level is 19.4 ^oC. In contrast, the temperature level in coastal areas ranges between a minimum of 8.5 ^oC and a maximum of 16 ^oC during winter with a minimum of 22.8 ^oC and a maximum of 32.7 ^oC during summer giving an annual average temperature of 19.9 ^oC (Malami, 2014). For monthly temperature values, see Table 2.4 and 2.5.

Table 2.4: Average, maximum and minimum temperature of inland areas (Malami, 2014)

	JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUNE**	**JULY**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**Annual**
Avg.	10.4	10.9	13.1	17.2	22.1	26.3	29.1	28.7	25.6	21.3	15.7	11.9	19.4
Max.	15.7	16.3	19.2	24.2	29.6	33.9	36.7	36.6	33.4	28.5	22.1	17.3	26.1
Min.	5.4	5.5	7.0	10.4	14.8	19.0	21.9	21.7	18.7	14.8	9.9	6.8	13.0

Table 2.5: Average, maximum and minimum temperature of coastal areas (Malami, 2014)

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	Annual
Avg.	12.5	12.6	14.2	17.2	21.0	25.1	28.0	28.2	25.9	22.4	17.7	14.2	19.9
Max.	16.0	16.1	18.1	21.4	25.3	29.4	32.5	32.7	30.5	26.8	21.6	17.7	24.0
Min.	8.8	8.5	9.6	12.2	15.6	19.6	22.6	22.8	20.5	17.6	13.5	10.4	15.2

2.1.2 Mechanism of carbonation process in concrete:

Portlandite, $Ca(OH)_2$, is a common concrete compound that is formed naturally as a result of cement hydration process. It is the concrete compound that is known to fill the majority of concrete microstructure, and it is also well known for its effect of yielding a high pH level in concrete. This alkalinity both helps to maintain integrity of all other concrete compounds and also ensures the stability of the "passive layer" around the reinforcing bars that prevents the corrosion (Bertolini et al., 2014; Lu & Dai, 2014; Poursaee, 2016).

As CO_2 gas from the atmosphere penetrates into concrete and combines with the present moisture, a weak carbonic acid (H_2CO_3) is being formed, as seen in equation 2.2. Later on this carbonic acid proceeds to react with portlandite in concrete, as seen in equation 2.3, consuming and converting it to $CaCO_3$. This new product do not provide the desirable effect of portlandite; with the formation of $CaCO_3$ the high pH value starts to drop, causing negative effects in concrete and as the pH value drops to 10, the initiation of reinforcement corrosion also becomes possible (Bertolini et al., 2014; Lu & Dai, 2014; Poursaee, 2016). Carbonation starts from concrete's surface then progresses gradually inward. Once the concrete cover thickness is affected by it, the steel bars also become prone to related negative effects (Dyer, 2014).

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (2.2)$$

$$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2H_2O \quad (2.3)$$

Carbonation depth increases by time, and the advancing rate is a function of relative humidity (RH): the penetration of the CO_2 into the concrete is inversely proportional with RH, but the reaction with the CH directly proportional with saturation of concrete. The net result of these two factors is that carbonation highest impact ranging between 50-70% of RH. Midrange RH leads to highest rate of carbonation; in this humidity range no active corrosion occurs of any significance. Consequently, highest threatens comes from environments leading to corrosion caused by carbonation that have semi dry and wet cycles. In hot climates Carbonation is considered as major factor influencing concrete durability, where concrete is dry usually but occasionally saturated by rainstorms. Carbonation and Chloride could act synergistically, causing deleterious effect on concrete in hot coastal areas (Bertolini et al., 2014).

Carbonation penetrates concrete in a decreasing rate by age, this decrement is according to three factors. Firstly, the gas should penetrate deeper into concrete. Secondly, concrete turns more impermeable by time due to continuity of hydration. Finally, carbonation contributes in permeability reduction, by both filling pores by carbonate and due to water releasing reaction of carbonation, leading for contribution of this water in further hydration (Bertolini et al., 2014).

When the concrete cover is fully carbonated, alkalinity maintaining passive film protecting reinforcement vanishes and corrosion starts to attack steel bars from their surface deeper on. In this circumstance, a deeper view on steel bar's surface shows consisting of local microcells in clusters. When enough moisture occurs, currents start to flow activating these local cells, initiating corrosion. For that process, corrosion generally occurs somehow uniformly along steel surface. Thus, leading to what verified as "general corrosion" (Zhao & Jin, 2016).

2.2 Consequences of Carbonation in Concrete

Carbonation term doesn't always mean deterioration of concrete properties. Porosity, however, is observed to be lower in the carbonated areas, this can be explained because of the higher volume of calcium carbonates rather than calcium hydrate "CH", which means providing more surface strength and hardness, with reduction of surface permeability (Domone & Illston, 2010; Papadakis et al., 1989).

When pH level drops, hydration products which provide strength of concrete and calcium silicate hydrate C-S-H that plays the binding role start to decompose leading to strength drop.

Additionally, shrinkage caused by carbonation might occur, changing properties of surface, hence cracking near exposed structural element surface occur (Bertolini et al., 2014).

Beside strength loss, carbonation of concrete might lead to corrosion of reinforcing steel caused by dropped pH level. Dropped pH level at the depth of reinforcing steel leads to instability of passive film surrounding and protecting steel, hence occurring carbonation-induced corrosion, also due to rust higher volume, it will cause higher stresses on the concrete cover which will lead cover to become cracked and defused (Elmoaty, 2018; Moreno, 2013; Papadakis et al., 1989; Zhao et al., 2017), Figure 2.4 illustrates the effect of carbonation on the steel reinforcement, and Figure 2.5 show The impact of reinforcement corrosion on concrete.

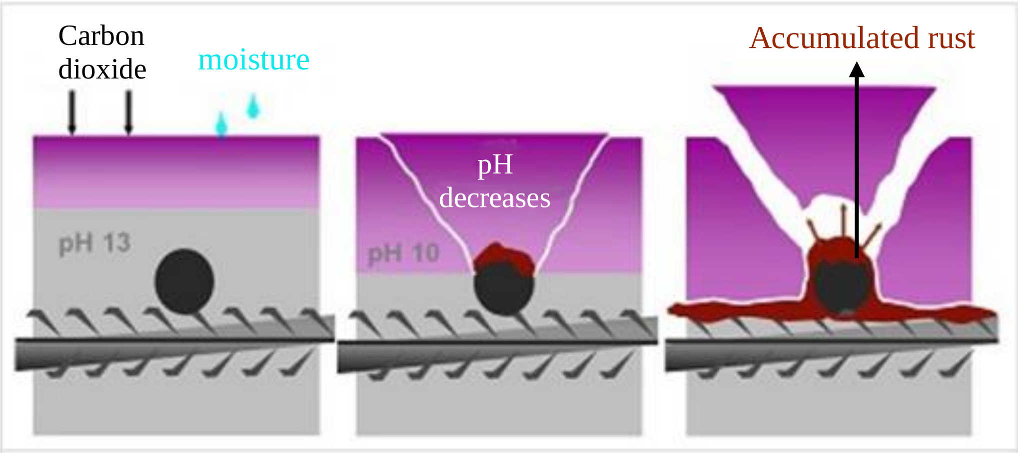


Figure 2.4: The effect of carbonation on steel (Jedidi & Benjeddou, 2018)

Figure 2.5: The impact of reinforcement corrosion on concrete (Zonneveld, 2015)

2.3 Test Methods Used to Study Carbonation in Concrete

There are multiple methods to measure the depth of carbonated region like infra-red spectroscopy, thermogravimetric analysis, microscopy, X-ray diffraction, chemical analysis or the phenolphthalein test. Phenolphthalein test is the widely used and simplest among tests, and it's about spraying a freshly split surface of a concrete sample with phenolphthalein based solution (Hobbs, 1998; Richardson, 2002). This indicating solution method is the first choice to be used in all studies on carbonation, because it's easy to be applied in field tests (Richardson, 2002). This indicator is sensitive to PH value and changes its color to magenta from the original colorless state in a range of PH of 8.3 to 10. On a broken concrete surface the change in color is sudden at a greater value of pH than 9.0 to 9.5. It does not require a skilled person to use and gives reproducible results. The test is carried out on freshly broken surfaces that must be clean from any contaminations such as dust to be sprayed with the solution.

