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Comparison of carbonation depths measured on in-field exposed existing r.c. structures with predictions made using *fib*-Model Code 2010

Matteo Guiglia, Maurizio Taliano *

Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Italy

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ABSTRACT

The *fib*-Model Code for Service Life Design, which is referenced within Model Code 2010, considers different deterioration mechanisms of concrete structures. In particular, it proposes a physical model for the assessment of the carbonation depth in time, which, for existing structures, requires data, such as the type of cement and the water-to-cement ratio of the concrete, that are often unavailable. In the paper the theoretical results obtained with the *fib*-model are discussed and compared with experimental data obtained during an extensive campaign carried out on cast-in-place uncracked concretes of in-field exposed existing r.c. structures from a highway infrastructure. This comparison has highlighted the key role played not only by the environment, but also by the quality of the concrete through the inverse effective carbonation resistance of concrete, $R^{-1}_{NAC,0}$, on the evolution of the carbonation depth in time. The direct measurements of the carbonation depth on existing r.c. structures allows the inverse effective carbonation resistance of concrete to be determined and correlated to the concrete mean compressive strength at 28 days obtained from compressive tests on cores taken from the investigated structures.

1. Introduction

A performance-based methodology can be adopted to obtain a correct maintenance and management of buildings and civil infrastructures, applying the limit state approach. The general safety, economic and sustainability requirements are modelled in quantitative models and qualitative procedures [1] that deal with:

- The analysis of the behaviour of the structure under mechanical (static, dynamic and fatigue) loads.
- The analysis of the behaviour under physical, chemical and biological attacks.
- The management of obsolescence, which is the cause of the demolition of buildings or infrastructures in about 50% of all demolition cases, that is, the inability to satisfy changing functional (human), economic, cultural or ecological requirements.

It is possible to combine the traditional safety and serviceability calculations with durability models concerning the degradation behaviour and the assessment of the service life of a structure, but in practice it is usually preferable to separate them, as traditionally occurs in standards.

As far as r.c. structures are concerned, the service life includes an initiation phase in which carbonation or chlorides depassivate the steel, and this is followed by a propagation period during which the steel actively corrodes [1–4]. In a performance based design approach, the end of the planned service life is recognised over time through the attainment of predetermined limit states, such as the depassivation of reinforcements, the spalling of concrete (serviceability limit states) or the loss of bond between concrete and steel and an extreme reduction in the reinforcement section (ultimate limit states).

The phenomena that occur on concrete cannot only be connected to material properties, since they originate from a combination of material properties and environmental macro- and micro-climatic parameters [5].

In order to be used as the basis for the service life design approach, a *fib*-Model Code for Service Life Design [6] (*fib*-MCSLD) was prepared by *fib* Task Group 5.6 and has recently been considered as reference in Volume 2 [7] of *fib*-Model Code 2010 (*fib*-MC2010). Various deterioration mechanisms, such as carbonation-induced corrosion, chloride-induced corrosion and freeze/thaw attack, with or without de-icing agents, are examined in this document. The *fib*-Model Code 2010 [7] in particular proposes a physical model that can be used to assess the evolution of the carbonation depth in time, taking into account the relevant environmental and concrete quality parameters. However, the

* Corresponding author. Address: Corso Duca degli Abruzzi, 24, 10129 Torino, Italy. Tel.: +39 011 5644912; fax: +39 011 5644899.

E-mail addresses: matteo.guiglia@polito.it (M. Guiglia), maurizio.taliano@polito.it (M. Taliano).

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Nomenclature

b_c	exponent of regression for the calculation of k_c
b_w	exponent of regression for the calculation of $W(t)$
COV	coefficient of variation (for the carbonation depth or compressive strength of concrete)
C_S	CO_2-concentration
$C_{S,atm}$	CO_2-concentration in the atmosphere
$C_{S,emi}$	additional CO_2-concentration due to emission sources
$f_c(t)$	value of the compressive strength at an age t of a 150 mm by 300 mm concrete cylinder
$f_{c,cube}(t)$	value of the compressive strength at an age t of a 150 mm concrete cube
f_{cm}	mean value of the concrete compressive cylinder strength at 28 days
$f_{cm}(t)$	mean value of the concrete compressive cylinder strength at an age t
$f_{cm,cube}(t)$	mean value of the compressive strength at an age t of a 150 mm concrete cube on a relatively small portion of each structural element, a rough circle of about 1.0 m in diameter
k	carbonation rate constant
k_c	execution transfer parameter
k_e	environmental function
k_t	test-method factor
$N_{h\geqslant 2.5\text{mm}}$	number of rainy days
p_{sr}	probability of driving rain on the surface of the considered structural element
$R^{-1}_{ACC,0}$	inverse carbonation resistance of concrete obtained from an accelerated test performed in the laboratory (subscript "0")
RH_{real}	relative air humidity
$R^{-1}_{NAC,0}$	inverse effective carbonation resistance of concrete obtained on dry concrete specimens (RH = 65%) tested in the laboratory (subscript "0") under natural conditions
t	time
t_0	reference time
t_c	curing period
ToW	time of wetness, which is equal to the annual frequency of days with significant rainfall (rainy days with amounts of rain above 2.5 mm)
$W(t)$	weather function
$x_c(t)$	carbonation depth of concrete at time t
$x_{c,exp}(t)$	experimental value of the carbonation depth of concrete at time t
$x_{cm,exp}(t)$	mean value of the experimental values of the carbonation depth of concrete at time t on a relatively small portion of each structural element, a rough circle of about 1.0 m in diameter
ε_t	error term
σ	standard deviation (for the carbonation depth or compressive strength of concrete)

application of this theoretical model to existing r.c. structures is influenced by the difficulty of characterising the cast-in-place concrete, which is particularly demanding because of various factors (e.g. macro- and micro-climate, curing) that can produce an elevated scattering of the physical and mechanical properties of concrete. This is the case of the inverse carbonation resistance of concrete which, for the durability design of new structures [7,8], can be evaluated by means of accelerated carbonation tests [9,10], while the following investigation options can be adopted for existing structures [1]:

(a) From literature data, if the composition of the concrete is known (e.g. the type of cement and the water-to-cement ratio [6,11]).
(b) Accelerated carbonation testing with specimens from the structure (e.g. cores).
(c) Direct measurement of the carbonation depth on the structure.

In the present paper, the theoretical model of the carbonation depth proposed in *fib*-MCSLD and *fib*-MC2010 is discussed and applied to experimental results obtained from an extensive campaign. This experimentation includes cast-in-place uncracked concretes characterised by low and medium compressive strengths (20–50 N/mm^2) and concerns more than 120 in-field exposed existing r.c. structures, built along 135 km of a highway infrastructure, in different geographical areas. The comparison between the experimental and theoretical data has highlighted the key role played by the environment and the concrete quality parameters on the evolution of the carbonation depth. The direct measurement of the carbonation depth on the structure allows the inverse effective carbonation resistance of concrete to be determined in existing r.c. structures according to option *c* and then to be correlated to a simple and comprehensive material property, such as the compressive strength of concrete. This also leads to some relationships of the carbonation rate constant (mm year$^{-0.5}$) being obtained that can be used to assess the carbonation depth in the case of existing structures. Concrete strength can therefore be assumed as a rough indication of permeability, a parameter which influences the carbonation rate. This is an alternative approach to the approach that is based on the measurement of water absorption by immersion, which is often used in practice but also frequently criticised because of its inaccuracy [12].

