Nordic Concrete Research – Publ. No. NCR 73 – ISSUE 2/ 2025 – Article 6, pp. 99-120

ISSN online 2545-2819
ISSN print 0800-6377

DOI: 10.2478/ncr-2025-0025

Received: Oct. 1, 2025
Revision received: Nov. 21, 2025
Accepted: Nov. 24, 2025

Sufficient Sampling to Determine the Cover Depth of Reinforcement and Carbonation Depth for In-use and Reclaimed Concrete Elements

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ABSTRACT

This study addresses how many samples are sufficient to reliably estimate the cover depth of reinforcement and the carbonation depth of indoor load-bearing concrete elements. A Monte Carlo simulation with 10,000 iterations for extreme values of real cases was used to evaluate the standard error of the mean for different numbers of samples. To evaluate the cover depth of reinforcement, the simulation results suggest that 150 measurements are statistically sufficient for a certain reinforcement type and for each element type. However, hollow-core slabs can be treated as a distinct population due to their consistently low variability in cover depth. Reliable preliminary estimate can be obtained with only 10 measurements, while 30 measurements are sufficient to achieve high statistical reliability. To estimate the carbonation depth, 12-14 samples are recommended. The carbonation depth varies between elements and among samples, so the utmost care should be taken when determining sampling spot and the value for an individual sample.

Key words: Reclaimed concrete elements, Reuse, Number of samples, Carbonation depth, Cover depth of reinforcement.

1. INTRODUCTION

The problematically high emissions produced by the construction industry have led to the development of solutions to decrease negative environmental impacts. One of the leading causes of emissions in the construction industry is the production of concrete. Solutions for replacing the constituents in the production of concrete with production-side streams and recycled concrete have been studied with the aim of minimizing emissions [1, 2, 3]. However, the production emissions can be reduced the most by avoiding the manufacturing process altogether – i.e., avoiding the creation of new products. This has led to an increase in studies on reusing concrete elements [4, 5, 6].

One of the main barriers for reusing and maintaining existing concrete elements is the lack of technical guidance and performance assessment [7]. The guidance and performance assessment are needed for the evaluation of properties for structural design and service-life assessment. When evaluating the structural capacity of concrete elements, measurements of the compressive strength of concrete, its geometry, and type, as well as the amount and location of reinforcement are needed. The reinforcement details affect the structural capacity and fire safety of the concrete elements [8]. The cover depth of reinforcement – i.e., the location of the reinforcement – is also a main parameter for the service-life assessment of concrete elements, as it protects the reinforcement from external factors [8].

The thickness of the concrete cover varies mainly due to the design of the element and the quality of its production. When designing elements, the cover depth is usually chosen based on guidelines. However, these guidelines are updated over time, leading to variations in cover depths across decades. During manufacturing, the variation of the cover depth can be caused by several factors that affect the stability of the reinforcement during casting. These factors include the number and placement of spacers, the degree of accuracy when bending and tying the reinforcement, and the diligence of workers and supervisors. Additionally, the method used to measure the cover depth of existing concrete elements can add variation. The cover depth of existing concrete elements is commonly measured by a cover meter, which is an electromagnetic method. The presence of more than one reinforcement bar, tie wires, iron content, and surface coating can decrease its accuracy by about 15% [9].

When it comes to service-life of concrete structures, carbon dioxide (CO_2) in the air reacts in the presence of moisture with portland cement ($Ca(OH)_2$), reducing the pH of pore water from 13 to about 8 [10]. This reaction is known as carbonation. The carbonation itself does not decrease the service-life of concrete, but it allows the reinforcement to corrode, which can cause a significant reduction in the service-life. The high alkalinity of new concrete forms a passive layer on the reinforcement that prevents the activation of the corrosion process [11]. However, when the carbonation front reaches the reinforcement, the protective layer will break down and corrosion can begin. The corrosion of the reinforcement may start when the concrete pH reaches the value of 11 and the relative humidity (RH) in the concrete is above 65-70% [11, 12]. The corrosion rate increases significantly when the RH in the concrete exceeds 80-85%, see Figure 1 [12, 13, 14]. Another factor that breaks down the protective layer is the presence of chloride ions [11]. The effect of chlorides is beyond the scope of this study, as it typically concerns outdoor structures exposed to external chlorides. This study focuses on concrete elements that have undergone carbonation indoors, noting that the future exposure conditions – whether for existing elements or in potential reuse scenario – remain unknown.

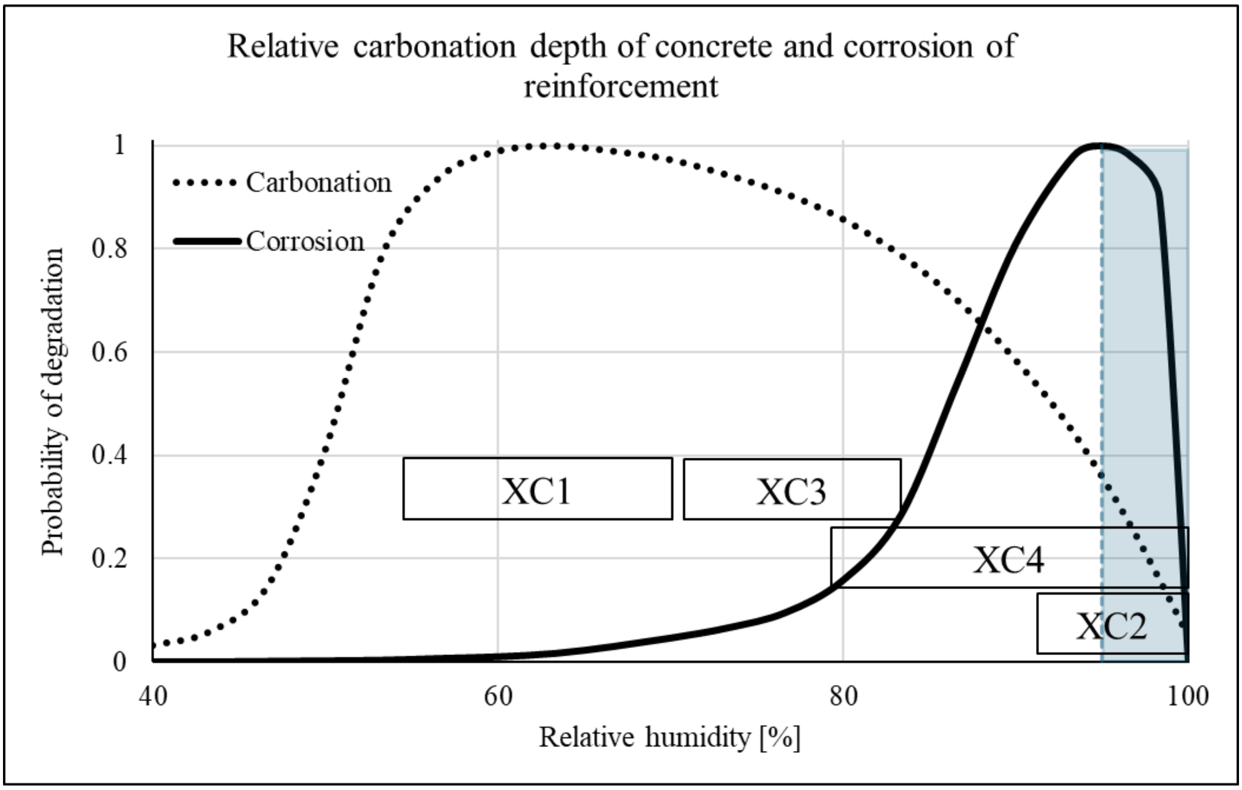


Figure 1 – The effect of the relative humidity of concrete on the carbonation rate of concrete and corrosion of reinforcement. Reproduced and translated from Hunkeler 1994 & 2008 [13, 14].