Advancing of carbonation front does not have a constant rate due to the heterogeneous structure of concrete like higher density aggregates that will not be colored by phenolphthalein. Thus, it may be necessary to measure the maximum and determine the average carbonated depth (Figure 2.6). An indication of the quality of concrete and the surrounding environment are provided by average depth. Threatening of carbonation on durability of concrete can be determined by determining whether the carbonation reached reinforcement or not (British Standards Institution, 2006; RILEM Committee TC56, 1988).

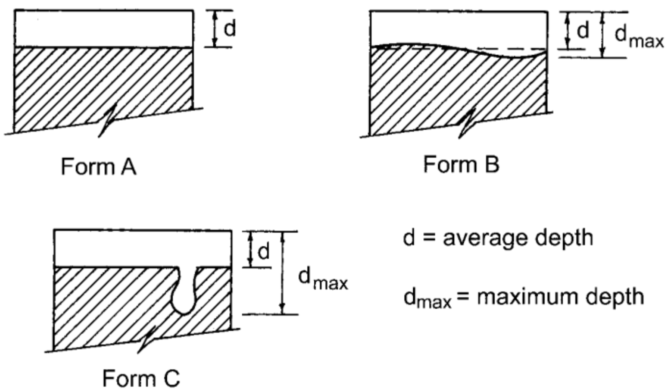


Figure 2.6: Forms of carbonation profile encountered in practice (British Standards Institution, 2006; RILEM Committee TC56, 1988)

2.3.1 Laboratory tests:

Prepared samples are placed in a chamber with constant condition like relative humidity, temperature, CO_2 concentration, and pressure. Rate of carbonation can be measured according to phenolphthalein method. The readings are taken as shown in Figure 2.7, and the average of these readings was taken using Equation 2.4 (Arredondo-Rea et al., 2012).

$$X = \frac{x1 + x2 + \cdots + x12}{12} \tag{2.4}$$

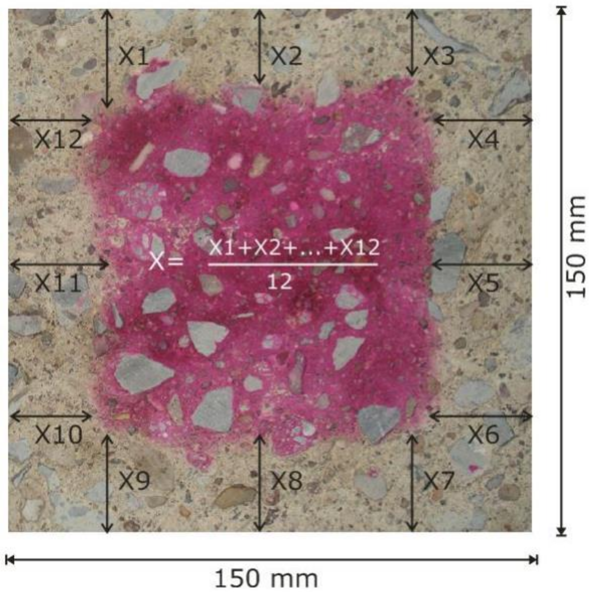


Figure 2.7: Readings location of carbonation depth (x) (Arredondo-Rea et al., 2012)

2.3.2 Field tests:

Readings on cores are the best way for structures in service. On-site, however, testing may be done by making a 50 mm diameter hole and exposing the edges of the hole with a chisel and hammer. Then Phenolphthalein may be sprayed onto the currently broken surface.

The phenolphthalein test can be also applied on site by breaking off pieces of concrete and spraying the exposed concrete. This may be blurry in case of concentrate readings on edges of beams and columns. Although they are the easiest to be broken off, but they may have high carbonation depths that may not be the general case of the whole structure. The corners will face biaxial penetration of CO_2, as shown in Figure 2.8, and due to compaction difficulties, permeability of corners concrete of shutters may not be representative of the whole member (Richardson, 2002).

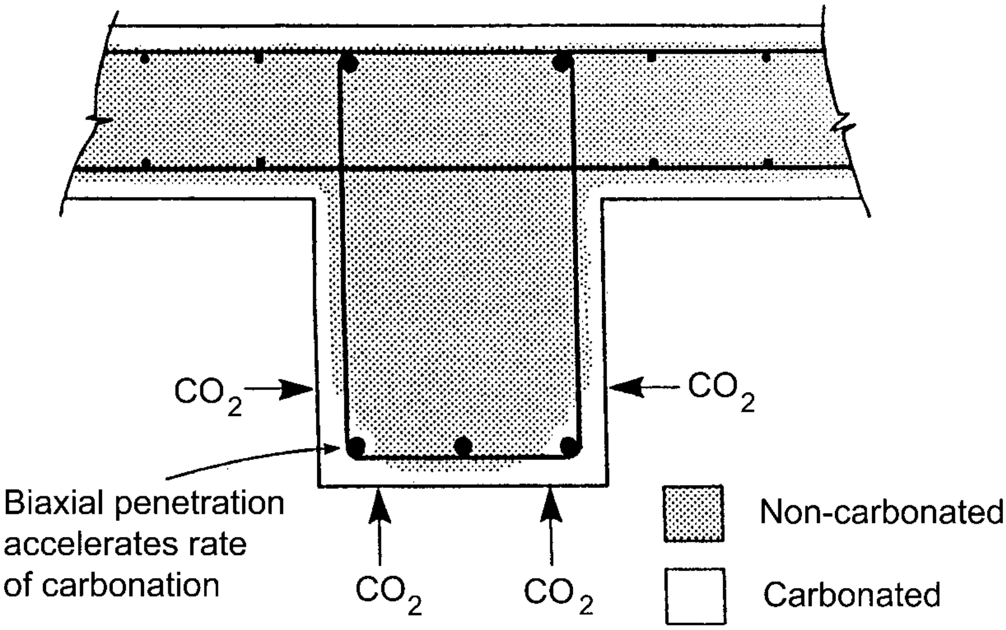


Figure 2.8: Influence on carbonation profile of biaxial penetration of carbon dioxide (Richardson, 2002)

2.4 Previous Studies:

Alexander et al. (2007) studied the carbonation rates for reinforced concrete bridges in coastal (Cape peninsula and Durban) and inland (Johannesburg) areas of South Africa. The influence of environment and materials on the rate of carbonation were interpreted for approximately 90 bridges with an age ranging from eleven to seventy-six years. The carbonation rate was measured by using phenolphthalein indicator test. The highest rate of carbonation was found in inland areas due to relatively dry environment. According to the exposing conditions and strength grade of concrete data were organized. The rate of carbonation depended mostly on the nature of precipitation and ambient temperature.

Overall, the studied bridges with an age exceeding 30 years constructed from grade 30 concrete had an average rate ranging between 0.3mm/year and 0.7mm/year. Exposure conditions had little effect on the rate of carbonation when characterized by degree of shelter for both inland and coastal areas, caused by average precipitation period and relative humidity. It was also found that new structures had a higher carbonation rate than older structures which might possibly be due to the change in characteristics of the cement used in order to accomplish construction as fast as possible.

