

Nordic Concrete Research	
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Quantifying CO₂ Emission and Sequestration in Outdoor and Indoor Concrete Structures



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ABSTRACT

Accurate quantification of concrete carbonation is critical for Life Cycle Assessments (LCA) and structural diagnostics of urban infrastructure. This reality case study at Linköping University's Norrköping campus utilizes high-resolution ThermoGravimetric Analysis (TGA) to evaluate CO₂ sequestration concrete structure exposed to Nordic climate. Through incremental depth profiling (0-4.5 cm), the study compares an outdoor wall (constructed in the 1950s and 2004) and an indoor parking floor (constructed in 1997).

The TGA results enabled the quantification of calcium hydroxide depletion and calcium carbonate formation, providing a chemically based assessment of carbonation progression. The outdoor wall exhibited significantly higher carbonation levels, reaching a maximum CO₂ uptake of 7.75 %, whereas the indoor parking floor showed limited carbonation, with values as low as 0.70 %. These results indicate that environmental exposure conditions, particularly moisture availability and atmospheric interaction, exert a stronger influence on carbonation kinetics than the chronological age of the concrete.

The depth-resolved thermogravimetric profiles also enabled identification of a partial carbonation zone within the outdoor structure. The study demonstrates that TGA provides a reliable method for assessing carbonation states in existing concrete structures and offers useful insights into the CO₂ sequestration potential of aging urban infrastructure under Nordic environmental conditions.

Key words: Carbonation, CO₂ sequestration, Thermogravimetric Analysis (TGA), Nordic climate, Urban infrastructure.

1. INTRODUCTION

Concrete is the cornerstone of modern infrastructure and the second most consumed substance on earth, surpassed only by water [1]. Current global cement production—the primary binder in concrete—is approximately 4.1 billion tons per year [2], corresponding to an estimated 30 billion tons of concrete annually. This consumption is projected to drive demand even higher, with global concrete production expected to increase by 12 % to 23 % by 2050 [3] to support an urbanizing population of 9.7 billion people [4]. This demand of concrete is attributed to its unique engineering properties, including exceptional high compressive strength (typically ranging from 20 to 40 MPa for residential use and exceeding up to 100 MPa for high-performance infrastructure), durability, fire resistance and thermal mass [5-7]. The availability of the raw material such as aggregates and water close by significantly reduces transportation-related carbon footprints compared to materials like timber or steel, which often require international shipping [8]. While aggregates and water are often available locally, the environmental footprint is significantly influenced by the transport of cement clinker, which may still require substantial shipping. Moreover, its ubiquity comes at a staggering environmental cost. The cement industry is responsible for approximately 6-8 % of global anthropogenic CO₂ emissions [1]. As the world strives to meet the climate goals set by the Paris Agreement, the construction sector is under immense pressure to decarbonize. Most of the emissions (approximately 85 %) originate from the production of Portland cement clinker, which releases CO₂ as the calcium carbonate decomposed. When considering typical cement compositions and mix designs, this corresponds to approximately 0.1 kg CO₂ per kg of concrete [9-11]. As a result, reducing the carbon footprint of concrete has become a major focus in the context of global climate targets.

In contrast to its emissions during production, concrete possesses the unique, intrinsic ability to re-absorb atmospheric CO₂ throughout its service life and post-demolition phase through carbonation. This process involves the diffusion of CO₂ into the pore structure of concrete, where it dissolves in pore water and reacts with hydration products such as calcium hydroxide and calcium silicate hydrates to form calcium carbonate. Global estimates suggest that cement-based materials produced between 1930 and 2013 have reabsorbed approximately 4.5 Gt of carbon, partially offsetting process emissions [12]. However, carbonation is often excluded from Life Cycle Assessments (LCA) and national greenhouse gas inventories due to uncertainties in modelling and a lack of reliable field-based data [13,14].

Carbonation is governed by both material properties and environmental conditions, including pore structure, moisture availability, and CO₂ exposure [14]. The fundamental influences of relative humidity and temperature on these kinetics are well-documented in established literature, such as Neville [15] and Betonghandboken [16]. The reaction is typically most active at intermediate relative humidity levels (approximately 60-80 %), where sufficient pore water enables CO₂ dissolution while maintaining adequate gas permeability [14]. At lower humidity, carbonation is limited by insufficient moisture for CO₂ dissolution, whereas at higher humidity levels, pore saturation restricts CO₂ diffusion [14]. In addition, material parameters such as water-to-cement ratio and pore connectivity significantly influence carbonation rates, with higher porosity generally promoting faster CO₂ ingress [17-20].

While carbonation is generally considered detrimental in reinforced concrete, both indoors and outdoor, due to reduced alkalinity and the risk of reinforcement corrosion [21-23], it can be beneficial in non-structural elements. In such cases, the formation of calcium carbonate leads to densification of the microstructure, reduced porosity, and improved surface hardness and durability [24]. Furthermore, carbonation represents a natural CO₂ uptake mechanism,

contributing to the long-term sequestration of atmospheric carbon in cement-based materials [12]. A schematic illustration of the carbonation process and its representation in ThermoGravimetric Analysis (TGA) is shown in Figure 1. TGA enables the quantification of carbonation by measuring mass loss associated with the thermal decomposition of calcium carbonate and calcium hydroxide, providing a direct chemical assessment of CO₂ uptake in concrete [24].

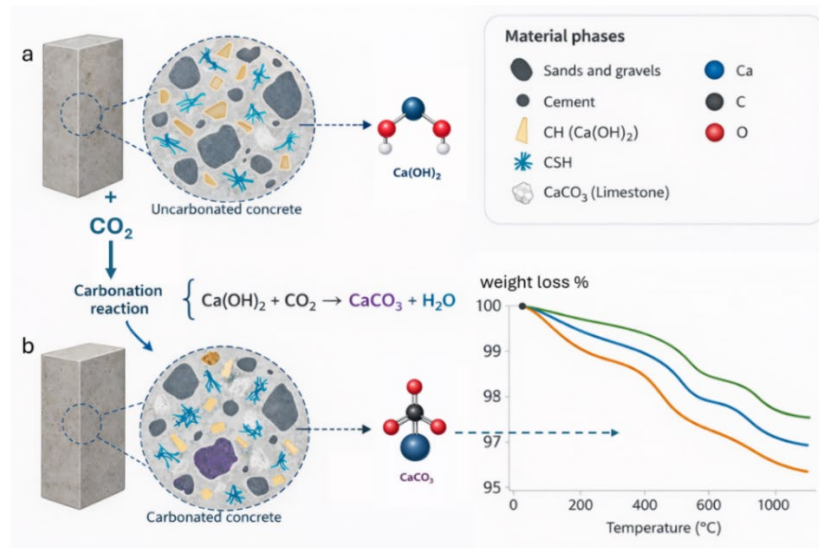


Figure 1 - Carbonation process in concrete. a) illustration of uncarbonated concrete. b) concrete after carbonation and schematic illustration of carbonation in concrete and its representation in thermogravimetric analysis (TGA), showing the transformation of Ca(OH)₂ to CaCO₃ and the corresponding mass loss during heating, is provided in Sections 3 and 4. [15].