2. The experimental programme

An extensive experimental campaign was carried out to characterise the materials that were used for an important Italian highway infrastructure. The testing programme, which analysed structures along about 135 km, included both in situ and laboratory tests on cast-in-place uncracked concretes which came from more than 120 works of art: bridges, viaducts, tunnels, flyovers, underpasses and retaining walls.

The campaign involved about 1350 compression tests on concrete specimens (cores) extracted from the structures, and the same number of carbonation depth tests. The tested concretes were characterised by low and medium compressive strengths (20–50 N/mm^2), and were up to 5 years old. Other information concerning the concrete mix design (cement type, kind and quantities of aggregates, water-to-cement ratio, admixtures), the curing time and the fabrication process was not available. However, in spite of the lack of information on the composition of the investigated concretes, some considerations on the cement types available on the Italian market in the considered period can be found in the annual Italian Cement Industry reports. These reports show that the three types of cement most in demand (year 2000) and which accounted for 72.0% of the total production, were: CEM II/A-L, CEM II/B-L, and CEM I, all three of which belong to the Portland cement category. CEM II/A-L was confirmed as being the most frequently used in construction, with a market share of 48.4%; second place was taken by CEM II/B-L, which accounted for 14.0%, and third place by CEM I, with a 9.6% share.

The concrete cores were taken using 100 mm diameter drills and a diamond core bit with constant water application. Thanks to the use of ultrasonic wave measurements, it was possible to investigate areas that did not present any surface cracking. The carbonation tests were carried out using a 1% phenolphthalein solution in ethyl alcohol [13]. The dates of the carbonation tests being known, as they coincide with those of the core drilling, as well as the dates of the concrete casting, which were provided by the construction company, it was possible to associate the ages of the concretes to the measured carbonation depths, $x_{c,exp}(t)$. Concrete specimens were then prepared in the laboratory from the extracted materials, with a height-to-diameter ratio of 1.0, and subjected to compression tests. According to EN13791 [14], these actual core results are equivalent to the strength values of 150 mm cubes, $f_{c,cube}(t)$ manufactured and cured under the same conditions. These results were then converted to cylinder strength values, which are equivalent to strength values of 150 mm by 300 mm cylinders, using the following relationship:

$$f_{cm}(t) = 0.83 \cdot f_{cm,cube}(t) \tag{1}$$

The variability connected to the testing method [15] is another element that causes scattering of the experimental data. In order to reduce the influence of this aspect, reference is here made to a relatively small portion of each structural element, that is an approximate circle of about 1.0 m in diameter, in which the concrete properties can be assumed constant. The experimental data, such as the ages of the concrete, the number of extracted cores, the measured carbonation depths (mean value $x_{cm,exp}(t)$, standard deviation σ_{xc} and coefficient of variation COV_{xc}) and compressive strengths (mean value $f_{cm,cube}(t)$, standard deviation σ_{fc} and coefficient of variation COV_{fc}) have been provided in annex A, with reference to the various investigated small portions of each structural element, for three geographical areas in which the structures are built. Variability due to the testing method can therefore be represented through the coefficient of variation, which is given by the ratio between the standard deviation and the mean value of the measurements repeated on the same concrete. The variation coefficient values of the carbonation depth and the compressive strength, referring to the various investigated small portions of each structural element, present mean values of 13.7% and 8.1%, respectively. As far as the compressive strength is concerned, the mean value of the coefficient of variation is similar to that found in the literature [16,17]. Moreover, if the values of the coefficients of variation are plotted together with the compressive strength of the concrete, a high scattering can be observed. It results that the coefficients of variation are not influenced by the compressive strength of the concrete. This also confirms that the above mentioned values of the variation coefficient are representative of the variability connected to the testing method.

Three geographical areas have been considered in annex A in order to contain structures no further apart than 40 km and to take into account as homogeneous the macro-climate characteristics of the surrounding environment. Other information on the meteorological data concerning these geographical areas is given afterwards.

All these data are analysed hereafter and compared using the mathematical model of the carbonation depth in time proposed in *fib*-MC2010.

3. Modelling the concrete Carbonation according to *fib*-MODEL CODE 2010

fib-MC2010 identifies four different levels of performance-based design that present different degrees of sophistication:

- A full probabilistic design, which needs environment data and their statistical elaboration, besides the definition of the material properties. This approach can be applied to assess existing structures, but is rarely used for new structures because of the lack of statistical data [4].
- A partial factor design (semi-probabilistic), in which the deterioration mechanisms are modelled with deterministic data, while the probabilistic nature of the problem is taken into account by means of partial safety coefficients.
- A deemed-to-satisfy design, which is based on tabulated numbers of the water-to-cement ratio, concrete cover, crack width, etc.
- Avoidance of deterioration by means of the use of non-reactive materials or by avoiding situations that can lead to deterioration, e.g. the use of stainless steel in order to prevent corrosion induced deterioration or avoiding the saturation of concrete to prevent the risk of frost attack.

The full probabilistic model is based on Fick's first law of diffusion, which states that the flux of mass through the unit area of a section, J, is proportional to the concentration gradient $\partial C/\partial x$ and the diffusion coefficient:

$$J = -D \cdot \frac{\partial C}{\partial x} \tag{2}$$

The model also considers the concrete quality, the environmental actions and the execution as the factors of influence that allow the evolution, in time, of the carbonation depth $x_c(t)$, in mm, to be assessed through the following formula [6]:

$$x_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot R^{-1}_{NAC,0} \cdot C_S} \cdot W(t) \cdot \sqrt{t} \tag{3}$$

where t = time (year); k_e = environmental function; k_c = execution transfer parameter, which takes into account the influence of the adopted curing measures, and which can differ from the natural conditions in the laboratory; $R^{-1}_{NAC,0}$ = inverse effective carbonation resistance of concrete, in (mm^2/year)/(kg$_{CO2}$/m^3), obtained on dry concrete specimens (RH = 65%) tested in laboratory (subscript "0") under natural conditions (NAC); C_S = CO_2-concentration (kg$_{CO2}$/m^3); $W(t)$ = weather function.

According to *fib*-MC2010 [7], Eq. (3) can also be written in the following form:

$$x_c(t) = k \cdot W(t) \cdot \sqrt{t} \tag{4}$$

where k is the carbonation rate constant (mm year$^{-0.5}$) that reflects the influence of the concrete quality and the environmental actions.