The carbonation mechanism has been studied by several researchers. Many internal factors – i.e., concrete characteristics – influencing the carbonation rate have been identified, such as the water to cement ratio, cement type, aggregate, and admixtures [15, 16, 17, 18]. In general, the higher the porosity of the concrete cover, the higher is the rate of carbonation. This indicates that a higher water to cement ratio and the higher porosity of the aggregate corresponds to a higher rate of carbonation [18]. The porosity and carbonation rate can also be affected by different concrete surface finishes. The effect of surface finish can be seen in the study by Lahdensivu [19], where the carbonation rate of balcony structures was studied to be higher when the surface of the concrete is floated compared to the form surface. It has also been found that a lower amount of calcium hydroxide ($Ca(OH)_2$) in the hydrated cement leads to a higher rate of carbonation, as a lower amount of CO_2 is needed to react with the available $Ca(OH)_2$ within a given depth [16]. This effect is more pronounced in blended cements, where the $Ca(OH)_2$ content is typically lower. However, blended cements also tend to produce a denser microstructures, which can reduce the permeability of the material and thus slow the overall carbonation process.

In addition, external factors, such as RH, temperature, CO_2 concentration in the surrounding environment, and stress distribution, affect the carbonation rate as well. The carbonation depth has been found to increase up to an RH of 70-75% [20, 21]. Below 40% RH, there is insufficient moisture for the carbonation reaction, while at an RH higher than 75%, the moisture fills the small pores and hence reduces the diffusion of CO_2. In terms of the effect of temperature, there is a linear correlation with the carbonation depth; a higher temperature accelerates the reaction, leading to a higher rate of carbonation [22]. One of the key external factors in carbonation is the CO_2 concentration in the surrounding environment. The carbonation reaction can proceed even at low CO_2 concentrations, and higher CO_2 levels generally lead to greater carbonation depth [23]. However, the relationship between CO_2 concentration and carbonation depth is non-linear: as CO_2

concentration increases, the rate of increase in carbonation depth diminishes, meaning that increase in CO_2 concentration contributes progressively less to further depth advancement. This non-linearity arises because, at lower concentrations, CO_2 reacts rapidly with available $Ca(OH)_2$, resulting in a sharp increase in carbonation rate. As CO_2 concentration continues to rise, the amount of CO_2 exceeds the required amount for the carbonation reaction, and the process becomes increasingly limited by the reaction rate rather than CO_2 availability. Wang et al. have also found that the carbonation reaction increases under tensile stress due to the formation of microcracks in the concrete [24]. In contrast, under compressive stress, the behaviour was found to be more complex: according to the findings of Wang et al. [25], carbonation depth initially decreases as compressive stress increases, up to approximately 30% of the concrete's compressive resistance. Beyond this threshold, however, further increase in compressive stress lead to a rise in carbonation depth. Several models considering the aforementioned factors have been developed for estimating carbonation depth [17, 20, 21, 26]. However, the most common prediction model in practice is the Equation 1, where material characteristics and environmental factors are included in the carbonation coefficient specific to the concrete and test conditions (Equation 1).

$$x = K\sqrt{t}\,, \tag{1}$$

where x is the carbonation depth [mm], K is the carbonation coefficient determined through testing [mm/year$^{1/2}$], and t is exposure time in years.

There are several methods for measuring the carbonation depth, but the most common method is using a phenolphthalein indicator on the freshly broken surface of concrete [9]. The indicator dyes the free $Ca(OH)_2$ pink, while the carbonated area is uncoloured. The line between the carbonated and non-carbonated area corresponds to a pH value of 9, which means that the indicator underestimates the depth where carbonation has occurred. As the corrosion may start at a pH value of 11 [12], careful interpretation of the colour pattern is important. The procedure for measuring the carbonation depth is described by RILEM [27] and in European Standard EN 12390-10 [28].

Although reinforcement details and the carbonation reaction, including factors affecting their variation, are known quite accurately, a limited number of studies exist on the actual deviation of reinforcement depth and carbonation depth within buildings, individual concrete elements, and samples [10, 29, 30]. However, none of these studies focus on the effect of variation on the sufficient numbers of samples and measurements. It is self-evident that the sufficient number of samples is dependent on the variation [31], and therefore this study reports sampling simulations for several carbonation depth and concrete cover depth measurements with various variations from real-life buildings. The simulation results are used to study the common probability of the error in the estimation of carbonation and concrete cover depth populations. Conclusions are drawn regarding what is the sufficient number of samples and locations for carbonation depth measurements for existing indoor concrete elements. The need to determine a sufficient number of samples and measurements is particularly important for indoor concrete elements that have been in use for many decades, are exposed to more severe conditions, or have uncertain details.

2. RESEARCH MATERIALS AND METHODS

2.1 Cases

Results from indoor concrete columns, beams, walls, and hollow-core slabs regarding cover depth and carbonation depth were used in the study. The test results for carbonation depth simulations were collected from four different buildings, and the structures were both cast-in-place and precast concrete elements. For cover depth simulations, two cases were analysed with five different element types. While the number of cases is relatively limited, the selected cases exhibit both low and high variability in carbonation depth and cover depth. This range of variability enhances the generalizability of the findings across a broader spectrum of existing buildings. However, it is acknowledged that the study focuses exclusively on indoor structural elements. Other exposure classes – such as outdoor elements exposed to weathering – were not included, and results may differ under those conditions. This limitation was intentional, as indoor structures typically offer higher reuse potential. In contrast, elements like facades often face significant reuse constraints due to deficient durability properties and insufficient energy efficiency relative to current regulations. Table 1 provides more detailed information about the buildings used in the study.

Table 1 – Details of the cases used in the research.

Case	Age (approx.)	Casting method	Structures	Tests
1	40	Precast	Columns, Beams, Hollow-core slabs	Cover depth, Carbonation depth
2	35	Precast	Walls, Hollow-core slabs	Cover depth, Carbonation depth
3	50	Cast-in-place	Columns, Beams, Walls	Carbonation depth
4	46	Precast	Walls, façade inner panel	Carbonation depth

2.2 Cover depth of reinforcement measurements

Concrete cover depth measurements was conducted for all reinforcement types in case 1 and case 2. Each reinforcement type was measured separately using a Proceq Profometer PM-650 device, which operates with an electromagnetic field to detect the presence of steel and has a measuring accuracy of approximately ±1 mm to 4 mm. Measurements were taken from randomly selected elements and locations within the buildings. The number of cover depth measurements for each building and reinforcement type are presented in Table 2. The measurement accuracy is considered relatively small and does not affect the simulations or the conclusions of this study. Moreover, any potential variation introduced by the device's accuracy is inherently included within the measured data and thus considered in the analysis.

Table 2 – Details of the cases used in the research.

Case	Structure type	Reinforcement type	Number of measurements
1	Beam	Main	454
		Tie	604
	Column	Main	564
		Tie	665
	Hollow-core slab	Strand	119
2	Wall	Door opening	194
		Jamb	304
	Hollow-core slab	Strand	108

2.3 Carbonation depth measurements

Carbonation depth was measured from beams, columns, and walls in cases 1, 2, 3, and 4 according to RILEM CPC-18 [27]. Measurements were taken from the core samples by using phenolphthalein liquid as an indicator. The values were measured from the top surface of the core to the edge of the non-carbonated pink area by using vernier calliper. The average carbonation depth of the samples were used in the simulations.