This study aims to bridge the gap between theoretical estimation and empirical reality by utilizing precise quantification method of TGA. Concrete samples were collected from non-structural elements at Linköping University's Norrköping campus, including an outdoor wall and an indoor parking floor, representing different exposure conditions and service ages. By applying incremental depth profiling between 0 to 4.5 cm, the study evaluates carbonation gradients, identifies the partial carbonation zone, and quantifies CO₂ uptake under Nordic climatic conditions. The results provide insight into the influence of environmental exposure on carbonation kinetics and the potential role of existing concrete infrastructure as a long-term carbon sink.

2. RESEARCH METHODOLOGY

ThermoGravimetric Analysis (TGA Discovery 550) was used to quantify the CO₂ uptake quantification. Pulverized concrete samples were heated from ambient temperature to 900 °C with 10 °C/min increase rate while continuously monitoring its weight.

Samples were obtained from buildings at Linköping University (campus Norrköping), from basement indoor car park represents a specific micro-environment, and outdoor walls, representing typical Nordic semi-urban environments. Concrete powder samples were collected using the profile drilling (incremental sampling) method, which is commonly applied in forensic investigations of concrete to evaluate depth-dependent chemical changes such as carbonation and chloride ingress. A total of six sampling positions were selected across the two structures. At each position, a single drill hole was produced to collect powdered material at three depth intervals: 0–

1.5 cm, 1.5–3.0 cm, and 3.0–4.5 cm. This single-hole incremental approach was strictly maintained to preserve the resolution of the carbonation gradient and prevent the data dilution that occurs when homogenizing powders from multiple adjacent locations. These depth increments allow the evaluation of carbonation gradients from the surface toward the interior of the concrete.

To prevent cross-contamination between depth increments, the drill hole was cleaned after each sampling step using a portable vacuum or compressed air to remove residual powder before continuing to the next depth. This procedure ensured that the collected material corresponded to the specific depth interval. Three drill holes were produced at each sampling location, and powder was collected from the three defined depth intervals in each hole, resulting in 18 depth-resolved samples across two investigated structures. Sampling was conducted at two locations with different construction periods. The indoor parking floor (PS1-PS3) was constructed in 1997. The outdoor wall consists of two concrete types: WS1 and WS2, constructed in the 1950s, and WS3, constructed in 2004. These structures provide concrete samples with different exposure histories and ages for carbonation assessment.

A key objective of this study was to evaluate the carbonation state of existing infrastructure through 'blind' chemical analysis, specifically when original mix designs, binder types, and water-to-cement ratios are no longer available. Due to the non-structural but integrated nature of the sampled walls and floors, destructive testing (such as core extraction) to determine the compressive strength class was not possible. Consequently, the TGA method was employed as a non-dependent diagnostic tool to characterize the material based solely on its current chemical profile.

3. RESULT

3.1 TGA thermograms and identification of decomposition phases

Thermogravimetric analysis was performed on the 18 powdered samples collected from the constructions at campus Norrköping. Representative ThermoGravimetric (TG) and Derivative ThermoGravimetric (DTG) curves for the surface layer (0-1.5 cm) are presented in Figure 2 for the outdoor wall (Figure 2a) and the indoor parking floor (Figure 2b). These samples were selected to illustrate the characteristic thermal decomposition behaviour and the extent of carbonation near the exposed surface. The thermogravimetric profiles of the samples follow the established sequential decomposition of cementitious compounds described in the literature [25]. As expected, both the samples exhibit initial mass losses below 250 °C, consistent with the evaporation of free water at 105 °C and the subsequent dehydration of calcium silicate hydrates (C-S-H). A second mass-loss region between approximately 350 °C and 450 °C is associated with the dehydroxylation of portlandite ($\text{Ca}(\text{OH})_2$). At higher temperatures, typically between 500 °C and 700 °C, a distinct mass-loss peak is observed corresponding to the thermal decomposition of calcium carbonate (CaCO_3).

Clear differences in the relative intensity of these thermal events were observed between the two investigated environments. The outdoor wall samples exhibit a pronounced DTG peak within the carbonate decomposition range, indicating a higher content of CaCO_3 in the surface layer. In contrast, the indoor parking floor samples show a comparatively weaker carbonate peak and a more distinct portlandite decomposition signal, suggesting that a larger fraction of $\text{Ca}(\text{OH})_2$ remains uncarbonated. These thermogravimetric characteristics confirm that the investigated samples follow the expected decomposition behaviour of hydrated cementitious materials while

also revealing differences in carbonation states between the indoor and outdoor concrete elements. The identified temperature ranges were subsequently used for the quantitative determination of $\text{Ca}(\text{OH})_2$ and CO_2 uptake from the TGA data.