3.1. Influence of concrete quality

Among the various parameters that are involved, the inverse effective carbonation resistance of concrete, $R^{-1}_{NAC,0}$, takes into account the influence of the concrete quality on the carbonation depth. It can be assessed through direct or indirect test methods. The direct test method, which offers a rather poor repeatability [1], is an accelerated test that allows the inverse carbonation resistance of concrete under accelerated conditions, $R^{-1}_{ACC,0}$, to be determined [9,10]. When this method is used for the durability design of new structures, it is carried out on concrete specimens with the same composition as that of the design and which are cured under defined laboratory conditions. The corresponding value under

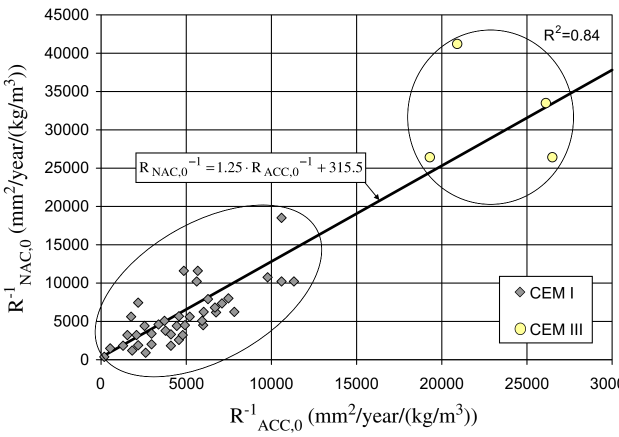

Fig. 1. Diagram of the inverse carbonation resistances[6,7], obtained under natural conditions (NAC) and from accelerated tests (ACC).

natural conditions is therefore obtained using the following expression [6] (Fig. 1):

$$R^{-1}_{NAC,0} = k_t \cdot R^{-1}_{ACC,0} + \varepsilon_t \tag{5}$$

where $R^{-1}_{ACC,0}$ = inverse carbonation resistance of concrete in an accelerated test under laboratory conditions; k_t = test-method factor (average value: 1.25); ε_t = error term (average value: 315.5 $(mm^2/year)/(kg_{CO2}/m^3)$).

As an alternative, if the concrete composition is known, above all the type of cement and the water-to-cement ratio, a value of $R^{-1}_{ACC,0}$ may also be chosen from a database or from literature data [6,11].

In the case of existing structures, the inverse effective carbonation resistance of concrete, $R^{-1}_{NAC,0}$, can be obtained indirectly by measuring the carbonation depth on the existing structure. From Eq. (3) it results that

$$R^{-1}_{NAC,0} = \frac{x_c(t)^2}{2 \cdot k_e \cdot k_c \cdot C_S \cdot t \cdot W(t)^2} \tag{6}$$

The latter methodology has been adopted in this work to correlate the inverse effective carbonation resistance to the compressive strength of concrete. In this way, it is possible to overcome the difficulty of characterising the cast-in-place concrete of existing structures, whose physical and mechanical properties are influenced by additional factors (e.g. macro- and micro-climate, curing) that can produce an elevated scattering. However, Eq. (6) is not useful for young concrete structures, in which the carbonation has not yet taken place to a sufficient extent to allow it to be measured [1].

3.2. Influence of environmental actions

Environmental actions are considered in terms of the chemical and physical conditions to which the structure is exposed, as well as the mechanical actions. Environmental exposure conditions affect the degree of water saturation of concrete and therefore control the penetration of CO_2 into the concrete. As an example, a rain event on an unsheltered element can lead to saturation of the concrete surface, and it can therefore prevent, at least temporarily, advancement of the carbonation front. Since carbonation is restricted to the concrete cover, it seems reasonable to assume a constant degree of water saturation of the concrete for unsheltered members, that is equal to the relative humidity of the surrounding air [1].

The effects of environmental actions are taken into account in Eq. (3) through the adoption of some parameters, such as the environmental function k_e, the CO_2-concentration of the ambient air C_s and the weather function $W(t)$, which make it possible to consider the various characteristics of the environment surrounding the structure at different levels:

- The macro-climate characteristics of the geographical area in which the structures are located, such as the relative humidity of the atmosphere, the number of rainy days per year, the amount of precipitation water and the CO_2-concentration of the ambient air.
- The micro-climate characteristics of the site in which a single structure is placed, e.g. an increase in relative humidity due to the presence of rivers.
- The exposure conditions of each particular portion of the structure, connected to the exposure of the concrete surface, such as factors that can modify dry-wet cycles (water infiltration across the joins, water sprayed from vehicles), inclination of the rain direction and the presence of shelters.

The environmental function, k_e, which considers the influence of the relative humidity of the atmosphere, is given by

$$k_e = \left\{ \left[1 - \left(\frac{RH_{real}}{100} \right)^5 \right] \bigg/ \left[1 - \left(\frac{65}{100} \right)^5 \right] \right\}^{2,5} \tag{7}$$

where RH_{real} = relative air humidity obtained at the nearest weather station.

The CO_2-concentration of the ambient air, C_s, can be calculated with the equation:

$$C_S = C_{S,atm} + C_{S,emi} \tag{8}$$

where $C_{S,atm}$ = CO_2-concentration of the atmosphere, which in *fib*-MC2010 is assumed equal to 0.00082 $kgCO_2/m^3$; $C_{S,emi}$ = additional CO_2-concentration due to emission sources.

The weather function, $W(t)$, takes into account the effects of the exposure conditions of each portion of the structure on the evolution of carbonation, and is expressed as

$$W(t) = \left(\frac{t_0}{t} \right)^{\frac{(p_{sr} \cdot ToW)^{b_w}}{2}} \tag{9}$$

where t = time, in years; t_0 = reference time, in years, which means the age at which the ACC-test is performed (e.g. t_0 = 28 days = 0.0767 years); p_{sr} = probability of driving rain on the surface of the considered structural element; ToW = time of wetness, which is the annual frequency of days with significant rainfall (rainy days with amounts of rain above 2.5 mm); b_w = regression exponent, which, on average, is equal to 0.446.

Both the probability of driving rain and the time of wetness depend on the number of rainy days $N_{h \geq 2.5mm}$. In particular, the probability of driving rain p_{sr}, which is introduced to correlate the number of rainy days to the orientation of the concrete surface, is assumed as the ratio between the number of rainy days with wind in a direction that can wet the surface and the total number of rainy days. Two limit situations can therefore be considered. In the case of concrete sheltered from rain (ToW = 0 and p_{sr} = 0), it results that $W(t)$ = 1, namely the evolution of carbonation is not influenced by the number of rainy days. Instead, for external concrete unsheltered from rain and permanently wet (ToW = 100% = 1 and p_{sr} = 1) it results that:

$$W(t) = \sqrt{t_0/t} \tag{10}$$

Substituting Eq. (10) in Eq. (3) and eliminating the variable time t, the carbonation depth remains constant in time for external concrete unsheltered from rain and permanently wet.

3.3. Influence of execution

On-site curing conditions influence the inverse effective carbonation resistance of concrete. To this aim, Eq. (6) introduces the execution transfer parameter k_c

$$k_c = \left(\frac{t_c}{7}\right)^{b_c} \tag{11}$$

where t_c = period of curing, in days; b_c = regression exponent, which, according to *fib*-MC2010, is equal to -0.567.