Li et al. (2018) investigated the carbonation effect of existing concrete structures in one of the coastal cities (Shenzhen) of China. A relationship analysis had been done between the influence of external factors, carbonation depth and internal factors. The tests that were used in order to determine the carbonation rate and the strength for the obtained samples are phenolphthalein indicator test and compressive strength, respectively. The evaluation of carbonation risk in concrete structures were made using a prediction model. From the results obtained, the amount of carbonation in outdoor ends was less than indoor ends. This was reported to happen due to decreasing average concentration of carbon dioxide at outdoor ends and also the availability of surface coating. The correlation of natural carbonation depth with concrete's compressive strength and the mortar's cover thickness was found to be negative. Concrete structures which existed for 25 years showed no carbonation for a thickness exceeding 8 mm of mortar coating. Last but not least, the prediction model results showed a good compatibility with data tested where the influence of both external and internal factors had been considered during the test. Also, carbonation on existing concrete structures which might have surface coatings or not can be predicted by the model which might be helpful during durability design.

Monteiro et al. (2012) had investigated the abnormal corrosion problems of reinforced concrete structures have significantly increased in the recent years. This happens due to carbonation, the penetration of carbon dioxide through the porous system of concrete causes a low pH around the reinforcement allowing a progressive increase in corrosion. The relationship between concrete's age and carbonation depth are described by different analytical models. The first law by Fick: $x = k\sqrt{t}$ results are most frequently used, where the carbonation coefficient is represented by K. This coefficient shows a significant change when compared with different structures since it strongly depends on the characteristics of concrete, carbon dioxide concentration, cement type and humidity. For a better evaluation of K, this paper provides a statistical study on concrete structures exposed to air. The results of this study are obtained from over 100 measurements done on structures that had existed for over 99 years. Statistical analysis was done for the obtained result in order to obtain correlations between k and factors such as compressive strength of concrete, structures age and exposure conditions. Recommendations were made after the analysis on how to cover reinforcement bar during design.

Han et al. (2013) had studied a major factor that effects the durability of steel bars is the corrosion of reinforcement which is caused by carbonation, thereby the safety of concrete and long-term performance is decreased. The aim of the study was to evaluate the carbonation effects on harbor concrete structures and quantify its effects according to in situ data tests done at 436 points in different harbor facilities. The relationship between cover depth and carbonation depth, also concrete strength and carbonation depth were all investigated. The tests that were used in order to determine the carbonation rate and the strength for the obtained samples are phenolphthalein indicator test and compressive strength, respectively. In addition, evaluations according to the concept of reliability were made for steel corrosion initiation probabilities, or failure probability of durability. The in-situ test results showed that harbor concrete structures had a ratio less than 0.2 for carbonation depth to cover depth. The carbonation effect on the failure probability of durability obtained was less than 10 % in most of the cases. Therefore, the final conclusion of the research mentioned that the durability of harbor concrete structures effected by carbonation is not of a great importance as it is on other structures durability such as subway tunnels or building interiors.

Durán-Herrera et al., (2015) had investigated seven set of concretes for their natural and accelerated carbonation resistance, mostly concentrating on the evaluation of viscosity/shrinkage and/or internal curing modifiers effects on carbonation resistance. Also, ordinary portland cement (OPC) of five different types were evaluated where two of the OPC contains 20 % Class F fly ash which were used for replacing cement on a mass basis. The observed correlation between the natural and accelerated carbonation coefficient measured were looking good for all seven mixtures. On the other hand, the observed correlation between the carbonation resistance of the specimen and their compressive strength for each day out of 28 days, with viscosity/shrinkage modifier contained mixtures which exhibits abnormal behavior on high carbonation resistance at low strength level was lesser. Two of the mixtures gave the lowest carbonation coefficients for the natural and accelerated exposure. The first one contains viscosity/shrinkage modifier mixed with water and the second one contains a solution bearing the same admixture which is used for pre-wetting fine aggregates with low-weight. In addition to that, the carbonation coefficient was higher in both natural and accelerated exposure for fly ash mixture when compared to their corresponding ordinary portland cement concretes.

CHAPTER 3
MATERIALS AND METHODOLOGY

3.1 Acquisition Samples from Existing Structures:

Concrete core samples extracted from existing buildings in N. Cyprus were received as a result of collaboration established between Chamber of Civil Engineering in TRNC and Civil Engineering Department of Near East University. The following information regarding the sample characteristics were provided by the Chamber as presented in Table 3.1:

- Cities where sample were collected; hence the locations could be classified as inland or coastal.
- Date of construction; hence the age of the structure.
- Current compressive strength of samples.

The exact month of construction within the year as well as the month when compressive strength testing took place were not known. So, it was assumed that all structures were tested and constructed on the same month for the purpose of estimation structures age approximately. Also, the exact identification of the structure as well as the name of the owner were not provided by the chamber due to privacy issues. Figure 3.1 illustrates the method of sampling, which considered as a destructive testing method.

A total of 149 samples were collected from 39 structures whose ages arrived from 3 to 50 years old, distributed around major cities in N. Cyprus, like Nicosia, Kyrenia, and Famagusta, samples were divided into two main categories, “inland areas” which includes samples from Nicosia, and “coastal areas” which includes samples from Kyrenia and Famagusta that are shown in Figure 3.2. Figure 3.3 was generated using Google earth 7.3.2 application showing sampling locations, where red pointers refer to coastal locations, while yellow pointers refer to inland locations.

Table 3.1: Data given by Chamber of Civil Engineering in TRNC. (a) The data of inland structures areas; (b) The data of coastal structures areas

a			b		
Structure No.	**Age of Sample (years)**	**Current Strength (MPa)**	**Structure No.**	**Age of Sample (years)**	**Current Strength (MPa)**
1	44	20.06	22	4	32.17
2	4	26.28	23	4	32.85
3	46	15.11	24	4	23.90
4	28	12.70	25	4	30.43
5	16	25.88	26	4	29.12
6	44	28.96	27	44	20.32
7	44	18.90	28	44	27.98
8	8	29.63	29	3	35.57
9	33	32.16	30	14	38.58
10	50	33.35	31	22	25.14
11	10	34.99	32	4	44.92
12	44	18.37	33	46	19.17
13	18	21.82	34	23	13.87
14	28	15.44	35	44	22.25
15	49	15.77	36	3	26.00
16	8	43.55	37	26	41.55
17	37	61.89	38	44	19.93
18	11	24.14	39	44	34.28
19	42	34.06			
20	42	18.37			
21	43	14.80			

Chamber of Civil Engineering reported that all concrete samples were extracted and tested under compression following the European standard. Hence the received concrete had the diameter larger than 50 mm.

Figure 3.1: Taking core samples from existing structures ("Concrete Core Drilling," 2014)

Figure 3.2: A selection of concrete core samples that used in this study, (NEU Civil Engineering Laboratory, 2018)

Figure 3.3: Sampling locations, (image prepared by Google Earth Application)

3.2 Testing Method:

3.2.1 Carbonation depth measurement:

It was checked that all samples match the criterion of minimum 50 mm diameter according to BS EN 14630 (2006), then carbonation depth test was decided to take place on all samples. Carbonation depth is measured by using an indicating solution called "Phenolphthalein" that is sprayed on the surface of the concrete samples. The noncarbonated areas with pH level higher than 10 turns to purple color. Otherwise the area will show no color change indicating a low pH and hence being affected by carbonation.

Phenolphthalein solution is prepared by adding 1 g of phenolphthalein powder to 70 ml of Ethyl alcohol, and diluting the whole solution to reach 100 ml by addition of approximately 30 ml of distilled water. The equipment used are shown in Figure 3.4.

Figure 3.4: The equipment that are used for phenolphthalein solution preparation, (NEU Civil Engineering Laboratory, 2018)

Samples are divided into two equal parts using splitting machine (Figure 3.5), regarding minimizing damages on the sample, Figure 3.6 show the sample after splitting. Then, phenolphthalein solution is sprayed on the whole inner surface of the sample, Figure 3.7 show the samples after splitting and applying phenolphthalein.