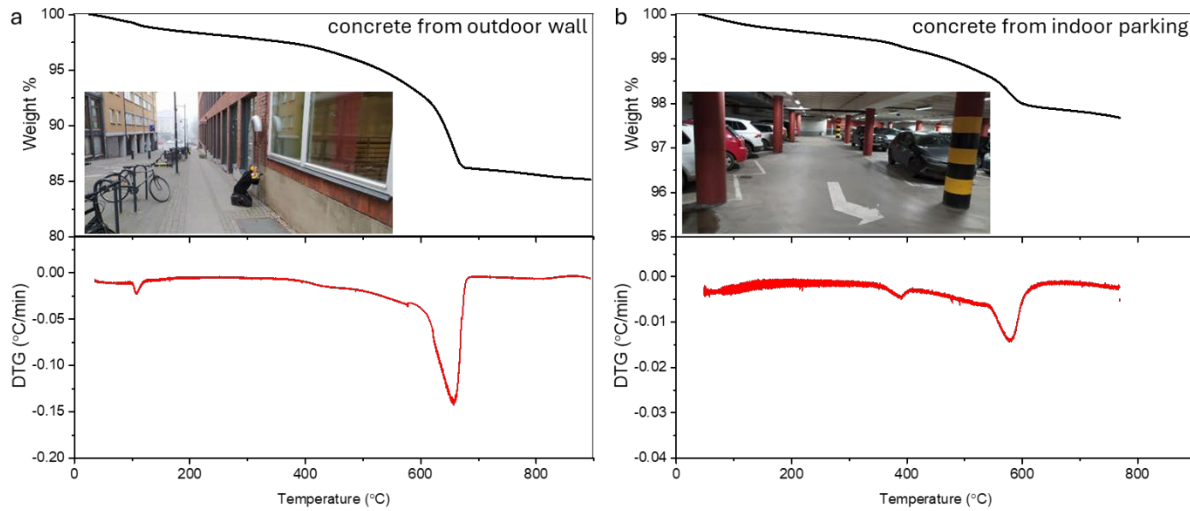


Figure 2 - TGA analysis of concrete samples obtained from a) outdoor wall and b) indoor parking floor. Top panels show the weight loss percentage and bottom panels show the derivative curve versus temperature. Insets show where the samples were taken.

3.2 Quantification of CO_2 uptake and $\text{Ca}(\text{OH})_2$ content

The thermogravimetric data were used to quantify the carbonation level and the remaining portlandite content in the investigated concrete samples. The quantification was based on the mass losses associated with the thermal decomposition of calcium carbonate (CaCO_3) and the dehydroxylation of calcium hydroxide ($\text{Ca}(\text{OH})_2$), identified from the DTG peaks described in Section 3.1. To minimize the influence of residual moisture and loosely bound hydrates, all mass-loss calculations were normalized to the sample mass at 200 °C (W_{200}). This reference temperature excludes the evaporation of free water and the initial stages of C–S–H dehydration typically occurring below 200 °C, providing a stable baseline for chemical quantification.

The CO_2 uptake was calculated from the mass loss associated with the decomposition of CaCO_3 . In this study, CO_2 uptake percent is defined as the amount of CO_2 absorbed by the concrete matrix relative to the stable weight of the pulverized sample at 200 °C (W_{200}). This normalization minimizes the influence of residual moisture and allows for a direct chemical comparison between samples of different ages and exposure histories. For the outdoor wall samples, the carbonate decomposition interval was defined between 575 °C and 700 °C, while for the indoor parking floor samples the interval 565 °C to 600 °C was used based on the observed DTG peak positions (Table 1). The CO_2 uptake was calculated as:

$$\text{CO}_2 \text{ Uptake}[\%] = \left[\frac{\Delta W_{(\text{carbonate})}}{W_{200}} \right] \times 100 \quad (1)$$

where $\Delta W_{(\text{carbonate})}$ represents the mass loss within the carbonate decomposition temperature interval.

The $\text{Ca}(\text{OH})_2$ content was determined from the mass loss related to the dehydroxylation reaction. The stoichiometric relationship between $\text{Ca}(\text{OH})_2$ and the released H_2O was applied using the

molecular mass ratio: ($M_{\text{Ca(OH)}_2}/M_{\text{H}_2\text{O}} = 74.09/18.01 = 4.11$). Hence the Ca(OH)_2 content can be calculated as:

$$\text{Ca(OH)}_2 [\%] = \left[\frac{\Delta W_{\text{CH}}}{W_{200}} \right] \times 4.11 \times 100 \quad (2)$$

where $\Delta W_{\text{(CH)}}$ represents the mass loss measured in the portlandite decomposition range (Table 1). The temperature intervals used for the calculations were determined from the DTG curves by identifying the onset and offset temperatures of each decomposition peak. These intervals were subsequently applied consistently for the quantitative analysis of all samples, as summarized in Table 2.

Table 1 – Thermal decomposition windows.

Sample Site	Phase	Start Temp (°C)	End Temp (°C)
Outdoor Wall	Ca(OH)_2 (Portlandite)	350	408
	CaCO_3 (Calcite)	575	700
Indoor parking floor	Ca(OH)_2 (Portlandite)	380	410
	CaCO_3 (Calcite)	565	600

Table 2 – The mass loss from TGA analysis of samples from outdoor walls and indoor parking floor. Multiple TGA measurements were conducted for the same sample type to ensure reproducibility, the results here show example of one measurement from each obtained sample.

Place	Specification										
	Sample	Depth (cm)	age	W _{ref} (mgr)	W _{CH1} (mgr)	W _{CH2} (mgr)	W _{carbonate1} (mgr)	W _{carbonate2} (mgr)	CaCO ₃ Content (%)	CO ₂ Uptake (%)	Ca(OH) ₂ Content (%)
Outdoor Wall	WS1D1	0.0 – 1.5	70	18.44	Without peak	Without peak	17.57	16.14	17.59	7.75	~0
	WS1D2	1.5 – 3.0		17.61	17.54	17.49	17.27	16.98	3.69	1.62	1.10
	WS1D3	3.0 – 4.5		13.10	12.99	12.93	12.76	12.66	1.82	0.80	2.04
	WS2D1	0.0 – 1.5	70	14.56	Negligible	Negligible	13.93	13.17	11.87	5.23	~0
	WS2D2	1.5 – 3.0		13.94	13.83	13.77	13.34	13.12	3.58	1.58	1.68
	WS2D3	3.0 – 4.5		18.62	18.54	18.47	18.22	18.19	0.38	0.17	1.66
	WS3D1	0.0 – 1.5	20	17.78	17.61	17.44	17.38	16.87	6.51	2.87	3.86
	WS3D2	1.5 – 3.0		12.69	12.67	12.63	12.55	12.53	0.30	0.13	1.10
	WS3D3	3.0 – 4.5		11.55	11.49	11.46	11.31	11.25	1.08	0.48	1.35
Indoor Parking floor	PS1D1	0.0 – 1.5	30	17.13	17.20	17.05	16.95	16.83	1.59	0.70	3.65
	PS1D2	1.5 – 3.0		12.09	12.01	11.89	11.67	11.59	1.45	0.64	4.32
	PS1D3	3.0 – 4.5		13.89	13.83	13.71	13.60	13.55	0.69	0.30	3.52
	PS2D1	0.0 – 1.5	30	11.17	11.12	11.07	10.91	10.77	2.91	1.28	1.69
	PS2D2	1.5 – 3.0		11.41	11.36	11.32	11.14	11.11	0.66	0.29	1.51
	PS2D3	3.0 – 4.5		12.42	12.37	12.33	12.24	12.22	0.26	0.11	1.42
	PS3D1	0.0 – 1.5	30	18.11	18.00	17.90	17.49	17.17	3.99	1.76	2.07
	PS3D2	1.5 – 3.0		11.53	11.40	11.29	11.00	10.88	2.44	1.08	4.13
	PS3D3	3.0 – 4.5		16.40	16.23	16.09	15.68	15.63	0.66	0.29	3.43