4. Basic assumptions for the interpretation of the experimental data

Experimental data and other information concerning micro- and macro-climate characteristics have been used here to obtain the inverse effective carbonation resistance of concrete, $R^{-1}_{NAC,0}$, through Eq. (6) and to correlate it to the concrete compressive strength. This correlation offers an additional possibility of obtaining the inverse effective carbonation resistance through a simple and comprehensive concrete parameter, such as the compressive strength, without knowing its composition, as usually occurs in practice for existing structures [18]. The basic idea behind the proposed correlation is supported by a physical reason. Non carbonated concretes with high strength show low porosity and a low permeability towards carbon dioxide, which causes concrete carbonation. In high strength concretes the carbonation rate in time is, in fact, reduced on the same moisture conditions. This aspect is taken into account in international standards (Eurocode 2, ACI-318) for the design of concrete structures that also require the use of higher strength concretes when the environmental conditions can favour the carbonation process. Moreover, in this paper, two characteristics of the same concrete are compared, but under different conditions with reference to carbonation: the strength of non carbonated concrete inside the considered structure and the carbonation depth of the same concrete at the surface. The compression strength is assumed as the material parameter to assess the good quality of the concrete, as a substitute for other material parameters that can affect it, such as the cement type, the additions and the water-to-cement ratio.

The macro-climate characteristics of the environment in which the structures are built have been taken into account considering three geographical areas in order to contain structures no further apart than 40 km and to take into account as homogeneous the macro-climate characteristics of the surrounding environment. Indicatively, the actual environmental conditions of examined structures can also be designated, according to *fib*-MC2010, to the exposure class "Corrosion induced by carbonation", sub-class XC3-"External concrete sheltered from rain" for the surfaces in sheltered zones (abutments, piers and tunnels). The sub-class XC4-"Concrete surfaces subject to water contact" is more appropriate for walls. The analysis of the experimentally determined chloride contents on the surface concretes indicates that the concrete surfaces were not exposed to sprays containing chlorides or subjected to chlorides from sea water.

Table 1
Meteorological data and environmental function (mean values).

Geographical area	RH_{real} (%)	$N_{h\geqslant 2.5\text{mm}}$	k_e
I	64	84	1.025
II	67	104	0.947
III	75	64	0.691

Table 1 shows the relative humidity, RH_{real}, and the number of rainy days, $N_{h\geqslant 2.5\text{mm}}$, for each geographical area, information that was obtained from public weather stations. The relative humidity has been calculated as the average of the relative humidity values measured in the diurnal hours throughout the year. Both the relative humidity and the number of rainy days have been defined referring to a 3-year period during the service life of the structures. On the basis of the meteorological data, the environmental function, k_e, is determined for each geographical area.

The number of rainy days for each geographical area also allows the weather function, $W(t)$, to be determined. The probability of driving rain, p_{sr}, has been assumed equal to zero, because the investigation refers to sheltered zones. The weather function therefore does not depend on the geographical area, which means $W(t) = 1$. This assumption is here considered unrealistic in the case of walls as they are unsheltered elements. This structural typology is characterised by moderate water stagnation because of its vertical surface, which complicates the analysis. For this reason, the walls have not been considered in the following calculation of the inverse effective carbonation resistance of concrete.

The CO_2-concentration of the ambient air, C_S, has been assumed equal to 0.00082 kgCO_2/m^3 for all the investigated structures, according to *fib*-MC2010 [8]. An additional CO_2-concentration, due to emission sources (0.00049 kgCO_2/m^3) has only been considered for tunnels.

As far as the curing conditions are concerned, a curing time of 3 days, which is typical in Italy, has been considered, the execution transfer parameter k_c has been calculated (k_c = 1.617) and the value of the regression exponent given in *fib*-MC2010 is adopted.

Finally, the inverse effective carbonation resistance of concrete under natural conditions, $R^{-1}_{NAC,0}$, has been obtained applying Eq. (6), which leads to:

$$R^{-1}_{NAC,0} = \frac{377 \cdot x_c(t)^2}{k_e \cdot t} \quad \text{for abutments and piers} \tag{12a}$$

$$R^{-1}_{NAC,0} = \frac{236 \cdot x_c(t)^2}{k_e \cdot t} \quad \text{for tunnels} \tag{12b}$$

These equations only differ because of the different CO_2-concentrations in the ambient air. The higher concentration of CO_2 assumed for tunnels leads to a lower inverse effective carbonation resistance of the concrete, as can be seen from the smaller numerical coefficient in Eq. (12b).

Further considerations can also be made concerning the compressive strength of concrete, which is in fact measured at the age of the inspection, although this property changes and evolves in time. According to *fib*-MC2010 [8], the evolution in time of the concrete compressive strength can be expressed as a function of the standardised mean value at 28 days, depending on the type of cement, temperature and curing conditions, through the following equation:

$$f_{cm}(t) = e^{s \cdot \left[1 - \left(\frac{28}{t}\right)^{1/2}\right]} \cdot f_{cm} \tag{13}$$

where t = time, in days; s = coefficient which depends on the strength class and hardening characteristics of the cement; $f_{cm}(t)$ = mean value of the compressive strength of concrete at age t; f_{cm} = mean value of the compressive strength of concrete at 28 days, correlated to the characteristic value through the relationship:

$$f_{cm} = f_{ck} + 8 \tag{14}$$

in which f_{cm} and f_{ck} are in N/mm^2.

Because of the lack of information on the cement types used for the studied concretes, a cement of medium strength and normal hardening characteristics has been considered, that is, a cement 42.5 N, to which a value of 0.25 corresponds for the above mentioned coefficient s, according to *fib*-MC2010 [8].

The mean compressive strength of concrete at 28 days, f_{cm}, can therefore be correlated to the experimental strength values measured at age t of the inspection (t in days) through the following equation:

$$f_{cm} = e^{-0.25 \cdot \left[1-\left(\frac{28}{t}\right)^{1/2}\right]} \cdot f_{cm}(t) \tag{15}$$

In order to have a better understanding of the different exposure conditions of each particular portion of the structure, the values of the inverse effective carbonation resistance and the compressive strength of concrete have also been divided into three structural typologies: abutments, piers and tunnels.

5. Comparison between the experimental and theoretical results

The inverse effective carbonation resistance under natural conditions is shown in Fig. 2a–c as a function of the mean value of the compressive strength at 28 days for the three structural typologies, on the basis of the assumptions made on the micro- and macro-climate characteristics. Each diagram also contains the curves of the correlation functions, which were obtained using the least squares method. Fig. 2d also shows the values of $R^{-1}_{NAC,0}$ that are obtained for walls when Eq. (11a) is applied. In the case of existing structures, despite the remarkable scattering of the experimental data, the concrete compressive strength at 28 days is here used as the concrete parameter to be correlated to the inverse effective carbonation resistance.

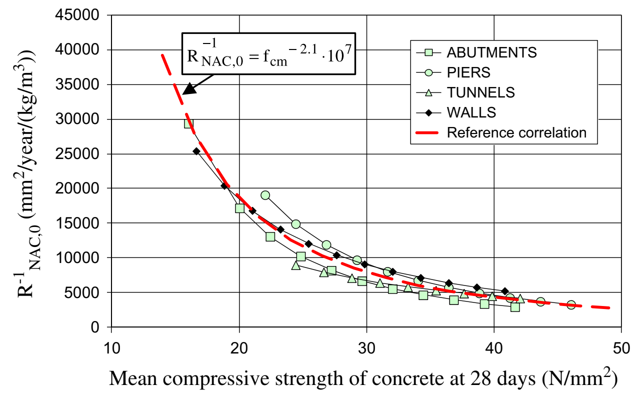

Fig. 3. Comparison between the correlation functions of the inverse effective carbonation resistance of concrete as a function of the mean compressive strength of concrete at 28 days.