After spraying phenolphthalein on split samples, uncolored section depth is measured (the uncolored section is from the upper or lower edge of the sample to the purple colored area as shown in Figure 3.8) by a ruler to the nearest mm, but for higher accuracy, Vernier Caliper tool was used, which can measure divisions of a mm (Figure 3.9). The uncolored section depth is calculated by taking three measurements then calculate and record the mean depth as defined in Equation 3.1. All samples are tested using the same method. Figure 3.8 declares how carbonation depth is measured.

$$d = \frac{x_1+x_2+x_3}{3} \qquad (3.1)$$

Figure 3.5: Splitting tensile machine, (NEU Civil Engineering Laboratory, 2018)

Figure 3.6: Sample after splitting, (NEU Civil Engineering Laboratory, 2018)

Figure 3.7: The samples after splitting and applying phenolphthalein, (NEU Civil Engineering Laboratory, 2018)

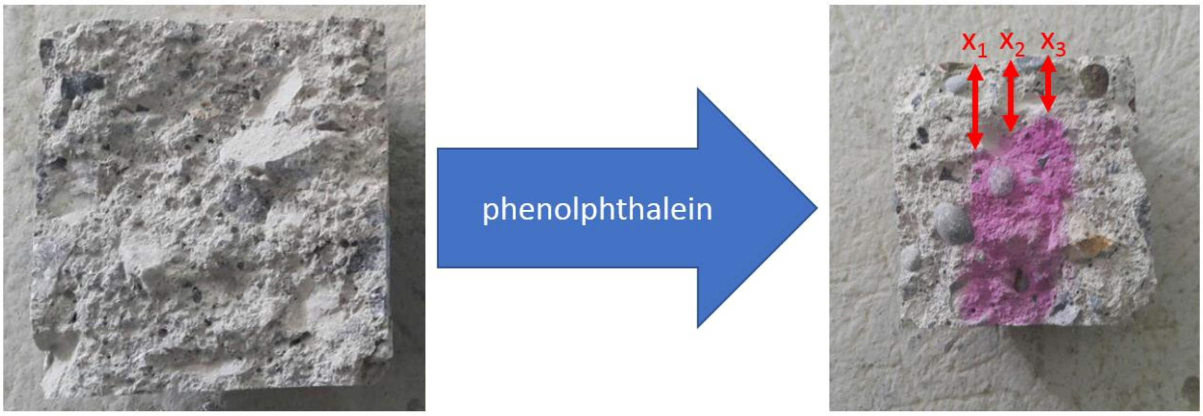


Figure 3.8: The sample after applying phenolphthalein indicator, and measuring of carbonation (red arrows), (NEU Civil Engineering Laboratory, 2018)

Figure 3.9: Measuring the carbonation depth by Vernier caliper, (NEU Civil Engineering Laboratory, 2018)

3.2.2 Carbonation depth calculation:

Carbonation occurs by time, a simplified formula to determine carbonation is provided in Equation 3.2 (Monteiro et al., 2012):

$$k = \frac{D_{carbonation}}{t^{0.5}} \qquad (3.2)$$

where

$D_{carbonation}$ = depth of carbonation from the surface of concrete

k = coefficient of carbonation

t = exposure duration

By this formula, the coefficient of carbonation (k) for each sample is calculated, by provided that the sample's age and current depth, the carbonation are known. From Equation 3.3, carbonation depth could be predicted at the designed age of the structure, or predict the time needed for fully carbonation of the concrete cover before carbonation reaches reinforcement by Equation 3.4:

$$D_{(carbonation)} = k \text{ x } t^{0.5} \quad (3.3)$$

$$t = \left(\frac{D_{carbonation}}{k}\right)^2 \quad (3.4)$$

From Table 4.1, carbonation depth for one of the samples can be predicted after 50 years lifetime, and how long will carbonation take to exceed a 30 mm concrete cover, sample No.5 will be checked, this sample was taken from a regular building, and according to BS EN 1990 (2010), structure's lifetime will be 50 years.

From Equation 3.2 coefficient of carbonation (k) is calculated as:

$$k = \frac{D_{carbonation}}{t^{0.5}} = \frac{26.20}{44^{0.5}} = 3.95 \text{ mm/year}^{0.5}$$

From Equation 3.3 depth of carbonation is calculated in 50 years as:

$$D_{\text{carbonation}} = k \times t^{0.5} = 3.95 \times 50^{0.5} = 27.93 \text{ mm}$$

From Equation 3.4 number of years needed for carbonation to reach depth of 30 mm will be:

$$t = \left(\frac{D_{carbonation}}{k}\right)^2 = \left(\frac{30}{3.95}\right)^2 = 57.69 \text{ years}$$

From Equation 3.2 coefficient of carbonation (k) is calculated as:

$$k = \frac{D_{carbonation}}{t^{0.5}} = \frac{26.20}{44^{0.5}} = 3.95 \text{ mm/year}^{0.5}$$

From Equation 3.3 depth of carbonation is calculated in 50 years as:

$$D_{carbonation} = k \times t^{0.5} = 3.95 \times (50)^{0.5} = 27.93 \text{ mm}$$

From Equation 3.4 number of years needed for carbonation to reach depth of 30 mm will be:

$$t = \left(\frac{D_{carbonation}}{k}\right)^2 = \left(\frac{30}{3.95}\right)^2 = 57.69 \text{ years}$$

According to these results, it was concluded that this structure matches the European specifications, and does not need any special maintenance procedures due to carbonation. Same previous steps are applied for the rest of the samples.

3.2.3 Strength evolution calculations:

According to BS EN1992-1-1 (2014), compressive strength at any age could be determined by Equation 3.5:

$$fcm(t) = \beta_{cc}(t)\ fcm \qquad (3.5)$$

with

$$\beta_{cc}(t) = \exp\left\{s\left[1-\left(\frac{28}{t}\right)^{0.5}\right]\right\} \qquad (3.6)$$

where:

fcm(t): Refers to mean compressive strength for concrete at t days

fcm: Refers to mean compressive strength at 28 days.

$\beta cc(t)$: Is a coefficient that correlated with age of the concrete t.

t: age of the concrete in days.

s: coefficient related to the type of cement and considered as:

0.20 for CEM 42,5 R, CEM 52,5 N and CEM 52,5 R (Class R)

0.25 for CEM 32,5 R, CEM 42,5 N (Class N)

0.38 for CEM 32,5 N (Class S)

Because of the lack of information on used cement specifications, all samples were assumed to be (Class N) with s = 0.25, because by calculations, strength in 28 days for s =0.20, 0.25 and 0.38 resulted as 16.43, 15.63 and 13.72 MPa respectively, that makes choosing the cement with s = 0.25 provides the least variations with other cement types, which make results more acceptable. The significance of the formula is to determine the compressive strength at 28 days, hence predicting compressive strength at any age. For the determination of compressive strength at any age, compressive strength at 28 days most be found first using Equation 3.7:

$$f_{cm} = \frac{f_{cm}(t)}{\beta_{cc}(t)} \tag{3.7}$$

Compressive strength at 28 days and 50 years could be predicted from Table 4.1, hence determining concrete development along this period, sample No.1 will be used from Table 4.1 as an example to determine compressive strength at both ages:

$$\beta_{cc}(t) = \exp\left\{s\left[1-\left(\frac{28}{t}\right)^{0.5}\right]\right\} = \exp\left\{0.25\times\left[1-\left(\frac{28}{44\times 365}\right)^{0.5}\right]\right\} = 1.27038$$

$$f_{cm} = \frac{f_{cm}(t)}{\beta_{cc}(t)} = \frac{20.06}{1.27038} = 15.79 \text{ MPa}$$

After applying previous steps to all samples collected from coastal and inland locations, a graph is performed to illustrate compressive strength development, and establish comparison between all samples from various locations.

3.3 Carbonation Depth Performance Satisfaction According to Eurocode EN1992-1-1

The sample conforms to the EN1992-1-1 (2014) standard specifications for concrete carbonation when the carbonation depth at 50 years lifetime of the structure is less than 30 millimeters, and therefore the reinforcement unreached by carbonation.