3.3 Depth-dependent carbonation profiles

Examples of the thermogravimetric profiles of the samples from outdoor wall (WS) and the indoor parking floor (PS) are shown in Figure 3. For each structure, samples were collected at three depth intervals (0-1.5 cm (D1), 1.5-3.0 cm (D2), and 3.0-4.5 cm (D3)), allowing the evaluation of carbonation gradients from the exposed surface toward the interior of the concrete. The calculated CO₂ uptake and Ca(OH)₂ contents for the investigated samples from the outdoor wall (WS) and the indoor parking floor (PS) are summarized in Figure 4. For the outdoor wall samples, a clear depth-dependent carbonation profile was observed. The highest CO₂ uptake was detected in the

surface layer (0-1.5 cm), where values reached up to 7.8 % in sample WS1D1, and relatively high in WS2D1 (5.2 %). In this region, the portlandite content was close to zero, indicating an advanced stage of carbonation. With increasing depth, the CO₂ uptake decreased significantly, while the Ca(OH)₂ content increased. At the depth interval of 1.5-3.0 cm, intermediate carbonation levels were observed, with moderate CO₂ uptake around 1.5 % and partially preserved portlandite. At the deepest interval (3.0-4.5 cm), the CO₂ uptake decreased further below 1 % and measurable amounts of Ca(OH)₂ were detected, indicating limited carbonation influence at this depth. In contrast, the indoor parking floor samples exhibited substantially lower carbonation levels across all investigated depths. The CO₂ uptake values in the surface layer ranged between 0.7 % and 1.7 %, while significant amounts of Ca(OH)₂ were still present. Only minor changes were observed with increasing depth, and the overall carbonation levels remained low throughout the sampled profile.

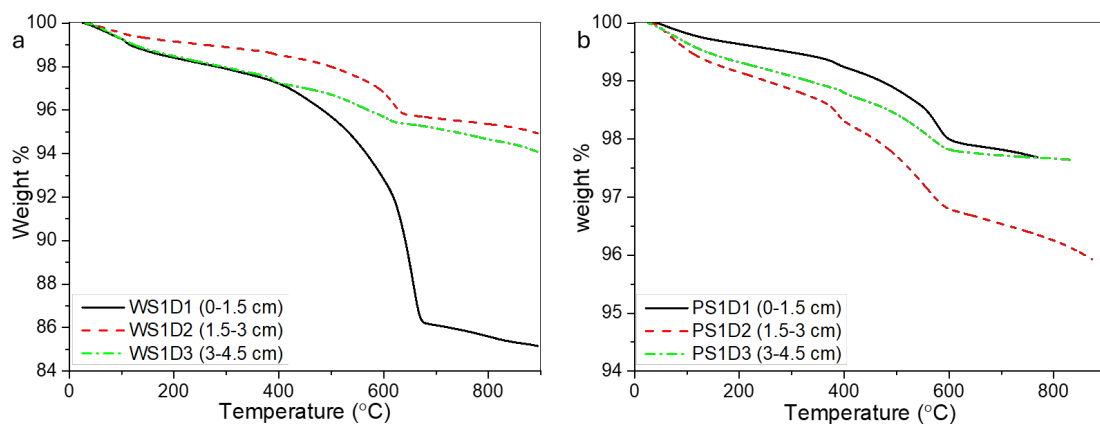


Figure 3 - Examples of TGA analysis of samples obtained from a) outdoor wall and b) indoor parking floor at three different depth.

These results demonstrate distinct differences in carbonation progression between the two investigated structures. The outdoor wall samples show a pronounced carbonation gradient with depth, whereas the indoor parking floor exhibits a relatively uniform chemical profile with limited carbonation. The depth-resolved TGA results therefore provide a quantitative description of carbonation development within the concrete elements. In addition, the variation observed between samples obtained from the same structure at similar depths indicates that the method can reliably capture differences in carbonation states under slightly varying environmental conditions.

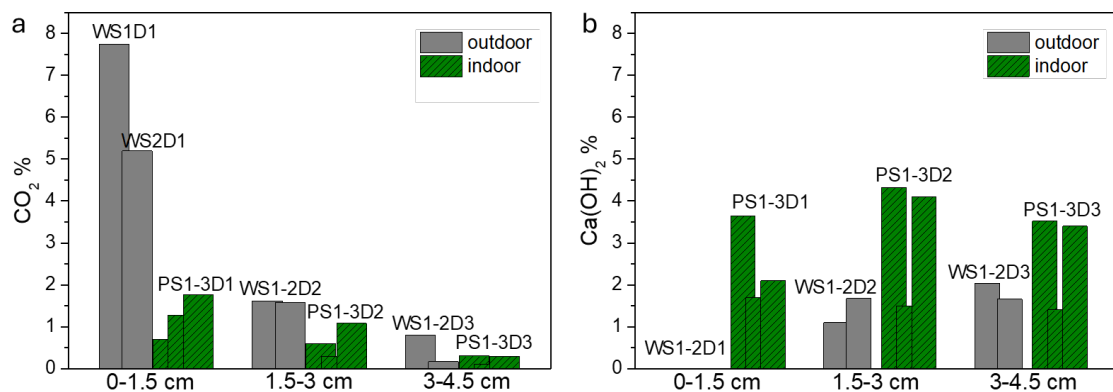


Figure 4 - The content of a) CO₂ and b) Ca(OH)₂ in outdoor and indoor samples at different depth.