Fig. 3 shows the reference curve that interpolates the three correlation functions (for abutments, piers and tunnels), whose equation is ($R^{-1}_{NAC,0}$ in mm^2/year/(kg/m^3), f_{cm} in N/mm^2):

$$R^{-1}_{NAC,0} = f_{cm}^{-2.1} \cdot 10^7 \tag{16}$$

Using this interpolation function, the inverse effective carbonation resistance is assumed as a concrete property, regardless of the various structural typologies. The level of reliability is lower than that shown in Fig. 1 where the inverse effective carbonation resistance is obtained from accelerated tests ($R^2 = 0.84$). However, the consequent simplifications are remarkable. In fact, the interpolating function, Eq. (16), can be used to obtain the theoretical val-

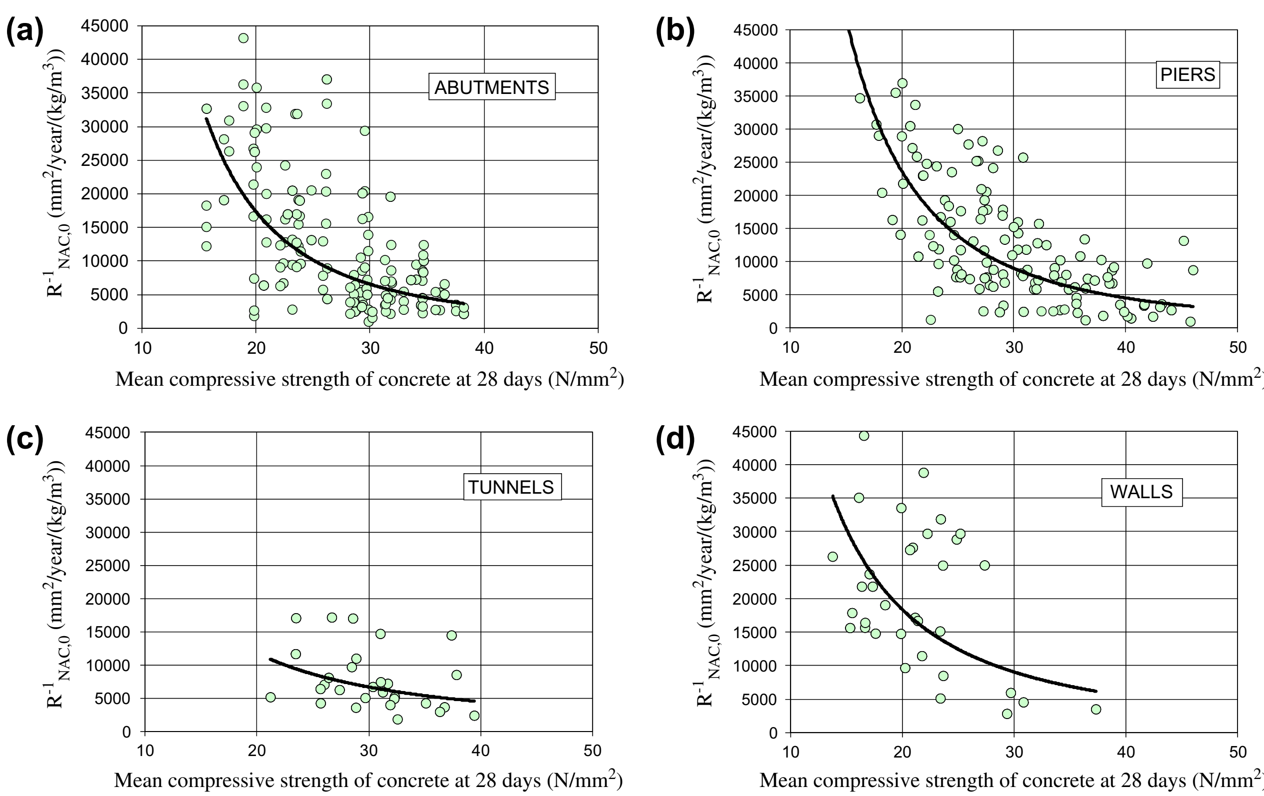

Fig. 2. Inverse effective carbonation resistance of concrete under natural condition, $R^{-1}_{NAC,0}$, as a function of the mean compressive strength at 28 days of concrete for: (a) abutments; (b) piers; (c) tunnels; (d) walls.

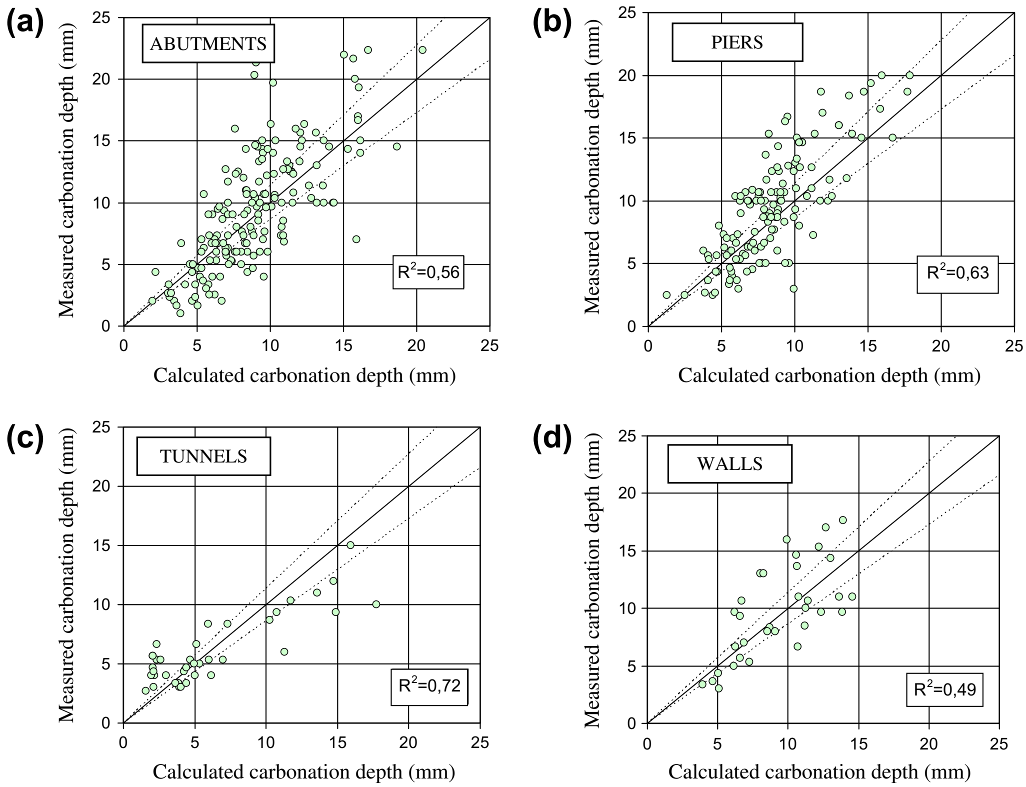

Fig. 4. Comparison between experimental and theoretical values of the carbonation depth for the considered structural typologies: (a) abutments; (b) piers; (c) tunnels; (d) walls.