CHAPTER 4
RESULTS AND DISCUSSIONS

Belonging to 39 different structures from inland and coastal areas of N. Cyprus, 149 extracted core samples were provided by Chamber of Civil Engineering in TRNC together with their current compressive strength test results. Carbonation depth measurements of all these samples were made on all of these samples in the NEU Civil Engineering laboratory as a part of this thesis study. The samples which had less than 1 mm carbonation, and the samples which had carbonation on the entire sample depth (and probably more) were eliminated. Figure 4.1.a, b, and c show the distribution of structures according to their location, as well as the ratio of eliminated structures at each location (i.e. inland or coastal structures).

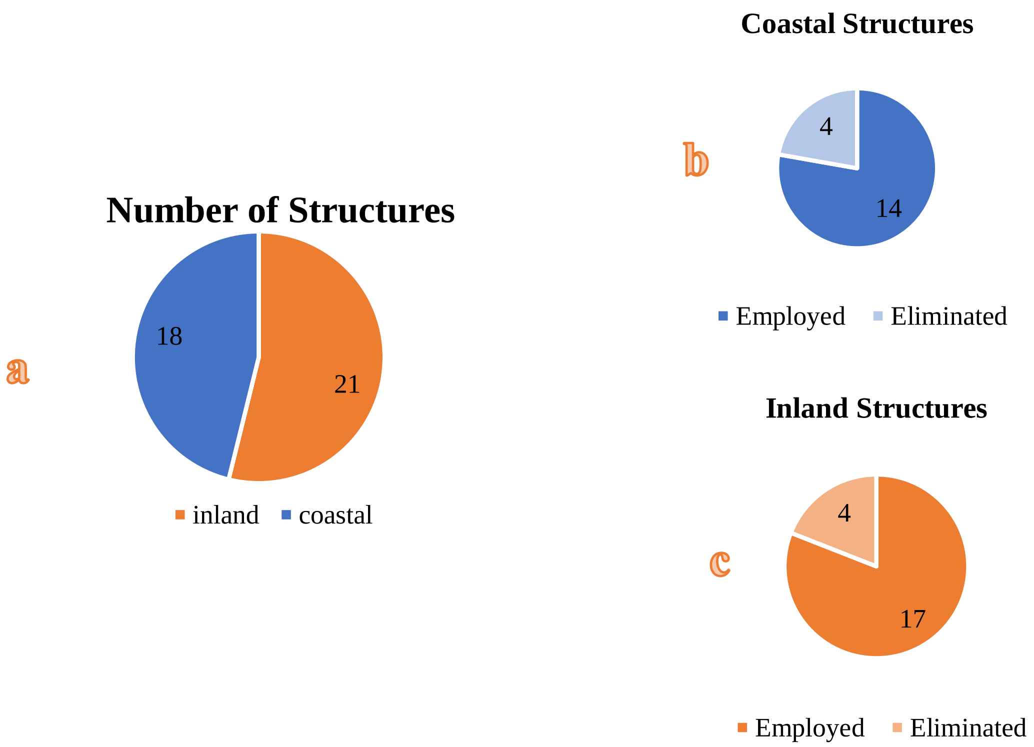


Figure 4.1: (a) general distribution of inland to coastal structures (b) proportional of eliminated structures within inland (c) proportional of eliminated structures within coastal

Experimental results and information regarding the inland and coastal structures are presented in Table 4.1 and 4.2, respectively. Both tables include data for each sample regarding the carbonation depth, age of sample, carbonation coefficient, current compressive strength, compressive strength at 28 days, carbonation depth at 50 years, years needed for 30 mm cover to be carbonated, expected compressive strength at 50 years, and if the sample meets the European standards BS EN 1990 (2010) or not. Samples that are eliminated either because the carbonation depth less than 1 mm, or entire sample depth is fully carbonated are highlighted in Table 4.1 and 4.2. The data given includes the age of samples, and their current compressive strength, while other results were obtained by laboratory experiments or have been calculated.

Table 4.1: 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)	Carbonation Depth Performance Satisfaction According to Eurocodes (yes/no)	Current Strength (MPa)	Theoretically Strength in 28 Days (MPa)
1	44	42.00	6.33	44.77	22.45	no	20.06	15.79
2	4	29.33	14.67	103.71	4.18	no	26.28	21.19
3	46	45.50	6.71	47.44	20.00	no	15.11	11.89
4	28	31.50	5.95	42.09	25.40	no	12.70	10.02
5*	16	63.50	15.88	112.25	3.57	no	25.88	20.50
6	44	26.20	3.95	27.93	57.69	yes	28.96	22.79
7	44	26.13	3.94	27.86	57.98	yes	18.90	14.88
8	8	5.23	1.85	13.08	262.89	yes	29.63	23.65
9	33	41.23	7.18	50.75	17.47	no	32.16	25.35
10	50	22.27	3.15	22.27	90.71	yes	33.35	26.23
11	10	38.60	12.21	86.31	6.04	no	34.99	27.86
12*	44	63.40	9.56	67.58	9.85	no	18.37	14.46
13	18	41.47	9.77	69.11	9.42	no	21.82	17.27
14*	28	72.00	13.61	96.21	4.86	no	15.44	12.18
15	49	65.43	9.35	66.09	10.30	no	15.77	12.40
16	8	3.28	1.16	8.21	667.89	yes	43.55	34.76
17	37	19.40	3.19	22.55	88.48	yes	61.89	48.75
18	11	16.73	5.05	35.68	35.36	no	24.14	19.20
19	42	11.46	1.77	12.50	287.96	yes	34.06	26.81
20	42	46.03	7.10	50.23	17.84	no	18.37	14.46
21*	43	76.00	11.59	81.95	6.70	no	14.80	11.64

* Note: highlighting refers to eliminated structures

Table 4.2: Carbonation depth and compressive strength information for coastal 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)	Carbonation Depth Performance Satisfaction According to Eurocodes (yes/no)	Current Strength (MPa)	Theoretically Strength in 28 Days (MPa)
22	4	3.50	1.75	12.37	293.88	yes	32.17	25.94
23	4	7.37	3.68	26.05	66.34	yes	32.85	26.48
24	4	1.38	0.69	4.88	1890.36	yes	23.90	19.27
25	4	2.25	1.13	7.95	711.11	yes	30.43	24.53
26	4	6.17	3.08	21.80	94.67	yes	29.12	23.47
27	44	33.83	5.10	36.07	34.59	no	20.32	15.99
28	44	46.27	6.97	49.32	18.50	no	27.98	22.02
29	3	10.58	6.11	43.19	24.12	no	35.57	28.84
30	14	8.47	2.26	16.00	175.77	yes	38.58	30.61
31	22	25.53	5.44	38.49	30.37	no	25.14	19.87
32	4	1.73	0.87	6.13	1198.22	yes	44.92	36.22
33*	46	72.70	10.72	75.79	7.83	no	19.17	15.09
34*	23	73.00	15.22	107.63	3.88	no	13.87	10.96
35	44	18.57	2.80	19.79	114.88	yes	22.25	17.51
36*	3	0.00	0.00	0.00	Not Applicable**	Not Applicable**	26.00	21.07
37*	26	0.00	0.00	0.00	Not Applicable**	Not Applicable**	41.55	32.80
38	44	25.32	3.82	26.99	61.78	yes	19.93	15.68
39	44	6.92	1.04	7.38	826.96	yes	34.28	26.98

* Note: highlighting refers to eliminated structures
** Note: Not Applicable refers to the samples that had less than 1 mm carbonation