3.4 Comparison of carbonation levels at 1.5 cm depth

To compare carbonation levels under different exposure conditions, a detailed analysis was performed for samples collected at the 0-1.5 cm depth interval from both investigated structures. The outdoor wall includes concrete sections constructed in the 1950s (WS1 and WS2) and 2004 (WS3), while the indoor parking floor was constructed in 1997 (PS1-PS3). Figure 5 presents the thermogravimetric profiles of these samples, while the calculated phase contents are summarized in Figure 6. The outdoor wall samples exhibit significantly higher carbonation levels compared with the indoor samples. The highest CO₂ uptake was observed in WS1D1, reaching approximately 7.8 %, while WS2D1 also showed a high carbonation level of 5.2 %. In contrast, the younger outdoor sample WS3D1 exhibited a lower CO₂ uptake of 2.8 %, accompanied by a measurable Ca(OH)₂ content, indicating that carbonation in this section is still progressing. In comparison, the indoor parking floor samples displayed considerably lower carbonation levels. The CO₂ uptake values ranged between 0.7 % and 1.8 %, while significant amounts of Ca(OH)₂ were still present in all samples. These results indicate that carbonation has only occurred to a limited extent in the indoor parking environment.

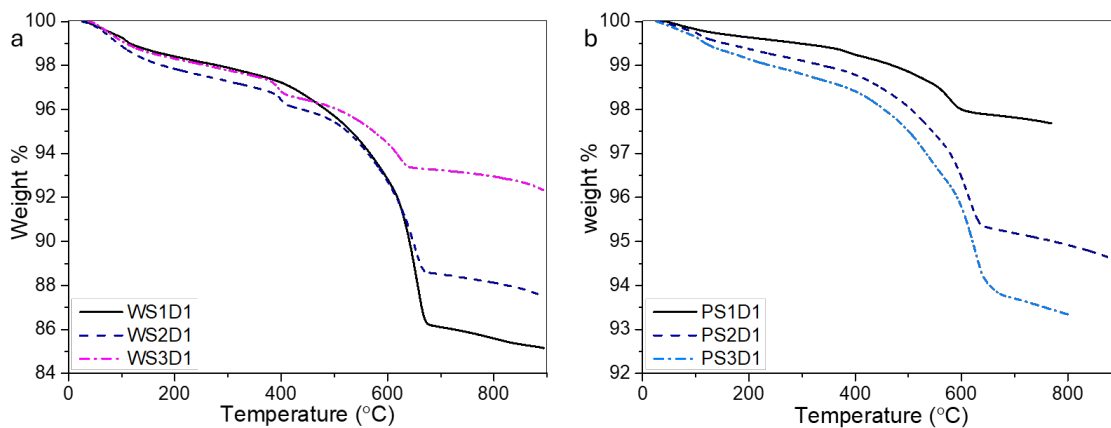


Figure 5 - Comparative TGA profiles for a) outdoor and b) indoor samples at 1.5 cm depth.

The comparison at the same sampling depth therefore highlights a clear difference between the two exposure conditions. The outdoor wall samples show substantial conversion of Ca(OH)₂ into CaCO₃ in the surface layer, whereas the indoor parking floor samples retain a larger fraction of uncarbonated portlandite. This contrast demonstrates the strong influence of environmental exposure on carbonation development in the investigated concrete structures.

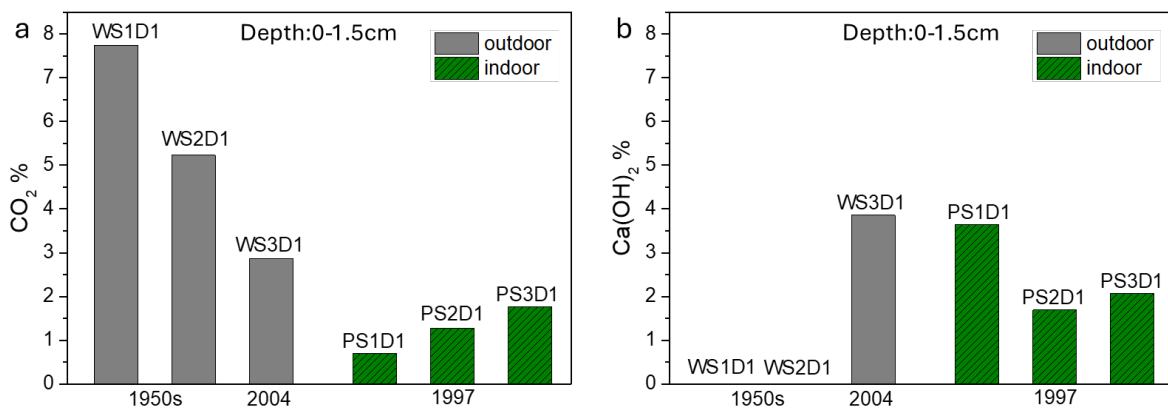


Figure 6 - The content of a) CO_2 and b) Ca(OH)_2 of sample from outdoor and indoor constructs at the depth of 1.5 cm.

4. DISCUSSION

The thermal analysis summarized in Tables 2 provides a quantitative assessment of the carbonation progress. The data reveal a strong contrast between the outdoor wall and the indoor parking floor, primarily governed by the interaction between chronological age and micro-climatic exposure.

4.1 Influence of exposure conditions and structural age

The thermogravimetric results reveal clear differences in carbonation behaviour between the investigated structures. The outdoor wall samples exhibit substantially higher CO_2 uptake compared with the indoor parking floor, particularly within the surface layer (0-1.5 cm). As shown in Tables 2, the outdoor samples reach CO_2 uptake values of up to 7.8 %, while the indoor samples remain below 2 % across all investigated locations. The outdoor wall includes sections constructed in the 1950s (WS1 and WS2) as well as a more recent section from 2004 (WS3), whereas the indoor parking floor was constructed in 1997. Although structural age influences the overall duration of exposure to atmospheric CO_2 , the results indicate that environmental exposure conditions play a dominant role in carbonation progression.

This effect is particularly evident when comparing the younger outdoor sample WS3D1 with the indoor samples. Despite being approximately 20 years old, the outdoor WS3D1 sample shows a CO_2 uptake of 2.9 %, which exceeds the carbonation levels measured in the indoor parking floor samples that are nearly 30 years old. This observation indicates that carbonation in the indoor environment has progressed only to a limited extent despite the longer service period. The higher carbonation levels observed in the outdoor wall can be attributed to continuous exposure to atmospheric CO_2 combined with environmental moisture cycles, which promote the diffusion of CO_2 into the concrete pore structure and facilitate the carbonation reaction. In contrast, the indoor parking floor is sheltered from precipitation and experiences lower humidity variations, conditions that may significantly reduce carbonation rates.