The carbonation distribution within-element was studied from six deconstructed beams in case 1. The exposure conditions of the beams were in indoor conditions (XC1). After deconstruction, the six individual beams were stored under cover outdoors for a year before within-element carbonation depth measurements. A total of 11-15 cores were drilled from undamaged parts of the beams after the bending test. Two types of cores were drilled, with diameters of 150 mm and 75 mm. A layer was cut from the top surface of the cores and split after cutting. The carbonation depth was then measured from the freshly broken surface of the layers with the phenolphthalein indicator. The carbonation depths were measured by a digital calliper at an interval of 0.5 cm. The sampling spots are presented in Figure 2.

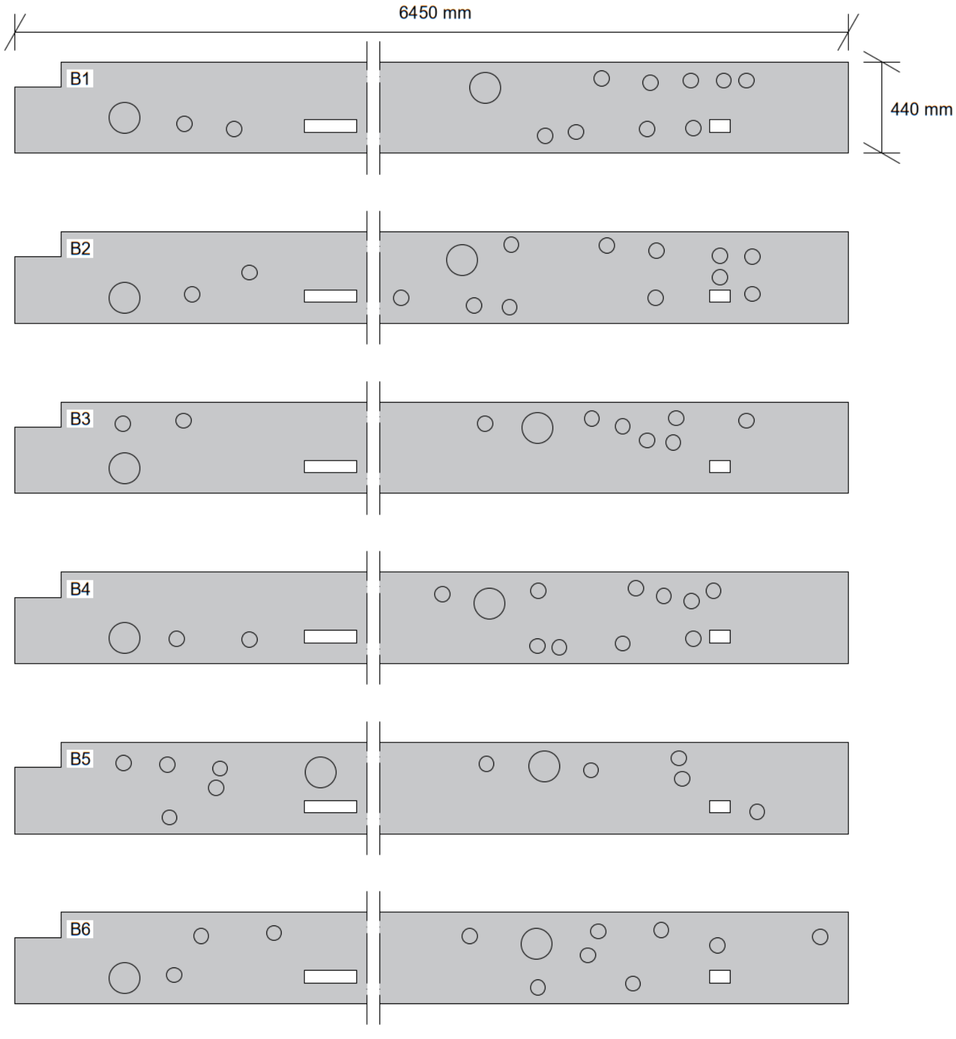


Figure 2 – Core sampling points of the six individual beams of case 1.

2.4 Methodology for statistical analysis

The effect of increasing the number of samples on estimation accuracy was studied by examining variation of experimental data among all cases for cover depth of reinforcement and carbonation depth. Sampling distribution variables, the average, and standard deviation were determined separately for each case, element type, and reinforcement type. A Monte Carlo simulation was used to simulate the extreme values (the highest and lowest) of the sampling variables, i.e. the average and standard deviation, to present the critical scenarios within the building population.

Monte Carlo simulation is a probabilistic technique that uses repeated random sampling to estimate the behaviour of a given data under uncertainty. In this study, the method was applied to simulate sampling distributions by randomly simulating samples from the empirical data, i.e. not assuming any distribution. For each predefined number of samples a total of 10,000 iterations were conducted, wherein a sample was simulated with replacement, and the standard error of the mean (SEM) was calculated. This process was repeated for the different number of samples to assess how increasing the number samples affects the error of the estimated mean value of the population. The simulated number of samples for the cover depth of reinforcement were 5, 10, 30, 50, 100, 150, 200, 300,…, 600 and for the carbonation depth 4, 6, 8,…, 20.

For each simulation the SEM was calculated by using Equation 2. The SEM values for the possible sampling means were then presented as the cumulative distribution functions (CDF), illustrating the probability distribution of the SEM for the sampling mean of a certain number of samples.

$$SEM = s/\sqrt{n}\,, \tag{2}$$

where s is the sample standard deviation and n is the number of samples.

It is worth noting that the SEM was calculated specifically for the sampling means. Based on the Central Limit Theorem (CLT), the distribution of sampling means approaches a normal distribution, if the number of samples is higher than 30 [31], regardless of the distribution of the population. This theorem validates the assumption of normality for the sampling mean distribution and the use of SEM.

When a relatively small number of samples is used for the estimation of the population, an error in the location of the distribution can occur. This error can be estimated with the SEM, which estimates how far the sample mean is from the population mean. As the SEM tends toward zero when the number of samples increase, the minimum sufficient number of samples for estimating the population mean can be evaluated from the interdependence between the number of samples and the SEM.

3. RESULTS AND DISCUSSION

3.1 Cover depth of reinforcement

Measurement results

The results of the cover depth measurements are presented in Table 3. It can be observed that the mean and median values are relatively high and close to each other. When examining the standard deviation of the measurements, significant variability can be noticed in wall elements. However, the standard deviation of the column ties of case 1 is notably high, too. This can be explained by several outliers in the measurements. Thus, any other reinforcement types and error measurements should be avoided in sampling. Correspondingly, the standard deviations of strand depths in hollow-core slabs are notably low, primarily due to the manufacturing process in which the strands are positioned in the machine. This contrasts with non-prestressed elements, where the reinforcement placement is typically performed by hands, resulting in greater error and variability. The mean values 30.5 mm and 44.8 mm were used together with the standard deviation values 3.0 mm and 22.0 mm in the simulation.

Table 3 – Cover depth measurement results.

Case	Structure type	Reinforcement type	Minimum [mm]	Maximum [mm]	Mean value [mm]	Median value [mm]	Standard deviation [mm]
1	Beam	Main	12	53	38.2	39	5.4
		Tie	6	87	26.9	26	8.9
	Column	Main	6	106	34.2	34	9.1
		Tie	7	80	31.4	28	14.3
	Hollow-core slab	Strand	22	37	28.5	29	3.0
2	Wall	Door opening	11	84	39.7	36	15.2
		Jamb	8	88	44.8	39	22.0
	Hollow-core slab	Strand	24	36	30.5	30	3.0

Sufficient number of samples

Figure 3 shows the influence of the number of samples on the accuracy of the cover depth estimation. The estimation error systematically decreases for both low and high variations as the number of samples increases. It can be seen from the simulation results (Figure 3) that the error can be up to 2.7 mm for p = 1.0 when the variation of the case is low (hollow-core slabs, σ = 3.0 mm), whereas for high variation case (σ = 22.0 mm), the error can be as high as 18.2 mm. In cases of high variation, a small number of samples can result in significant overestimation. When the number of samples is increased to 200, the visual distance of the CDF compared to 600 samples does not change significantly. However, a probability of 100% (p = 1.0) may be too conservative estimate. The effect of increasing the number of samples on the change in distance can be calculated. Table 4 presents the variation in SEM as the number of samples increases for probabilities of 95% (p = 0.95) and 80% (p = 0.8), along with the relationship between the SEM and mean value, as well as the change in SEM relative to the SEM of smaller number of samples.