4.1 Results of Carbonation Depth Measurements

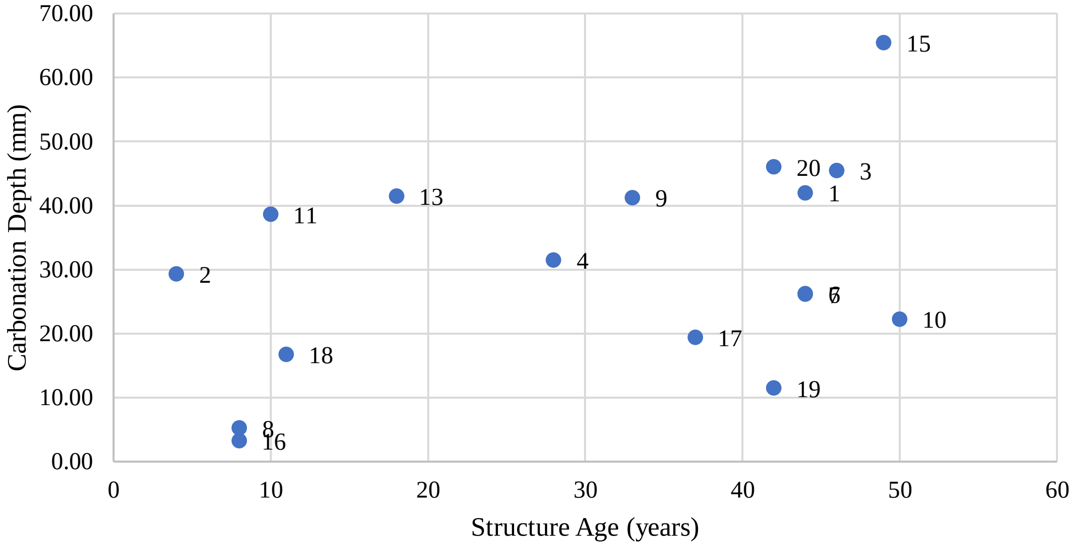


Figure 4.2: Current carbonation depth of inland structures at their current ages (the numbers refer to the building numbers listed in Table 4.1; structures no. 1-20)

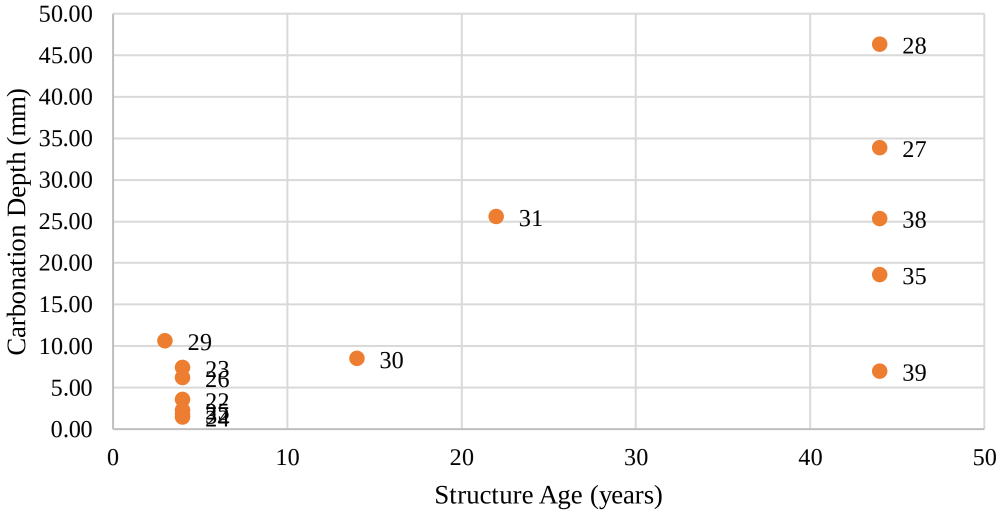


Figure 4.3: Current carbonation depth of coastal structures at their current age (the numbers refer to the building numbers listed in Table 4.2; structures no. 22-39)

Figures 4.2 and 4.3 show the comparisons between structures' ages and carbonation depths for inland and coastal areas, respectively. Carbonation depth is obtained to increase proportional with time. The values in Figure 4.2 and 4.3 refer to the structure number in Table 4.1 and 4.2.

By calculating carbonation coefficient from (Eq.3.2), and the expected carbonation depth at 50 years from (Eq. 3.3), and carbonation time needed to exceed 30 mm depth were determined by (Eq. 3.4). It was found that in inland areas only 41% of samples had not exceeded 30 mm, while in coastal areas the corresponding percentage was 71%.

In some samples, the depth of carbonation in concrete at the same age varies, though it is in the same area. This might be due to having influential factors other than the climate exposure conditions, such as characteristic compressive strength of the concrete used. As it is known, the concrete having low compressive strength include more porosity, enabling the progress of carbonation at a higher tare. The relationship between compressive strength and carbonation rate is illustrated in Figure 4.7 and 4.8. There might be exceptions due to other factors, such as missing information, sheltered / not sheltered structural elements, inside or outside the structure.

Figure 4.4 illustrates the carbonation depth for inland structures at current age and carbonation at the age of 50 years, also it represents the time required to reach 30 mm of carbonation depth for each structure. According to BS EN 1990 (2010) standard, the carbonation depth for any structure should not reach 30 mm before the age of 50 years. However, in the case of sample 1, 2, 3, 4, 9, 11, 13, 15, 18, and 20 that actually represent carbonation reaching 30 mm in these structures, the carbonation had reached 30 mm depth before age of 50 years, but for samples 6, 7, and 17 the carbonation depth is predicted to be 27.93, 27.86, and 22.55 mm at 50 years respectively. In addition to these, the carbonation depth of sample 10 at its current age which is 50 years is already less than 30 mm and equal to 22.27 mm. Furthermore, sample 8, 16, and 19 are estimated to age more than 100 years to reach 30 mm carbonation depth. So, 41 % of inland structures are observed to comply with requirements, while 59 % are observed to fail the criteria.