It is important to note that the indoor parking garage investigated in this study does not represent a typical indoor environment. While typical climate-controlled indoor structures often exhibit high carbonation rates due to moderate humidity, the basement parking floor (PS1–PS3) is

sheltered from precipitation and experiences a unique micro-climate. The extremely low humidity in this specific setting likely hindered the dissolution of CO_2 into the pore water, effectively stalling the carbonation process despite the structure's 30-year age. Consequently, these results highlight that carbonation kinetics in 'indoor' structures are highly dependent on the specific micro-environment rather than chronological age alone.

Furthermore, while carbonation-induced corrosion is often limited in dry indoor settings due to insufficient moisture, parking structures present a more complex durability challenge due to the frequent application of deicing salts. The presence of chlorides from these salts can initiate corrosion even at lower humidity levels, especially when the protective alkalinity of the concrete is compromised by carbonation. Consequently, quantifying the carbonation front in these structures via high-resolution TGA remains essential for accurate structural diagnostics and maintenance planning.

These results demonstrate that carbonation progression in existing concrete structures is controlled not only by the duration of exposure but also strongly by the surrounding environmental conditions. The comparison between indoor and outdoor structures therefore highlights the importance of micro-climatic exposure in determining the carbonation state and associated CO_2 sequestration potential of concrete elements. In fact, carbonation kinetics typically stall at relative humidity (RH) levels below 50% due to the lack of pore water needed to dissolve CO_2 . This provides a physical reason for unexpected indoor results.

4.2 Identification of the partial carbonation zone

The depth-resolved thermogravimetric analysis allows the identification of a transition region where carbonation is progressing but has not yet reached completion. This partial carbonation zone is characterized by the simultaneous presence of calcium carbonate (CaCO_3) and unreacted portlandite ($\text{Ca}(\text{OH})_2$), reflecting the ongoing conversion of hydration products during CO_2 ingress. In the outdoor wall samples, this transition zone appears within the 1.5-3.0 cm depth interval, where measurable CaCO_3 formation occurs together with remaining $\text{Ca}(\text{OH})_2$. The coexistence of these phases indicates that the carbonation front has migrated beyond the exposed surface layer but has not yet fully penetrated the concrete matrix. With increasing depth, the decreasing carbonate content and the gradual recovery of portlandite suggest that the influence of atmospheric CO_2 diminishes toward the interior of the element.

In contrast, the indoor parking floor does not exhibit a clearly developed partial carbonation zone within the investigated depth range. The persistence of portlandite and the limited formation of carbonate phases indicate that carbonation has remained confined to a very shallow surface region. This observation suggests that the carbonation front in the indoor structure is located within a thin outer layer that cannot be resolved using the 1.5 cm sampling increments applied in this study. The identification of this transition region highlights the advantage of thermogravimetric analysis for assessing carbonation progression. Rather than defining carbonation as a single boundary, the TGA-based approach reveals the gradual chemical evolution across the carbonation front and provides insight into the spatial distribution of carbonation products within the concrete matrix.

4.3 Reliability of the thermogravimetric analysis

The reliability of the thermogravimetric analysis is supported by the consistent thermal decomposition behaviour observed across the investigated samples. The TG-DTG curves exhibit well-defined and reproducible peaks corresponding to the dehydration of hydrated phases, the dehydroxylation of portlandite, and the decomposition of calcium carbonate. As shown in Figure 7, the TGA curves of concrete sample obtained from the same location show promising reproducibility. The positions of these thermal events remain consistent across the replicate measurements, indicating stable experimental conditions and reliable phase identification.

Additional confidence in the results is provided by the systematic relationship observed between CaCO_3 formation and $\text{Ca}(\text{OH})_2$ depletion. In the outdoor samples, increased carbonation levels correspond to reduced portlandite contents, reflecting the expected stoichiometric conversion during the carbonation reaction. At greater depths, the gradual increase in $\text{Ca}(\text{OH})_2$ together with decreasing carbonate content further confirms the presence of a chemically consistent carbonation gradient.

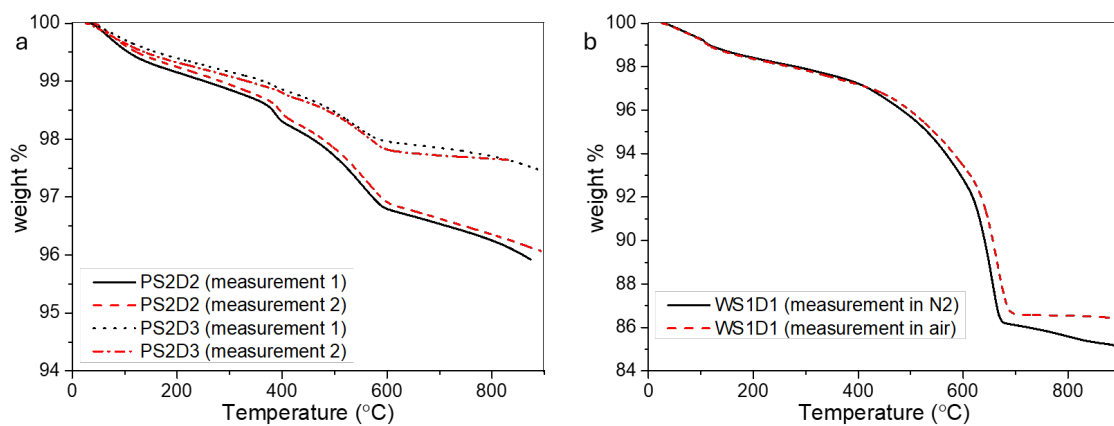


Figure 7- a) comparison of TGA curves of samples from the same locations. b) comparison of TGA curves of samples from the same location measured at N_2 and air environment.

The chemically specific and depth-resolved nature of thermogravimetric analysis enables meaningful interpretation of carbonation processes from targeted samples. Unlike indicator-based carbonation tests that rely on visual pH boundaries and often require extensive spatial sampling, TGA directly quantifies the decomposition of carbonation products and portlandite. In addition, the use of incremental depth profiling enhances the information obtained from each sampling location by capturing carbonation gradients and transition zones within the concrete matrix. The clear and systematic phase relationships observed across the investigated samples therefore provide a robust representation of the carbonation state and CO_2 uptake potential of the studied concrete structures.