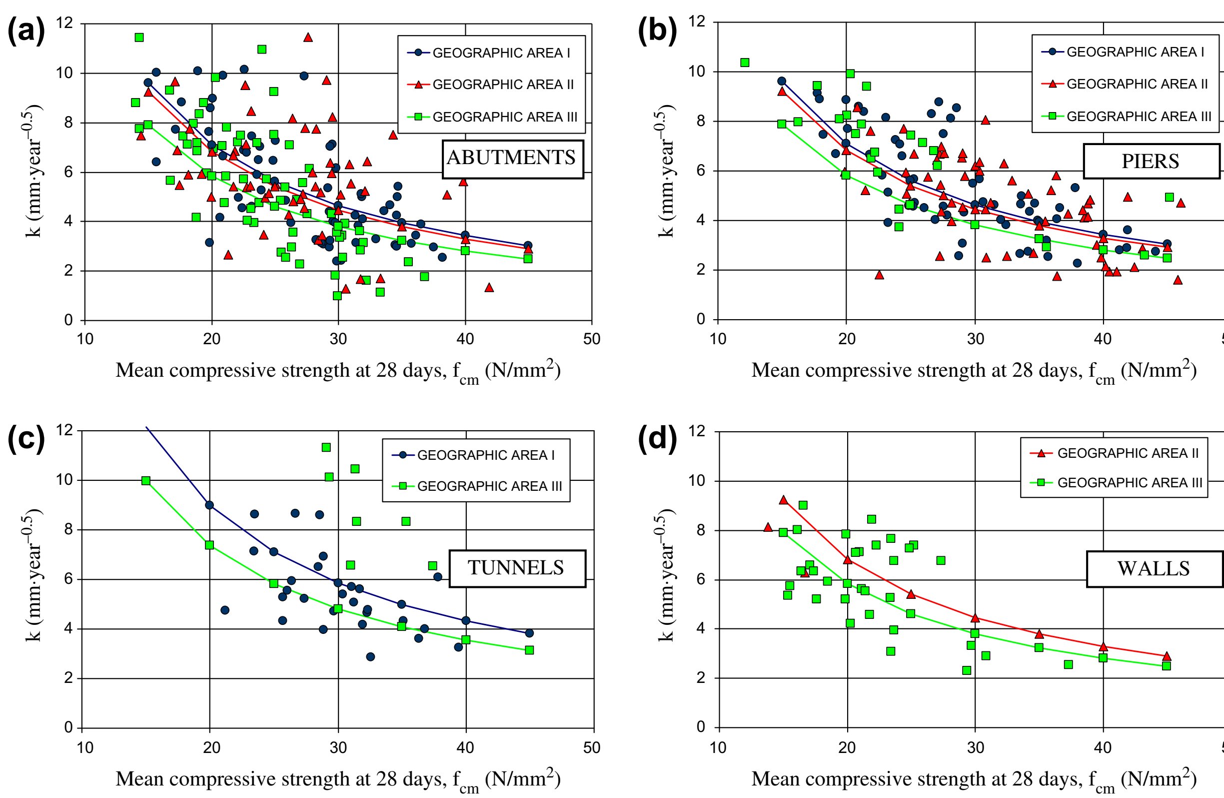

Fig. 5. Diagrams of the carbonation rate constant, *k*, as a function of the mean compressive strength of concrete at 28 days for the various structural typologies and the considered geographical areas: (a) abutments; (b) piers; (c) tunnels; (d) walls.

Table 2
Values of carbonation rate constants k from real indoor structures [19] and accelerated tests [20].

Concrete strength	Exposure condition	k (mm year$^{-0.5}$)
Low (<21 N/mm^2)	Real indoor structures	10
Medium (25–30 N/mm^2)		5
High (45–50 N/mm^2)		2
Low (18.5 and 20.5 N/mm^2)	Accelerated tests	16.9 and 15.5
Medium (26.5 and 27.0 N/mm^2)		11.9 and 10.8

ues of the carbonation depth of the concrete (in mm), through Eq. (3), as a function of only three parameters: the mean compressive strength at 28 days, f_{cm} (in N/mm^2), the age of the structure, t (in years), and the dimensionless environmental function, k_e, which only depends on the relative humidity of the air:

$$x_c(t) = 163 \cdot \sqrt{k_e \cdot f_{cm}^{-2.1}} \cdot \sqrt{t} \quad \text{for abutments and piers} \tag{17a}$$

$$x_c(t) = 206 \cdot \sqrt{k_e \cdot f_{cm}^{-2.1}} \cdot \sqrt{t} \quad \text{for tunnels} \tag{17b}$$

These correlations show the effect of the additional concentration of CO_2 assumed for tunnels which leads to an increase of the carbonation depth of the concrete in time, if other parameters (concrete strength and environmental function) are assumed constant.

It is worth noting that Eqs. (17a) and (17b) refer to concretes sheltered from rain for which the weather function $W(t)$ is equal to 1.0.

The accuracy and reliability of Eqs. (17a) and (17b) can be analysed in Fig. 4a–c where the theoretical values of the carbonation depth are compared with the experimental values. Despite the moderate level of reliability, this comparison shows that assessing the inverse effective carbonation resistance of the concrete through its compressive strength is very simple. However, this method is not very reliable, even considering that, as far as the carbonation depth is concerned, the variability connected to the testing method is equal to 13.7% of the measured value. The dotted lines in Fig. 4a–c graphically show this variability of the testing method. A comparison has also been performed for walls in Fig. 4d. In this case, the low reliability ($R^2 = 0.49$) confirms that the assumption on the environmental exposure made for the other structural typologies (sheltered elements) is not valid for walls. When the correlation functions of each structural typology are used, the reliability does not change.

An analogous analysis has also been performed in Fig. 5a–d, which compare the experimental values of the carbonation rate constant k, mentioned in Eq. (4), with the theoretical curves obtained for each geographical area as a function of the mean compressive strength at 28 days of the concrete. Assuming $W(t) = 1$ for the weather function, the equations corresponding to the theoretical curves can be represented by the terms that multiply the function $\sqrt{t}$ in Eqs. (17a) and (17b):

$$k = 163 \cdot \sqrt{k_e \cdot f_{cm}^{-2.1}} \quad \text{for abutments and piers} \tag{18a}$$

$$k = 206 \cdot \sqrt{k_e \cdot f_{cm}^{-2.1}} \quad \text{for tunnels} \tag{18b}$$

where f_{cm} is expressed in N/mm^2 and k in mm year$^{-0.5}$.

Higher values of relative humidity can be observed passing from geographical areas I–III. This leads to lower values of the carbonation rate constant and therefore lower values of the carbonation depth in time. As expected, in Fig. 5a–d the theoretical curves of k move down passing from geographical areas I–III. Despite a remarkable scattering, the values of the carbonation rate constant, k, are in agreement with published data [19] for various grades of concrete exposed to normal atmospheric conditions (Table 2). As already observed by other researchers [20], it can be seen that the carbonation rate constants in the accelerated tests are usually higher than those expected for typical indoor exposure. The same authors attribute these differences to the different CO_2 contents in the atmosphere (from 500 ppm up to 1000 ppm being recorded indoors) or in the air of the accelerated tests (60,000 ppm).