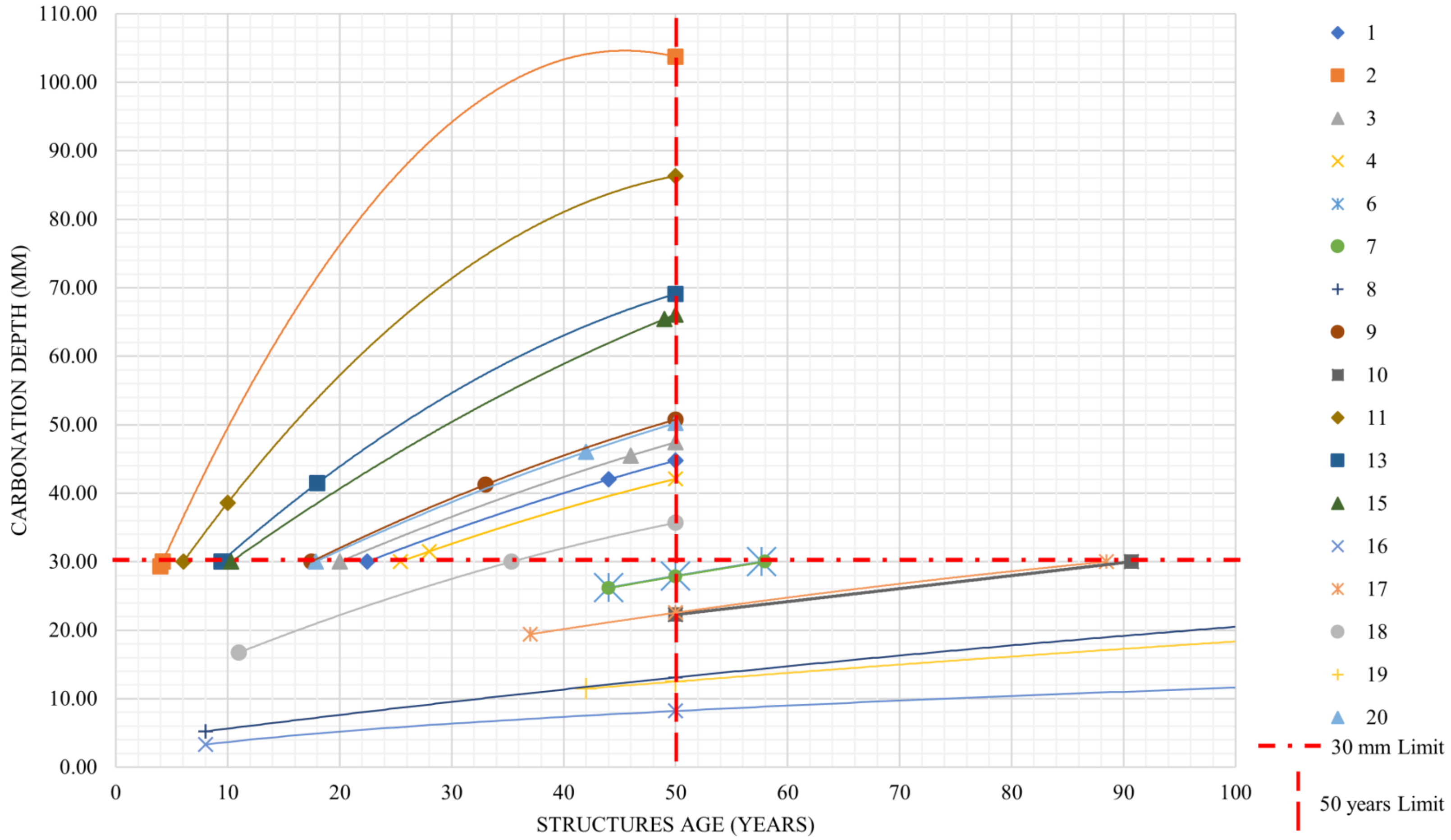


Figure 4.4: Carbonation depth for inland structures at current age, at 50 age years and the time required to reach 30 mm of carbonation depth

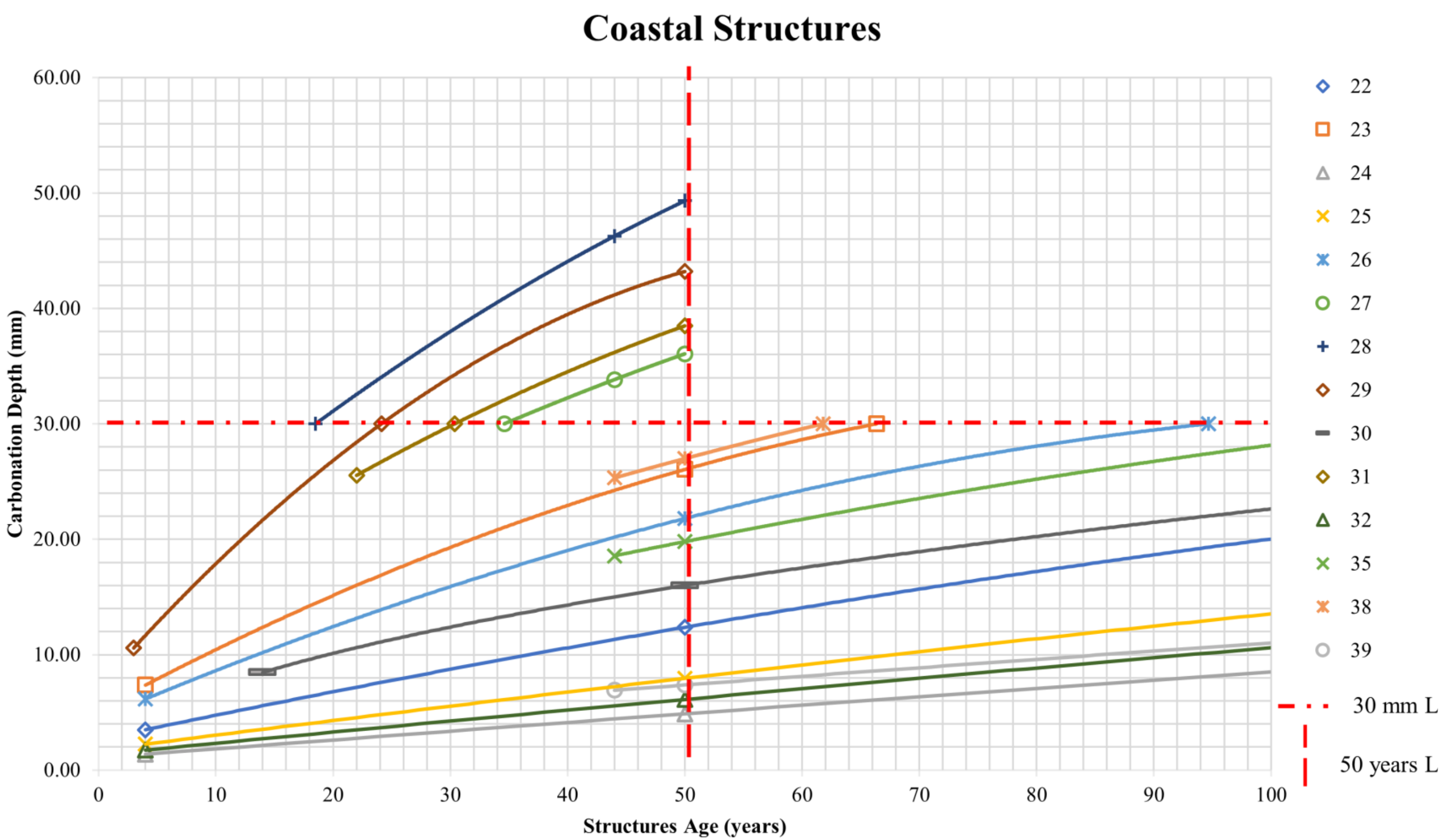


Figure 4.5: Carbonation depth for coastal structures at current age, at 50 years age and the time required to reach 30 mm of carbonation depth

Figure 4.5 represents same information as Figure 4.4 but in case of carbonation in coastal structures. However sample 27, 28, 29, and 31 had reached 30mm carbonation before age of 50 years but in the case of sample 23, 26, and 38 the predicted carbonation depth at 50 years is less than 30mm which is complying with BS EN 1990 (2010) standard, furthermore sample 22, 24, 25, 30, 32, 35, and 39 needs more than 100 years to reach 30 mm carbonation depth. So, 71% of coastal structures are observed to comply with requirements, while 29% are observed to fail the criteria.

These results suggest that the inland structures in Cyprus are more prone to the damage due to carbonation than coastal structures. Results reported by Alexander et al. (2007) also agrees with the findings of this thesis study. Figure 4.6 shows that the number of samples in coastal areas are complying with the European standard more than the samples in inland areas and vice-versa for non- complying structures.

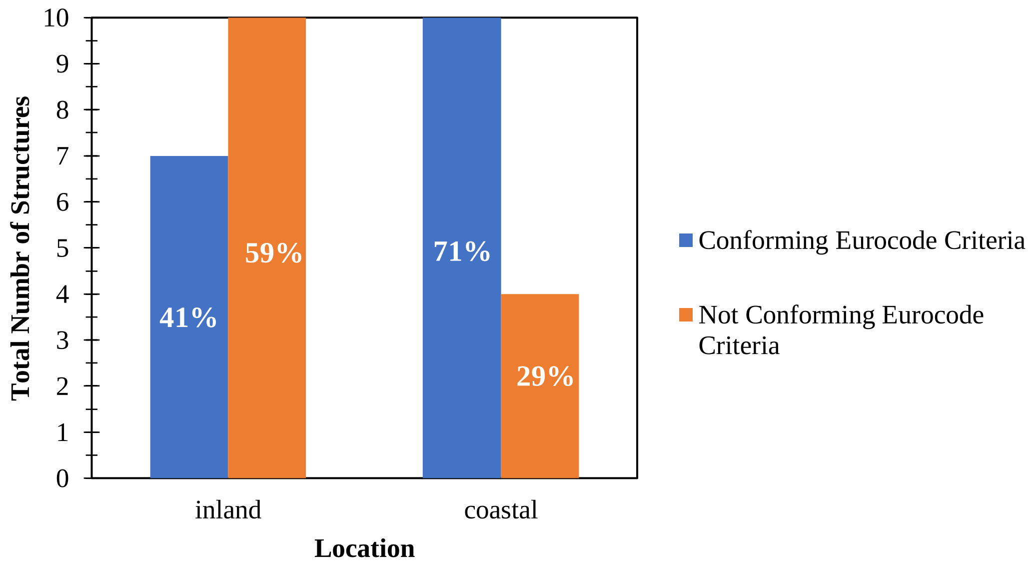


Figure 4.6: Comparison diagram of conforming and non- conforming samples in both inland and coastal areas