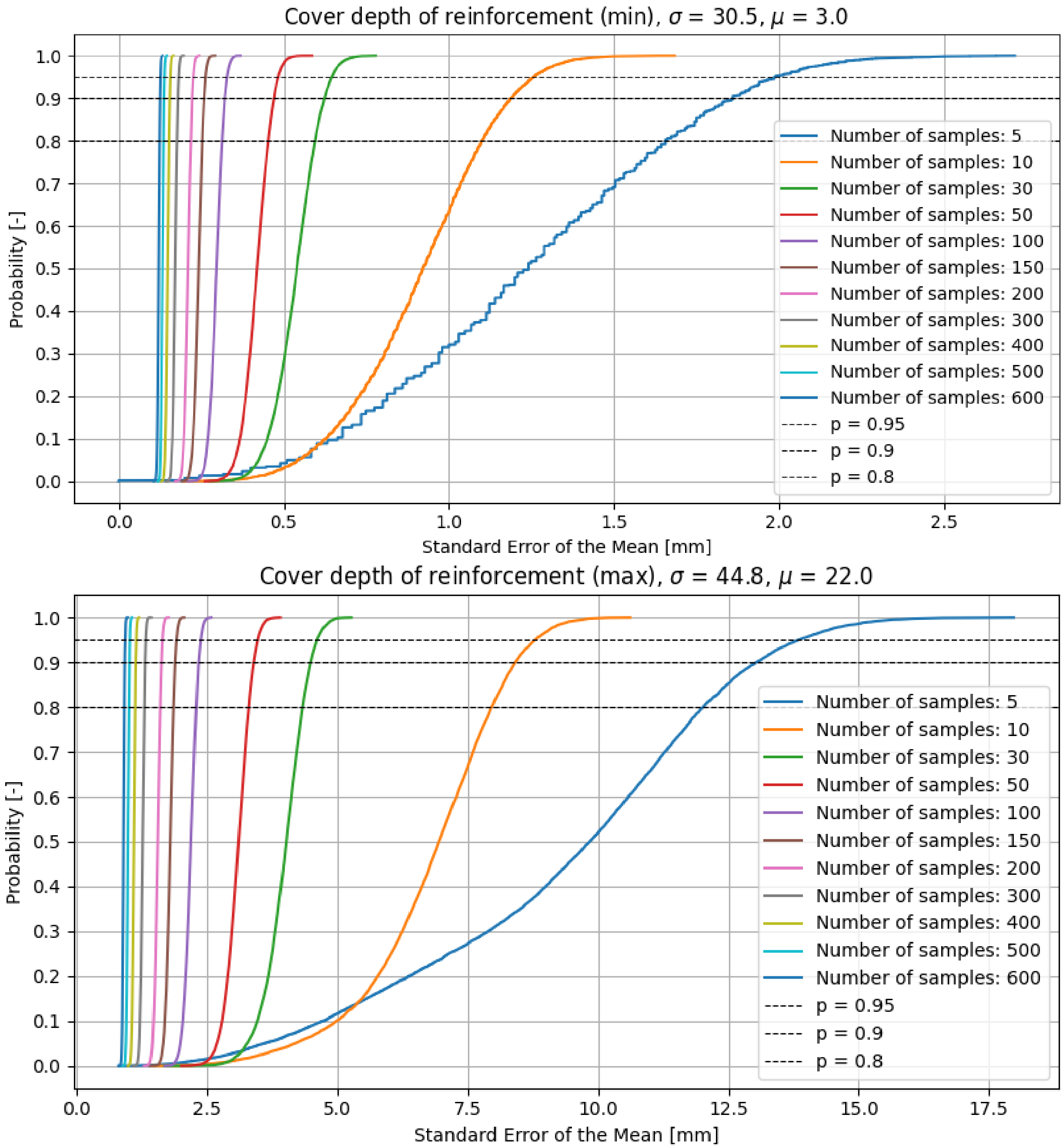


Figure 3 – The probability of the SEM for cover depth of reinforcement measurements for different numbers of samples.

Table 4 – The SEM of cover depth of reinforcement measurements for probabilities of 95% and 80%.

Cover depth of reinforcement (min), μ = 30.5 mm, σ = 3.0 mm						
n	SEM p = 0.95	Change	SEM/μ	SEM p = 0.80	Change	SEM/μ
5	1.990	-	0.065	1.661	-	0.054
10	1.263	0.365	0.041	1.098	0.339	0.036
30	0.647	0.488	0.021	0.596	0.457	0.020
50	0.482	0.255	0.016	0.452	0.242	0.015
100	0.329	0.317	0.011	0.314	0.306	0.010
150	0.264	0.198	0.009	0.254	0.192	0.008
200	0.226	0.145	0.007	0.218	0.140	0.007
300	0.182	0.193	0.006	0.177	0.188	0.006
400	0.157	0.141	0.005	0.153	0.137	0.005
500	0.139	0.110	0.005	0.136	0.108	0.004
600	0.127	0.091	0.004	0.124	0.090	0.004
Cover depth of reinforcement (max), μ = 44.8 mm, σ = 22.0 mm						
n	SEM p = 0.95	Change	SEM/μ	SEM p = 0.80	Change	SEM/μ
5	13.735	-	0.307	12.023	-	0.268
10	8.798	0.359	0.196	7.946	0.339	0.177
30	4.624	0.474	0.103	4.337	0.454	0.097
50	3.465	0.251	0.077	3.297	0.240	0.074
100	2.373	0.315	0.053	2.290	0.305	0.051
150	1.917	0.192	0.043	1.859	0.188	0.042
200	1.645	0.142	0.037	1.602	0.138	0.036
300	1.330	0.192	0.030	1.300	0.188	0.029
400	1.144	0.139	0.026	1.121	0.137	0.025
500	1.020	0.109	0.023	1.002	0.106	0.022
600	0.928	0.090	0.021	0.912	0.090	0.020

Table 4 demonstrates that the changes in SEM values decreases as the number of samples increases, where a change related to the previous SEM of over 5% can be considered statistically significant [32]. However, in Table 4, this 5% change in SEM is not achieved, as the substantial increase in the number of samples causes a relatively large change in SEM. The same 5% threshold is also applied to the SEM-to-mean ratio (SEM/μ), and both the relative change in SEM/μ and the corresponding SEM values are framed in the Table 4. These metrics – SEM and SEM/μ - provide more meaningful insights into the simulation results for reinforcement cover depth than absolute SEM values alone.

The SEM is a significant measure because it presents a possible error in the sampling distribution. The desired accuracy of the SEM should be determined individually, as no universal guideline can be concluded from the simulation results. However, when the relation between the SEM and mean value is considered, a 5% threshold (highlighted in Table 4) can be achieved for high variation with 150 samples for both probabilities of 0.95 and 0.80, and for low variation, with 10 (p = 0.95) and 5 (p = 0.8) samples.

The sufficient number of samples does not differ significantly between probabilities of 95% and 80%, but variations have a greater influence. Therefore, each building and reinforcement type should be considered individually as its own population. It is advisable to use a higher number of samples to avoid the need for further tests, since the variation cannot be determined beforehand. Additionally, testing the cover depth of reinforcement is a relatively quick process, so increasing the number of samples does not substantially affect the testing costs [9]. Notably, hollow-core slabs can be distinguished from other element types in terms of cover depth deviation. As indicated by the results in Table 3, the deviation in hollow-core slabs is consistently low, suggesting that a smaller number of measurements may be sufficient for this element type.