6. Conclusions

An extensive experimental campaign has been carried out on cast-in-place uncracked concretes of in-field exposed existing r.c. structures. The experimental values of the carbonation depth have been analysed using the theoretical model proposed in the *fib*-Model Code for Service Life Design and recently introduced in Model Code 2010. This analysis allows the inverse effective carbonation resistance of concrete in existing r.c. structures to be determined. A correlation function for the assessment of the inverse effective carbonation resistance for abutments, piers and tunnels has been proposed as a function of the mean compressive strength of concrete at 28 days.

The following conclusions can be drawn from the study:

- Reducing the scattering of the examined physical and mechanical properties of concrete is particularly demanding because they are influenced by different factors, that is macro- and micro-climate characteristics and variability connected to the testing method. Attempts have been made to reduce this scattering or to evaluate it. The examined structures have been divided into three geographical areas in which the macro-climate characteristics have been considered homogeneous and two micro-climate characteristics of the structures have been taken into account, one for abutments and piers and the other for tunnels. Assuming that the variation coefficients of the carbonation depth and the compressive strength are representative of the variability connected to the testing method, it appears from the study that the variation coefficient values are, on average, equal to 13.7% and 8.1%, respectively.
- The comparison between experimental measurements and theoretical values of the carbonation depth, obtained with the *fib*-model and the proposed correlation of the inverse effective carbonation resistance, has shown a moderate level of reliability of this correlation. This highlights the key role played by the environment in which the structures are built.
- However, the proposed correlation function offers an additional possibility of obtaining the inverse effective carbonation resistance through a simple and comprehensive concrete parameter, such as the compressive strength, without the necessity of knowing the composition of the concrete, as usually occurs in practice in the case of existing structures.
- The carbonation rate constant k (mm year$^{-0.5}$) can also be obtained theoretically, on the basis of the proposed correlation. The theoretical values of k have been compared with the experimental values. A remarkable scattering of the experimental values and a low reliability of the theoretical curves have been observed. However, instead of using a global carbonation rate constant, k, from the literature, the *fib*-model allows the carbonation rate constant to be obtained through a simple formula which takes into account the macro-climate conditions in explicit form.

Appendix A. Database of the experimental campaign

A.1. Geographical area I

Structure	Structural element	Service life (year)	Total number of extracted cores	Experimental carbonation depth			Experimental compressive strength		
				Mean value, $x_{cm}(t)$ (mm)	Standard deviation, σ_{xc} (mm)	$(COV)_{xc}$ (%)	Mean value, $f_{cm}(t)$ (N/mm^2)	Standard deviation, σ_{fc} (N/mm^2)	$(COV)_{fc}$ (%)
101	Pier	1.92	3	10.3	1.2	11.2	26.8	2.4	8.9
	Pier	1.92	3	12.7	1.2	9.1	26.1	1.5	5.6
	Abutment	1.84	3	9.3	1.5	16.4	33.2	5.1	15.4
	Abutment	2.01	2	12.5	0.7	5.7	26.0	0.7	2.7
102	Abutment	1.84	3	9.0	1.0	11.1	30.8	4.2	13.6
103	Abutment	1.92	3	9.0	1.0	11.1	34.9	3.3	9.5
104	Pier	2.42	3	7.0	1.0	14.3	38.6	4.4	11.4
	Pier	2.50	3	6.7	2.1	31.2	41.3	1.8	4.2
	Pier	2.52	3	9.0	1.7	19.2	37.4	2.9	7.8
	Pier	2.60	3	10.7	0.6	5.4	36.1	5.0	13.8
	Abutment	2.44	3	10.0	1.0	10.0	23.2	1.8	7.6
105	Pier	3.54	1	5.0			50.0		
	Pier	3.46	4	7.3	1.3	17.4	34.6	2.3	6.7
	Abutment	3.38	3	6.3	1.2	18.2	53.8	1.5	2.7
	Abutment	3.38	3	5.7	1.2	20.4	42.9	4.8	11.1
106	Abutment	2.96	3	9.3	0.6	6.2	51.6	3.0	5.8
107	Tunnel	0.72	3	4.0	1.0	25.0	42.3	4.3	10.2
108	Tunnel	0.43	3	3.3	0.6	17.3	43.5	2.7	6.2
	‘	0.52	3	4.7	0.6	12.4	40.0	0.4	1.1
	‘	0.52	3	3.3	0.6	17.3	45.3	3.2	7.1
	‘	0.52	3	3.0	0.0	0.0	44.8	3.9	8.7
	‘	0.59	3	5.3	0.6	10.8	40.8	5.3	13.0
	‘	0.59	3	6.7	0.6	8.7	37.8	2.6	6.9
	‘	0.60	3	4.3	0.6	13.3	44.8	2.5	5.5
	‘	0.81	3	5.3	0.6	10.8	37.8	1.2	3.1
109	Tunnel	0.43	3	4.0	1.0	25.0	52.7	5.8	10.9
110	Tunnel	0.77	3	5.0	0.0	0.0	44.4	0.1	0.3
	‘	0.85	3	5.0	1.0	20.0	43.6	2.9	6.6
	‘	0.85	3	3.0	1.0	33.3	56.6	1.5	2.7
	‘	0.85	3	3.3	0.6	17.3	52.2	1.8	3.5
	‘	0.93	3	8.3	1.5	18.3	33.8	0.6	1.7
	‘	0.94	3	8.3	1.5	18.3	41.2	8.0	19.5
	‘	1.02	3	5.3	0.6	10.8	37.1	3.1	8.4
	‘	1.02	3	4.0	0.0	0.0	41.7	2.9	7.0
111	Tunnel	4.42	2	6.0	0.0	0.0	48.8	0.4	0.7
	‘	4.42	3	11.0	1.7	15.7	41.0	0.5	1.2
	‘	4.42	3	10.0	0.0	0.0	31.8	1.6	4.9
	‘	4.42	4	15.0	0.0	0.0	35.1	1.6	4.7
	‘	4.68	3	9.3	1.2	12.4	38.5	5.4	14.1
	‘	4.68	2	12.0	0.0	0.0	39.0	0.7	1.8
	‘	4.68	3	10.3	1.5	14.8	48.4	3.4	7.0
	‘	4.68	3	8.7	1.5	17.6	55.1	5.1	9.3
	‘	4.68	3	9.3	1.2	12.4	52.6	7.6	14.5
112	Pier	1.45	3	5.7	0.6	10.2	37.0	1.8	4.7
	Abutment	1.37	3	5.3	0.6	10.8	32.7	1.4	4.4
113	Abutment	1.51	3	4.0	1.0	25.0	41.3	3.0	7.3
114	Abutment	1.46	3	6.0	1.0	16.7	32.3	0.6	1.9

Geographical area I (*continued*)