4.2 Results of Compressive Strength Calculations

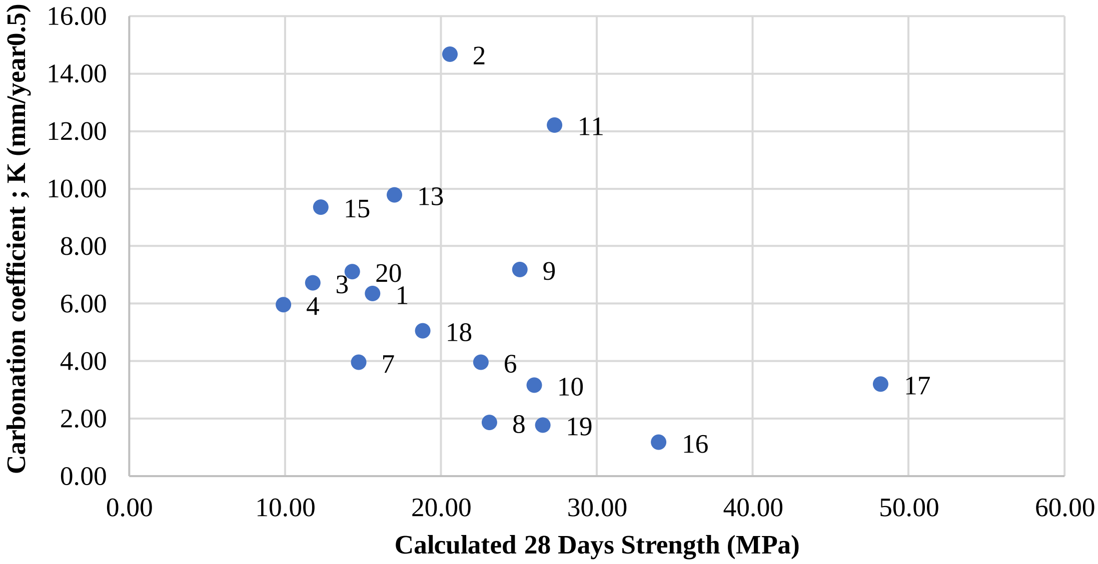


Figure 4.7: Compressive strength at 28 days versus carbonation coefficient for inland structures (the numbers refer to the building numbers listed in Table 4.1; structures no. 22-39)

Figure 4.7 and 4.8 show a decreasing tendency of carbonation coefficient with increasing compressive strength at 28 days age. This finding supports the conventional civil engineering experience which recommends to use higher compressive strength concrete when exposed to aggressive environments. In this way, the structure can manage to reach designed lifetime, Li et al.(2018) has also reported a similar observation. Figure 4.7 and 4.8 also illustrates the carbonation coefficient in inland and coastal areas, where the carbonation rate is generally higher in inland areas than in coastal areas.

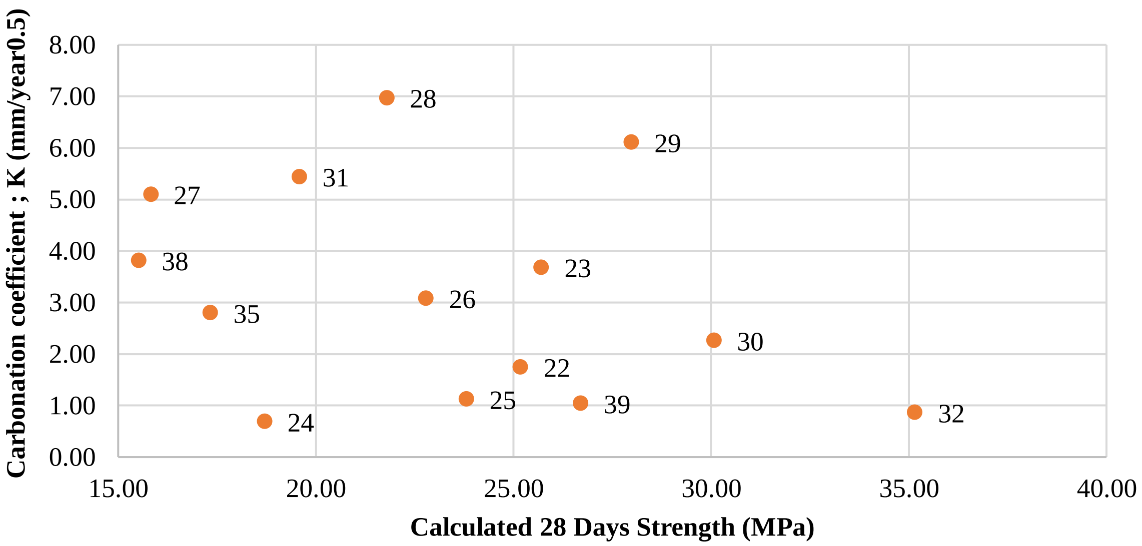


Figure 4.8: Compressive strength at 28 days versus carbonation coefficient for coastal structures (the numbers refer to the building numbers listed in Table 4.2; structures no. 22-39)

4.3 Correlation Between Compressive Strength and Carbonation Depth Performance

By calculations prepared, it was observed that for structures located among inland areas, samples that achieved 21.2 MPa or higher compressive strength at age 28 days, these samples showed satisfactory carbonation according to Eurocode by error margin of 9.5% , so samples with 28 days compressive strength of 21.2 MPa or higher are considered safe; while for structures located among coastal areas, calculation prepared showed that samples with 22.1 MPa or higher compressive strength at age of 28 days showed satisfactory carbonation according to Eurocode with an error margin of 5.88%, thus samples that achieve a compressive strength of 22.1 MPa or higher at 28 days are considered safe.

CHAPTER 5
CONCLUSSIONS AND RECOMMENDATIONS

This study includes experimental and theoretical investigations on 149 samples gathered from 39 existing reinforced concrete structures distributed along N. Cyprus, including inland areas such as Nicosia and coastal areas such as Famagusta and Kyrenia. These samples were gathered by Laboratory of Chamber of Civil Engineering in TRNC for strength examination. The depth tests took place in laboratory of Civil Engineering department at Near East University.

The following conclusions were drawn as results of experiments and calculations made:

1. Concrete carbonation rate in coastal areas has been observed to be lower in comparison with inland areas, expectedly due to external factors like higher relative humidity.
2. Carbonation Coefficient (k) has been observed to be inversely proportional with compressive strength, where the higher 28 days compressive strength is, the lower the carbonation constant is estimated.
3. Results indicate that the investigations on existing structures status leads to possibilities of predicting duration for new structures in which carbonation does not reach reinforcement, or predicting the age of an existing structures in which carbonation will reach the reinforcement.
4. The safe 28 days characteristic compressive strength values for inland and coastal regions are determined as 21.2 and 22.1 MPa respectively.

Considering the results and observations made in this thesis study, the following recommendations for future studies can be done:

Reproducing similar studies comparing inland and coastal exposure conditions on carbonation progress varying in countries having more varying conditions has the potential to provide further data on the subject and hence, the understanding on the carbonation progress in concrete might be increased. Recording designed and actual (i.e. on site) characteristics strength values, as well as concrete mix design information of the structures in a systematical and official manner (i.e. by the Chamber of Civil Engineers), could be beneficial for future studies aiming to provide understanding on the durability performance and strength evolution of reinforced concrete structures in Cyprus.

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