Based on the simulation results, using 150 samples ensures that the ratio of the SEM to the mean value is below 5%, even in high variation cases. Consequently, 150 samples are recommended as the minimum number of samples. For hollow-core slabs, however, a smaller number of samples may be appropriate due to their low variability. A number of samples of 10 may be sufficient for preliminary assessment, while 30 can achieve a SEM below 1 mm. This recommendation is further supported by the efficiency of the testing method, which facilitates the collection of additional measurements with minimal cost and effort.

3.2 Carbonation depth

Measurement results

The results of the carbonation depth measurements are presented in Table 5. In case 1, the carbonation depth is relatively low with only 5 mm maximum depth and a standard deviation of 0.62 mm. Inversely, in case 3, the maximum carbonation depth is relatively high, being 60 mm. However, the standard deviation of 6.46 mm is not particularly large when considered in relation to the average carbonation depth. This suggests that while an extreme value was observed, the overall variability within the dataset remains comparable. Importantly, the standard deviation directly influences the simulated SEM values (Equation 2), thus, these cases 1 and 3 were used in the simulation.

The high carbonation depth values observed in case 3 can be partly explained by the fact that the elements were cast-in-place concrete, which is more susceptible to quality inconsistencies. In this case, the concrete quality was found to be notably poor, with compressive strength measurements significantly lower than the designed compressive strength. This deviation from expected strength strongly supports the conclusion that the elevated values are a result of inadequate concrete quality during construction. In addition, the differences in indoor structures can be significant depending on the factors affecting carbonation (see the Introduction). Hence, it is necessary to evaluate buildings and structures individually.

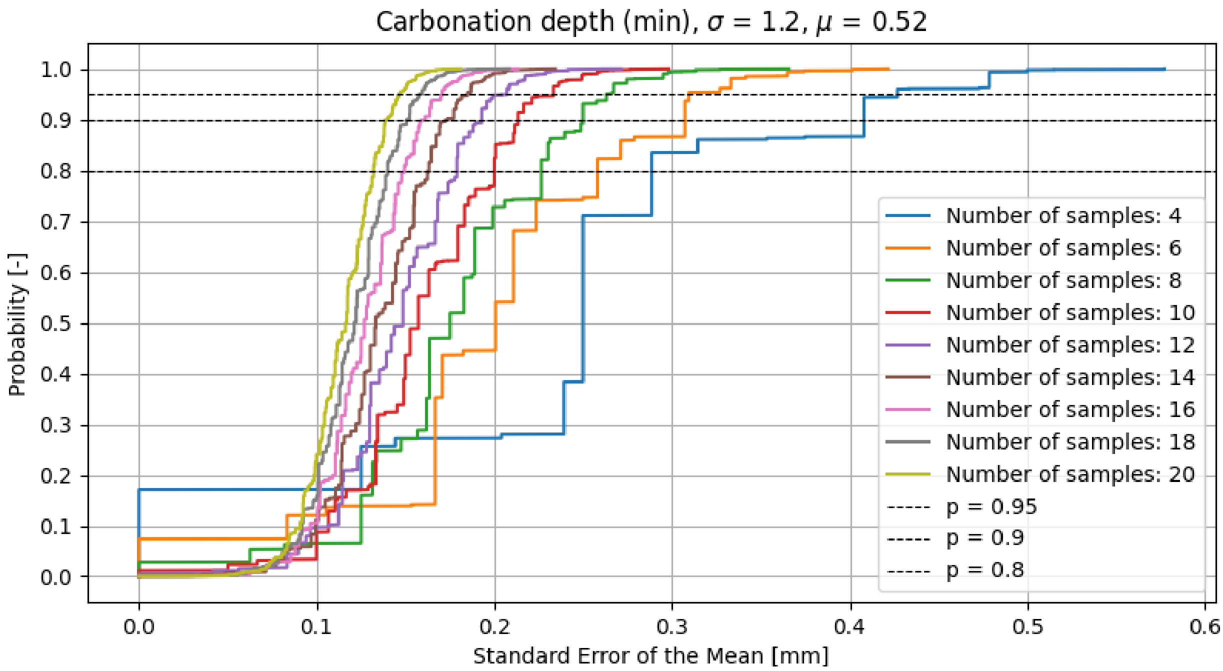
Table 5 – Carbonation depth results of the phenolphthalein indicator from cases 1,2,3, and 4.

Case	Structure type	Number of measurements	Minimum depth [mm]	Maximum depth [mm]	Average depth [mm]	Standard deviation [mm]
1	Beam	15	0	5	1.2	0.52
	Column	15	0	4	0.8	0.62
2	Wall	12	0	15	6.0	2.89
3	Beam, column, wall[a]	63	5	60	19.1	6.46
4	Wall	7	3	9	6.3	2.15
	Façade indoor	5	6	8	6.8	0.84

[a] The structural elements from which individual carbonation depth samples have been taken are not known. Therefore, the results include all the indoor structures from the building.

Sufficient number of samples

Figure 4 presents the probability of the SEM for carbonation depth measurements based on different numbers of samples and two cases of variability (σ = 0.52 mm and σ = 6.46 mm). For the case of low variability, the highest possible SEM is relatively low, being 0.58 mm with 4 samples. A low SEM indicates that the carbonation front has progressed evenly, meaning that even a small number of samples can provide high accuracy. Similarly, for high variation, the SEM increases significantly up to 5.8 mm with 4 samples. However, the error can be systematically reduced by increasing the number of samples. Table 6 presents how the SEM changes for probabilities of 0.95 and 0.8, along with the relation between the SEM and mean value. The 5% change in SEM relative to the smaller number of samples and the corresponding SEM values are also highlighted to emphasize their significance.



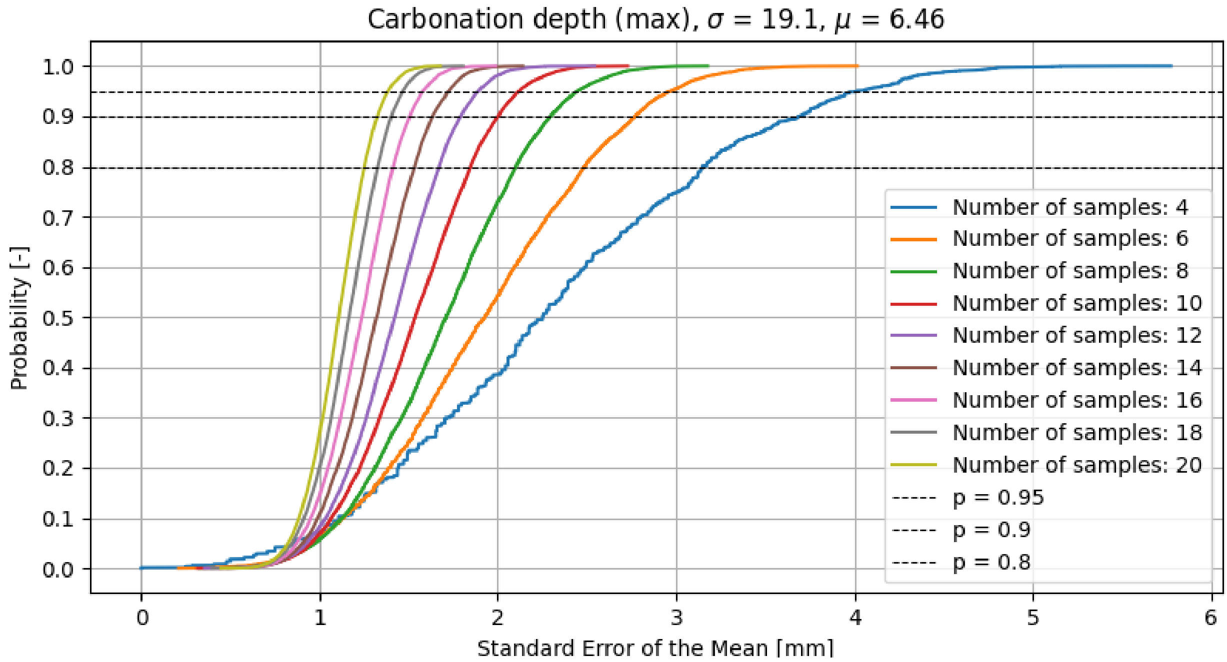


Figure 4 – The probability of the SEM for carbonation depth measurements with different number of samples.