While environmental models like SS-EN 16757 utilize concrete strength and moisture as primary inputs, our results suggest that in aging infrastructure, TGA can provide a more direct assessment of CO_2 sequestration when these historical parameters are missing. Furthermore, while instantaneous moisture content was not recorded, the 20-to-70-year exposure history suggests that long-term micro-climatic conditions—specifically the extremely low humidity of the sheltered parking garage—exerted a more significant influence on the carbonation front than the theoretical k -values predicted by standard models.

4.4 Carbon sequestration potential of the investigated concrete structures

The thermogravimetric analysis provides quantitative insight into the role of existing concrete structures as long-term sinks for atmospheric CO₂. The formation of calcium carbonate observed in the surface layers reflects the gradual carbonation of hydration products, primarily through the reaction between atmospheric CO₂ and calcium hydroxide present in the cement matrix.

The outdoor wall samples show a substantially higher degree of carbonation compared with the indoor parking floor. In the most carbonated outdoor samples, the near-complete depletion of Ca(OH)₂ in the surface layer indicates that a large portion of the available portlandite has already reacted to form CaCO₃. This condition represents an advanced stage of carbonation where the concrete matrix has approached its stoichiometric capacity for CO₂ uptake within the exposed zone. In contrast, the indoor parking floor retains significant quantities of unreacted Ca(OH)₂ across the investigated depths, indicating that the carbonation reaction has progressed only to a limited extent. This suggests that a considerable fraction of the theoretical carbonation capacity of the concrete remains unutilized under sheltered environmental conditions.

These observations highlight the strong dependence of CO₂ sequestration in concrete on environmental exposure. Concrete elements subjected to direct atmospheric interaction and moisture cycles may progressively accumulate carbonation products over long service periods, whereas structures located in protected indoor environments exhibit significantly slower carbonation development. The results therefore demonstrate that aging concrete infrastructure can contribute to long-term CO₂ uptake, particularly in outdoor exposure conditions where carbonation reactions are more actively sustained.

4.5 Carbonation kinetics and estimation of the carbonation coefficient

The progression of carbonation in concrete is commonly described by a diffusion-controlled relationship in which carbonation depth increases proportionally to the square root of exposure time:

$$x = k\sqrt{t} \Rightarrow k = \frac{x}{\sqrt{t}} \quad (3)$$

where x is the carbonation depth, t is the exposure time, and k is the carbonation coefficient, typically expressed in mm/year^{1/2}.

The depth-resolved TGA results provide a chemically based indication of carbonation progression, allowing the approximate position of the carbonation front to be inferred from the depletion of Ca(OH)₂ and the formation of CaCO₃. For the outdoor wall, carbonation products were detected across all investigated depth increments, indicating that the carbonation front has progressed beyond the deepest sampled layer. Assuming a carbonation depth of approximately 37.5 mm for the oldest outdoor section (~70 years), an approximate carbonation coefficient of $k \approx 4.5$ mm/year^{1/2} can be estimated. In contrast, the indoor parking floor shows very limited carbonation even at the shallowest sampling depth. Assuming that the carbonation front remains within the first sampling increment (<7.5 mm) after approximately 30 years of service, the corresponding carbonation coefficient is estimated to be $k < 1.4$ mm/year^{1/2}.

The large difference between these values highlights the dominant influence of environmental exposure on carbonation kinetics. The outdoor structure experiences continuous interaction with atmospheric CO₂ and environmental moisture cycles, which promote diffusion and carbonation reactions. In contrast, the sheltered indoor environment significantly limits these processes, resulting in substantially slower carbonation progression. These findings demonstrate that

carbonation rates and consequently the associated CO₂ uptake are strongly governed by micro-climatic conditions in addition to the age of the concrete structure.

According to SS-EN 16757, the carbonation coefficient (k) for indoor concrete is generally expected to be significantly higher than for outdoor concrete exposed to rain, as moisture saturation in outdoor elements typically hinders CO₂ diffusion. However, our empirical TGA results show the opposite trend. This discrepancy highlights the impact of extreme micro-climatic variations. In the investigated indoor parking garage, the lack of moisture may have limited the carbonation reaction to the near-surface layer. This suggests that for aging infrastructure where the concrete strength class and binder type are unknown, empirical TGA profiling provides a necessary correction to theoretical models that may overestimate sequestration in very dry indoor environments or underestimate it in specific outdoor Nordic conditions.

4. CONCLUSIONS

This study demonstrates the effectiveness of thermogravimetric analysis (TGA) for evaluating the carbonation state and chemical evolution of existing concrete structures. By quantifying the depletion of calcium hydroxide and the formation of calcium carbonate, the method provides a reliable chemical characterization of carbonation processes and avoids the limitations associated with conventional indicator-based testing. The depth-resolved TGA profiles enabled the identification of carbonation gradients within the investigated concrete elements and allowed the location of the partial carbonation zone to be determined. The results also showed strong internal consistency between Ca(OH)₂ depletion and CaCO₃ formation, confirming the reliability of the thermogravimetric approach for assessing carbonation in field samples.

A key finding of this study is the dominant influence of environmental exposure conditions on carbonation kinetics. Our findings regarding the dominant influence of environmental exposure over chronological age are consistent with established concrete technology principles. Specifically, the observed carbonation rates under Nordic conditions align with the behavioral trends described in *Betonghandboken* and Neville's *Properties of Concrete*, where moisture availability serves as the primary governing factor for carbonation kinetics. The outdoor wall samples exhibited significantly higher CO₂ uptake compared with the indoor parking floor, despite differences in structural age. The estimated carbonation coefficients indicate that carbonation in the outdoor environment proceeds substantially faster than in the sheltered indoor structure, highlighting the importance of moisture availability and atmospheric exposure in promoting carbonation reactions under Nordic climatic conditions.

The results further demonstrate that existing concrete infrastructure can act as a long-term sink for atmospheric CO₂ through the formation of calcium carbonate in the surface layers. At the same time, identifying the position of the carbonation front provides valuable information for structural durability assessment. The presented methodology therefore offers a useful tool for evaluating both the environmental and durability implications of carbonation in aging concrete structures.