Table 6 – The SEM of carbonation depth measurements for probabilities of 95% and 80%.

Carbonation depth (min), μ = 1.2 mm, σ = 0.52 mm						
n	SEM p = 0.95	Change	SEM/μ	SEM p = 0.80	Change	SEM/μ
4	0.427	-	0.356	0.289	-	0.241
6	0.310	0.275	0.258	0.258	0.106	0.215
8	0.263	0.150	0.219	0.227	0.122	0.189
10	0.233	0.113	0.194	0.200	0.117	0.167
12	0.207	0.112	0.173	0.179	0.105	0.149
14	0.185	0.107	0.154	0.163	0.087	0.136
16	0.171	0.078	0.142	0.149	0.086	0.125
18	0.158	0.074	0.132	0.140	0.063	0.117
20	0.146	0.073	0.122	0.132	0.056	0.110
Carbonation depth (max), μ = 19.1 mm, σ = 6.46 mm						
n	SEM p = 0.95	Change	SEM/μ	SEM p = 0.80	Change	SEM/μ
4	4.021	-	0.211	3.146	-	0.165
6	2.971	0.261	0.156	2.487	0.210	0.130
8	2.448	0.176	0.128	2.102	0.155	0.110
10	2.119	0.134	0.111	1.847	0.122	0.097
12	1.893	0.107	0.099	1.671	0.095	0.087
14	1.724	0.089	0.090	1.533	0.083	0.080
16	1.580	0.084	0.083	1.414	0.078	0.074
18	1.468	0.071	0.077	1.326	0.062	0.069
20	1.386	0.055	0.073	1.251	0.057	0.066

Based on Table 6, a number of samples between 12 and 14 is recommended for estimating carbonation depth with sufficient reliability. The recommendation is based on the observed behaviour of the SEM and its ratio to the sampling mean. Table 6 shows that as the number of samples increases, the SEM decreases, leading to more precise carbonation depth estimation. Significant reductions in the SEM are observed between 4 and 12 number of samples, but after n = 14, the marginal benefit become increasingly limited. For example, in the case of low variation, the SEM decreases from 0.207 mm at n = 12 to 0.146 mm at n = 20, representing a small benefit of only 0.061 mm despite a 67% increase in number of samples. Correspondingly, for high variation, the SEM decreases from 1.893 mm at n = 12 to 1.386 mm at n = 20.

A threshold of 0.1 is commonly used in engineering and material science for acceptable precision. In addition, achieving a threshold value under 5% is practically impossible due to the relatively small carbonation depths observed. As a result, any change in the error through increased number of samples remains proportionally large relative to the mean, making the error-to-mean ratio significant despite additional sampling. Threshold values for confidence intervals may also have been set in the national standards for the design of concrete structures. However, the 0.1 threshold value is achieved at around n = 14 for both low and high variation scenarios for the change of the SEM, suggesting that number of samples above this do not significantly reduce practical benefits of uncertainty.

While larger number of samples improve statistical reliability, they also lead to greater resource demands. Therefore, a number of samples of 12 to 14 offers a sufficient balance between statistical reliability and practical efficiency. This range ensures that the SEM is sufficiently reliable, while avoiding unnecessary sampling.

Within-member variation

The results of the carbonation depth measurements of six individual beams from case 1 are presented in Figure 5 and Table 7. Figure 6 shows Monte Carlo simulation results for probable SEM within an element. The variation in carbonation depth across different regions of the beams are presented separately in Tables 8 and 9.

While the differences between the beams are relatively small (Table 7), it is noteworthy that the average carbonation depth in both the beams and case 1 is relatively low. It is plausible that more significant differences would appear in cases with higher carbonation depths. Nevertheless, the variation within the beams is clearly evident. The standard deviation of carbonation depth within individual beams reached values as high as 5.9 mm, with an average value of 9.0 mm. These empirical values were used as input parameters in the Monte Carlo simulation to analyse the effect of the number of samples on the SEM.

As Figure 6 illustrates, the effect of increasing number of samples on the error is notable. With only two samples, the error exceeds 18 mm, indicating a high uncertainty in estimating the mean carbonation depth within an element. Even at a 0.8 probability, the error may still be around 4.8 mm. These results emphasize the importance of sufficient sampling in estimation of an individual element to achieve reliable estimates of carbonation depth.

The variability within elements is substantial. The carbonation depths on the left-hand side of the beams were between 87% and 204% higher than those on the right-hand side. No clear difference in concrete quality was identified, but this variation can be explained with factors affecting the carbonation rate in concrete, as discussed in the Introduction. Compressive strength tests did not reveal significant differences between the samples, which indicates a relatively consistent concrete quality across the measured elements and samples. The micro-climate might vary within an element due to air conditioning or partition walls.

Similarly, differences were observed between the upper and lower parts of the cross-section, as shown in Table 9. In beams B1 through B5, the carbonation depth in the lower part of the cross-section was higher than in the upper part, with differences between 16% and 124%. Beam B6 was an exception having only a marginal increase (0.2 mm) in the upper region. These findings align with the previous studies indicating that the carbonation rate is higher in the tensile stress areas [24, 25, 30].

The results emphasize the importance of strategic sampling in estimating carbonation depth within concrete elements. Rather than taking more than one sample from an element, it is essential to consider spatial heterogeneity of carbonation progression. Sampling from planned regions within an element – particularly those exhibiting higher susceptibility to carbonation – is essential for improving the reliability of population estimations. Based on the results, it is recommended to focus the sampling on the highly susceptible areas, such as high CO_2, favourable RH and tensile stress areas, in sense of service life. This ensures that the estimation reflects the most susceptible area of the element.

In addition to the regional considerations, the surface finish of the element may play a significant role in carbonation rate. Sampling should be focused on the most porous surfaces, where the carbonation rate is likely to be highest. Accordingly, to the findings of Lahdensivu [19], floated surfaces in concrete elements result in the highest porosity compared to form-finished surfaces. Therefore, whenever feasible, samples should be extracted from the floated surfaces, while form surfaces should be avoided to prevent underestimation of the carbonation depth.