5. PERSPECTIVE

The quantitative findings of this study demonstrate that the concrete matrix can sequester approximately 8 kg of CO₂ per 100 kg of concrete, or 50 kg per 100 kg of cement (If one assume a concrete density of typical 2300 kg/m³ and 350 kg cement/m³ concrete on arrive at a binding

capacity of 50 kg CO₂/100 kg cement approximately). This capacity enables the development of strategies that move beyond theoretical models toward the direct assessment and optimization of urban carbon sinks. Crushing concrete at the end of its service life to increase exposed surface area is an established technology for maximizing CO₂ uptake through accelerated carbonation . Therefore, by intentionally removing external layers or increasing the surface area of non-reinforced elements, gas diffusion could be accelerated to maximize CO₂ storage over a building's lifespan. This methodology highlights the potential of concrete to contribute to CO₂ uptake through carbonation. By enabling direct quantification of carbon absorption in non-structural elements, this approach offers a practical framework for evaluating both existing and future constructions. The gained insights could support the development of management and design strategies that consider carbonation as part of broader carbon mitigation efforts. In this context, urban concrete infrastructure may play a complementary role in long-term CO₂ sequestration while maintaining the durability requirements of structural materials.

Furthermore, these insights support more nuanced durability assessments. While carbonation-induced corrosion is generally not a problem for reinforced concrete in dry indoor environments due to low moisture availability, parking structures represent a critical exception due to the ingress of deicing salts (NaCl). In such micro-climates, the combined presence of chlorides and carbonation necessitates precise chemical profiling to ensure structural integrity.

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REFERENCES

1. Global Cement and Concrete Association (GCCA): “Concrete Future: The 2050 Global Roadmap to Net Zero CO₂”. London, UK, 2023, 40 pp.
2. U.S. Geological Survey (USGS): “Mineral Commodity Summaries: Cement”. Reston, Virginia, USA, 2024, 216 pp.
3. Worldwide Cement Consumption: “America’s Enduring Strength in a Global Market”. Washington, D.C., USA, 2025, Online Available: [Worldwide Cement Consumption - Volume Concrete - READY MIX CONCRETE PRODUCTS](#).

4. International Energy Agency (IEA): “Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach”. Paris, France, 2024, 226 pp.
5. American Concrete Institute (ACI): “ACI 318- 19: Structural Concrete Building Code Requirements”. Farmington Hills, USA, 2019, 628 pp.
6. National Fire Protection Association (NFPA): “NFPA 5000: Building Construction and Safety Code”. Quincy, USA, 2024, 684 pp.
7. Afaghi M, Klausen A B E. & Øverli J A: “A Review on Fatigue Performance of Concrete Structures Part II, Material Parameters and Environmental Factors”. *Nordic Concrete Research*, Vol. 68, No. 1, 2023, pp. 127–144.
8. National Ready Mixed Concrete Association (NRMCA): “A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by NRMCA Members – Version 3.2”. The Athena Sustainable Materials Institute, Ontario, Canada, 2022, 101 pp.
9. Andrew R M: “Global CO₂ Emissions from Cement Production”. *Earth System Science Data*, Vol. 10, No. 1, 2018, pp. 195-217.
10. Huntzinger D N & Eatmon T D: “A Life-cycle Assessment of Portland Cement Manufacturing: Comparing the Traditional Process with Alternative Technologies”. *Journal of Cleaner Production*, Vol. 17, No. 7, 2009, pp. 668–675.
11. Worrell E, Price L, Martin N, Hendriks C & Meida L O: “Carbon Dioxide Emissions from the Global Cement Industry”. *Annual Review of Energy and the Environment*, Vol. 26, No. 1, 2001, pp. 303–329.
12. Xi F, Davis S J, Ciais P, Crawford-Brown D, Guan D, Pade C, Shi T, Syddall M, Lv J, Ji L, Bing L, Wang J, Wei W, Yang K H, Lagerblad B, Galan I, Andrade C, Zhang Y & Liu Z: “Substantial Global Carbon Uptake by Cement Carbonation”. *Nature Geoscience*, 9 (12), 880–883. (2016).
13. Ashraf W: “Carbonation of Cement-Based Materials: Challenges and Opportunities”. *Construction and Building Materials*, Vol. 120, 2016, pp. 558–570.
14. Lagerblad B: “Carbon Dioxide Uptake during Concrete Life Cycle: State of the art”. Swedish Cement and Concrete Research Institute (CBI), *CBI-Report*, ISSN 0346-8240, 2007, 47 pp.
15. Neville A M: “Properties of Concrete”. 5th Edition, Pearson Education Limited, Harlow, UK, 2011.
16. Betonghandboken: “Material”. Utgåva 2, AB Svensk Byggtjänst, Stockholm, 1997.
17. Peng L, Shen P, Poon C S, Zhao Y & Wang F: “Development of Carbon Capture Coating to Improve the Durability of Concrete Structures”. *Cement and Concrete Research*, Vol. 168, 2023, Article 107154.
18. Wang D, Xiao J & Duan Z: “Strategies to Accelerate CO₂ Sequestration of Cement-Based Materials and their Application Prospects”. *Construction and Building Materials*, Vol. 314, 2022, Article 125646.
19. Strippel H, Ljungkrantz C, Gustafsson T & Andersson R: “CO₂ Uptake in Cement-Containing Products: Background and Calculation Models for IPCC Implementation”. IVL Swedish Environmental Research Institute, No. B2499, ISBN: 978-91-7883-660-4, 2025.
20. Chang C F & Chen J W: “The Experimental Investigation of Concrete Carbonation Depth”. *Cement and Concrete Research*. Vol. 36, 2006, pp. 1760–1767.
21. Hansen E J & Saouma V E: “Numerical Simulation of Reinforced Concrete Deterioration—Part 1: Chloride Diffusion”. *Nordic Concrete Research*, Vol. 96, No. 2, 1999, pp. 173-180.
22. Revert A B, Weerdt K D, Jakobsen U H & Geiker M R: “Impact of Accelerated Carbonation on Microstructure and Phase Assemblage”. *Nordic Concrete Research*, Vol. 59, No. 2, 2018, pp. 111-126.

23. Lahdensivu J, Lahdensivu E & Köliö A: “Case Study on the 20 Years Propagation of Carbonation in Existing Concrete Facades and Balconies”. *Nordic Concrete Research*, Vol. 60, No. 1, 2019, pp. 1–12.
24. Broomfield J P: “Corrosion of Steel in Concrete: Understanding, Investigation and Repair”. 2nd Edition, CRC Press, London, UK, 2003, 296 pp.
25. Scrivener K, Snellings R & Lothenbach, B (Eds.): “A Practical Guide to Microstructural Analysis of Cementitious Materials”. 1st Edition, CRC Press, Boca Raton, USA, 2016, 560 pp.