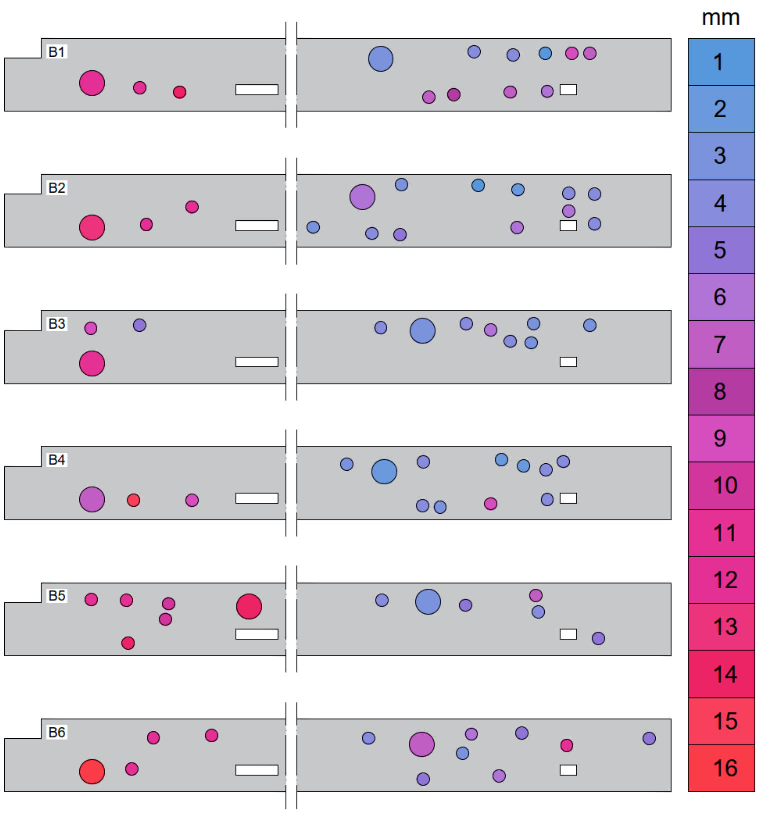


Figure 5 – Variability of the average carbonation depth values of the samples in different locations of the individual beams. The values present the carbonation depth in mm.

Table 7 – Carbonation depth measurements and results for the 6 individual beams of case 1.

Beam	Measurements [pcs]	Average depth [mm]	Maximum depth [mm]	Standard deviation [mm]
B1	227	7.7	27.2	4.8
B2	257	6.9	35.0	5.7
B3	197	6.0	22.3	4.5
B4	243	5.6	33.3	4.9
B5	214	8.8	24.2	5.6
B6	225	9.0	37.9	5.9

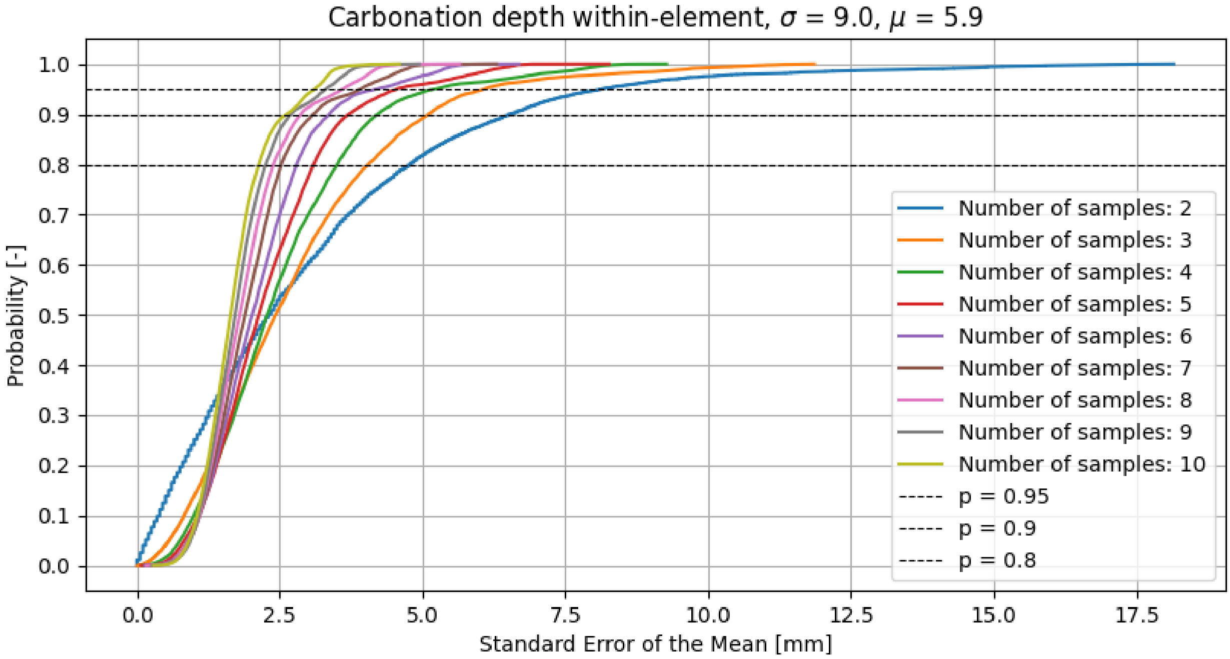


Figure 6 – Probability of the SEM within-element for carbonation depth measurements with different numbers of samples.

Table 8 – Carbonation depth measurements and results for the left and right side of the 6 individual beams of case 1.

Beam	Left side		Right side	
	Measurements [pcs]	Average depth [mm]	Measurements [pcs]	Average depth [mm]
B1	61	12.6	166	5.9
B2	61	14.0	195	4.6
B3	30	9.9	172	5.3
B4	60	10.6	181	3.9
B5	106	12.8	106	4.8
B6	73	14.1	151	6.6

Table 9 – Carbonation depth measurements and results for the upper and lower cross-section of the 6 individual beams of case 1.

Beam	Upper cross-section		Lower cross-section	
	Measurements [pcs]	Average depth [mm]	Measurements [pcs]	Average depth [mm]
B1	106	5.1	121	10.0
B2	106	4.0	120	8.6
B3	165	5.0	30	11.2
B4	153	4.3	89	7.8
B5	182	8.6	30	10.0
B6	182	9.0	45	8.8

3.3 Determination of the cover depth of reinforcement and carbonation depth for in-use and reclaimed concrete elements

The need to test the cover depth of reinforcement and carbonation depth depends on the future use of the elements. Concrete structures are designed for specific exposure classes [33], which may change due to repair or reuse. It was found from the literature [12, 13, 14] that the probability of degradation from corrosion is highest when the relative humidity is over 80-85%. In the current European standard EN 206 [33], this means that the probability of corrosion degradation is significant in an exposure class of XC4. According to the International Federation for Structural Concrete (fib) [34], the mean corrosion rate in exposure class XC4 is 5 μm/year, which corresponds to a loss of 1 mm of efficient reinforcement over 200 years. However, the critical corrosion penetration for concrete cover cracking has been estimated to be 67.5 μm [35]. Thus, it can be estimated that the cracking may occur within around 13.5 years in XC4, assuming the carbonation front has reached the reinforcement.

Significant corrosion risk is also present in exposure classes XC2 and XC3 [13, 14]. The corresponding mean corrosion rates for XC2 and XC3 are 4 μm/year (XC2) and 2 μm/year (XC3), which corresponds to a cracking time of 16.9 years (XC2) and 33.8 years (XC3) [34, 35]. The corrosion rate for XC2 is applicable in conditions where the concrete is not fully submerged in water, where the corrosion is negligible due to the lack of oxygen. These estimates do not fulfill the commonly accepted service-life requirement of 50 years. Consequently, it is necessary to assess service-life when elements are intended to use in any of these three exposure classes. In contrast, exposure class XC1 has a negligible corrosion risk with a mean corrosion rate of 0 μm/year [34], hence removing the necessity of service-life estimation.

Additional factors influencing the need for testing include structural capacity requirements, service-life requirements, and the knowledge level regarding the material properties. In cases where no structural capacity or service-life requirements exist for future use, testing may not be necessary. However, when such requirements exist, the decision to conduct further testing should be guided by the variation in the measured values.

The characteristic value can be reliably determined with a sufficient large number of samples, allowing for a statistically representative evaluation of the distribution characteristics. For carbonation depth, the characteristic value of interest is the higher end of the distribution, representing the worst-case scenario where the carbonation front has progressed furthest. In contrast, for reinforcement cover depth, the characteristic value should be based on the lower tail of the distribution, indicating the shallowest cover and thus the most vulnerable locations for corrosion and fire safety. These characteristic values for design can be calculated using statistical methods – such as percentile-based approaches or parametric estimations – provided that the underlying population is reliably known and the sampling is representative. This enables a robust basis for service-life design and safety assessments.

It was noted from the simulation results above, that low variability suggests high reliability, if sufficient number of samples have been used, thereby reducing the need for additional sampling. Correspondingly, when variability is high, higher number of samples is essential to achieve statistically representative estimates of cover depth of reinforcement and carbonation depth. Importantly, the variability must be assessed from a sufficient number of initial samples to ensure that the evaluation is reliable and not biased by undersampling. Sufficient number of samples from the simulation results can be considered as an initial sampling guideline.

No other simplified methods exist for reliable determining cover depth or carbonation depth variability in concrete elements. As such, the methods mentioned in this paper remains viable approach, further emphasizing the importance of carefully planned sampling strategy and number of samples. Strategic sampling, informed by both spatial variability and material characteristics, is therefore critical to achieving reliable assessments that support safe and durable use of concrete elements.

In the reuse of concrete elements, the population size of reusable elements must be carefully considered. In cases where only a limited number of elements are intended for reuse, the sufficient number of samples may be lower than the recommendations derived from the simulations conducted in this study. The present simulations primarily addresses scenarios with large populations, where obtaining a higher number of samples is feasible and practical.

For the evaluation of reinforcement cover depth, sampling is relatively straightforward and cost-effective, making it feasible to reach the recommended minimum of 150 samples or to test each individual element. However, hollow-core slabs can be treated as a separate category as was noticed from the simulation results, and reliable results can be obtained with only 10 preliminary measurements or with 30 measurements to achieve high statistical confidence. In contrast, the assessment of carbonation depth is considerably more labor-intensive and includes higher costs.

Accordingly, the sampling strategy should consider not only the spatial distribution of sampling locations but also by a critical evaluation of the necessity of sampling itself. This consideration ensures that resources are targeted effectively while maintaining the reliability and validity of the sampling. In particular, the strategy should account for differences in concrete batches and production variability across different element types, as these factors can introduce significant scatter in the results. The most efficient way to address this is to separate element types into distinct sampling groups – such as beams, columns, partition walls, exterior walls, hollow-core slabs, and other floor slabs. Furthermore, even within a single element type, there may be variations due to different manufactures or concrete batches, which should be separated. This situation is especially relevant in renovated buildings, where some original elements may have been replaced with new ones, or additional elements have been added. By recognizing and accounting for these distinctions, the sampling strategy becomes more robust and better suited to capturing the true variability within the elements.

Based on the simulation, literature findings, and the discussion, a decision-making flow chart in Figure 7 can be developed to guide decisions on testing requirements for the cover depth of reinforcement and carbonation depth. The flow chart helps to manage in-use concrete structures and reclaimed elements effectively, ensuring reliability while optimizing the number of samples required.

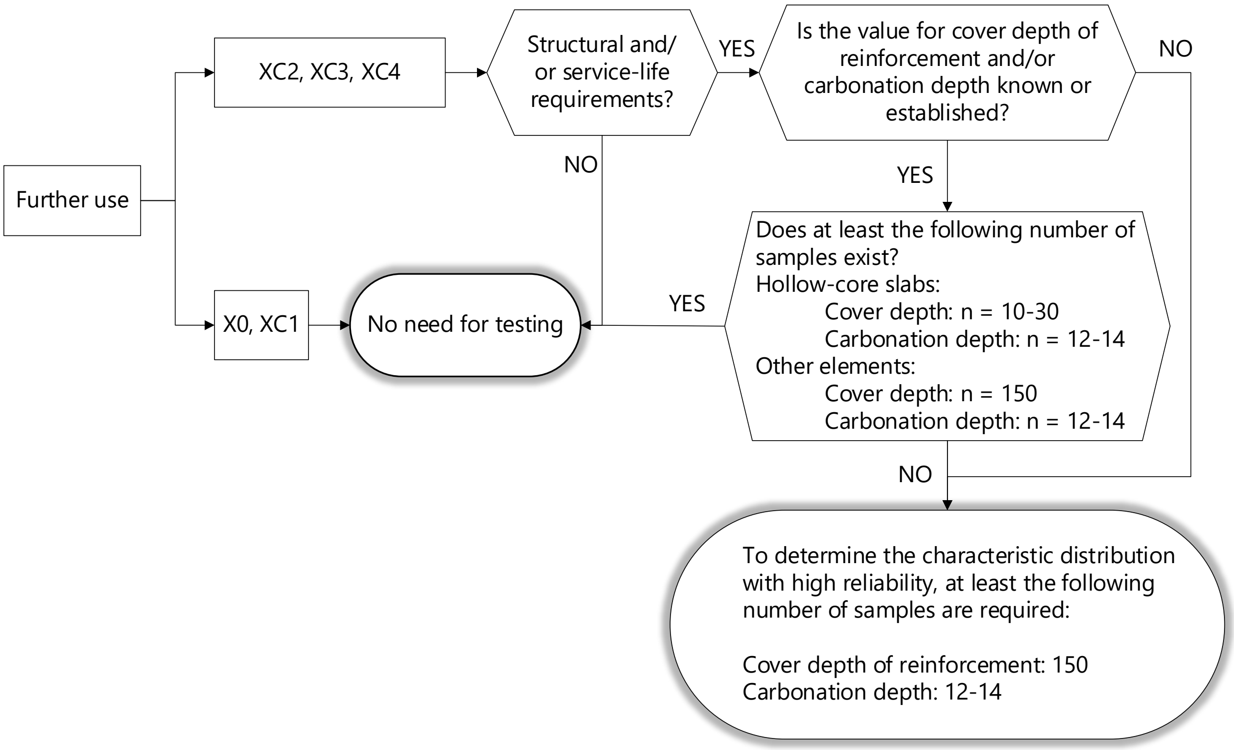


Figure 7 – The flow chart for assessing the need to test the cover depth of reinforcement and carbonation depth in existing concrete elements.

4. CONCLUSIONS

The minimum number of samples and measurements for determining the cover depth of reinforcement and the carbonation depth of in-use and reclaimed concrete elements were studied with statistical simulations by using experimental data. The following conclusions were drawn from the study:

- For estimating the cover depth of reinforcement, each element and reinforcement type should be considered separately due to potential differences in properties. Based on the findings, a minimum of 150 measurements are recommended to ensure reliable population estimates for every element type.
- For hollow-core slabs the variation was noticed to be low, and hence reliable cover depth of reinforcement results can be obtained with only 10 preliminary measurements, or with 30 measurements to achieve statistically high reliability.
- The sufficient number of samples for carbonation depth estimation is influenced by the element type and its inherent variability. For reliable population estimation, a minimum of 12 to 14 samples from different elements is recommended.
- Carbonation depth within individual elements can vary significantly, with observed differences as high as 204% in different parts of the element. To improve reliability, sampling should be focused on the most susceptible areas in the element – tensile stress

areas, porous surfaces, favourable RH, high CO_2 concentrations – ensuring reliable assessment of carbonation depth for service-life estimations for further use.
- The need for the determination of the cover depth of reinforcement and the carbonation depth depends on the intended future application. The cover depth of reinforcement should always be determined when structural capacity, fire safety, or service-life estimations are required. The carbonation depth must be determined when the elements will be used in exposure classes XC2, XC3, or XC4, as the probability of corrosion degradation can be significant. In contrast, for exposure class XC1, the probability of corrosion degradation is negligible, and carbonation testing is generally not needed.

FUNDING

The study was conducted as part of the 'Reusing precast concrete for a circular economy' (ReCreate) project. The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958200.

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