Structure	Structural element	Service life (year)	Total number of extracted cores	Experimental carbonation depth			Experimental compressive strength		
				Mean value, $x_{cm}(t)$ (mm)	Standard deviation, σ_{xc} (mm)	$(COV)_{xc}$ (%)	Mean value, $f_{cm}(t)$ (N/mm^2)	Standard deviation, σ_{fc} (N/mm^2)	$(COV)_{fc}$ (%)
115	Pier	1.42	3	5.7	0.6	10.2	44.8	2.4	5.3
	Abutment	2.07	3	6.0	0.0	0.0	30.5	2.3	7.5
116	Pier	4.94	3	18.7	1.2	6.2	32.0	1.8	5.6
	Abutment	4.94	3	22.0	2.6	12.0	31.3	0.9	3.0
117	Pier	4.78	3	6.0	0.0	0.0	51.2	1.6	3.1
	Abutment	5.11	3	6.7	0.6	8.7	56.3	3.4	6.1
	Abutment	5.11	3	10.0	0.0	0.0	50.4	1.0	2.0
118	Pier	4.87	3	16.0	1.0	6.3	35.8	2.4	6.7
	Abutment	4.95	3	15.7	0.6	3.7	35.8	2.0	5.5
	Abutment	4.96	3	7.0	2.6	37.8	29.8	1.6	5.2
119	Pier	3.56	3	10.0	0.0	0.0	56.4	1.8	3.1
	Abutment	2.87	3	5.0	0.0	0.0	43.5	0.9	2.0
	Abutment	3.70	3	4.7	0.6	12.4	45.1	2.5	5.6
120	Pier	4.70	3	12.3	1.5	12.4	45.5	9.5	21.0
	Abutment	4.05	3	14.3	4.0	28.2	44.2	3.0	6.7
	Abutment	4.71	3	10.0	3.6	36.1	34.8	1.9	5.4
121	Abutment	5.20	3	9.7	2.5	26.0	47.0	0.9	1.8
122	Pier	3.96	3	9.3	1.2	12.4	51.8	3.4	6.6
	Abutment	3.97	3	19.7	0.6	2.9	40.8	4.2	10.2
	Abutment	4.04	3	15.0	0.0	0.0	34.7	0.9	2.7
123	Pier	3.54	3	6.0	1.0	16.7	53.1	1.1	2.1
	Pier	3.79	3	10.7	1.2	10.8	44.6	0.8	1.8
	Abutment	4.62	3	15.7	1.5	9.8	37.5	0.7	1.8
124	Abutment	5.15	3	7.3	0.6	7.9	44.1	1.5	3.5
125	Abutment	5.18	3	9.7	1.5	15.8	51.9	5.3	10.3
	Abutment	5.18	2	10.0	1.4	14.1	44.0	0.7	1.6
126	Pier	1.62	3	10.3	0.6	5.6	41.3	0.3	0.6
	Abutment	1.71	6	7.0	1.9	27.1	42.8	2.5	5.9
	Abutment	1.71	3	4.0	0.0	0.0	50.6	2.1	4.2
127	Pier	3.13	3	7.7	3.1	39.8	43.4	4.7	10.9
	Abutment	4.62	3	11.3	0.6	5.1	35.8	2.9	8.1
128	Pier	3.19	3	12.7	2.5	19.9	36.0	5.3	14.7
	Abutment	3.19	3	11.0	1.0	9.1	44.4	1.5	3.4
129	Pier	4.03	3	11.7	1.5	13.1	34.1	5.8	17.0
	Abutment	4.03	3	13.0	1.7	13.3	37.2	2.4	6.4
130	Pier	3.95	3	8.0	1.7	21.7	40.3	5.7	14.0
	Abutment	4.12	3	8.0	1.7	21.7	39.3	4.0	10.3
131	Pier	3.78	2	10.0	0.0	0.0	34.8	1.8	5.1
	Abutment	3.78	3	15.0	1.7	11.5	25.7	1.5	6.0
132	Pier	2.43	3	13.7	2.3	16.9	40.3	1.8	4.3
	Pier	4.01	3	15.0	0.0	0.0	41.2	2.5	6.1
	Abutment	2.59	3	16.3	2.3	14.1	33.5	12.9	38.6
	Abutment	4.26	3	10.3	1.5	14.8	47.7	7.9	16.6
133	Pier	3.75	3	5.0	0.0	0.0	42.9	5.7	13.2
	Abutment	4.05	3	6.0	1.0	16.7	51.8	3.5	6.8
134	Pier	3.90	3	5.0	0.0	0.0	53.3	2.3	4.2
	Pier	4.75	3	10.0	0.0	0.0	37.3	3.3	8.8
	Abutment	2.48	3	7.3	0.6	7.9	50.4	8.3	16.5
	Abutment	3.29	3	6.0	1.0	16.7	49.1	2.1	4.3
	Abutment	3.29	3	4.3	1.2	26.6	44.5	2.6	5.9
	Abutment	3.48	3	7.7	0.6	7.5	47.6	1.7	3.6

(*continued on next page*)

Geographical area I (*continued*)

Structure	Structural element	Service life (year)	Total number of extracted cores	Experimental carbonation depth			Experimental compressive strength		
				Mean value, x_{cm} (t) (mm)	Standard deviation, σ_{xc} (mm)	$(COV)_{xc}$ (%)	Mean value, $f_{cm}(t)$ (N/mm^2)	Standard deviation, σ_{fc} (N/mm^2)	$(COV)_{fc}$ (%)
135	Pier	3.81	3	16.7	2.9	17.3	42.7	3.0	7.1
	Abutment	4.01	3	7.7	1.2	15.1	47.2	0.8	1.6
136	Pier	3.91	4	4.5	1.0	22.2	56.8	2.2	3.9
	Pier	4.41	4	5.8	1.0	16.7	66.0	5.6	8.5
	Pier	4.66	4	8.8	1.5	17.1	54.6	3.3	6.1
	Pier	4.82	4	10.3	1.3	12.3	50.4	5.4	10.6
	Abutment	3.66	3	6.0	1.0	16.7	46.8	0.3	0.6
	Abutment	3.66	5	6.0	1.4	23.6	42.8	3.7	8.6
	Abutment	4.22	4	10.5	5.3	50.1	47.6	5.3	11.2
	Abutment	4.24	4	5.3	0.5	9.5	57.2	1.4	2.5
137	Pier	4.59	3	10.7	1.2	10.8	50.4	1.4	2.7
	Abutment	4.87	3	13.0	2.0	15.4	35.3	2.2	6.2
138	Abutment	4.87	3	15.0	0.0	0.0	34.2	3.8	11.0
139	Pier	5.06	3	20.0	0.0	0.0	26.9	0.4	1.4
	Pier	5.06	3	17.3	2.5	14.5	30.2	2.4	7.8
140	Pier	4.75	3	8.3	1.5	18.3	48.6	2.4	4.9
	Abutment	4.91	3	22.3	1.5	6.8	28.3	4.8	17.0
141	Pier	4.09	3	9.3			47.1		
	Abutment	4.96	3	22.3	2.3	10.3	23.5	1.3	5.3
142	Pier	2.48	3	6.3	0.6	9.1	47.4	1.3	2.7
	Abutment	2.30	3	7.3	1.5	20.8	38.3	6.3	16.5
143	Pier	5.05	3	19.3	1.5	7.9	31.4	2.1	6.7
	Pier	5.07	3	15.0	0.0	0.0	32.8	0.9	2.6
144	Pier	5.05	3	18.3	3.5	19.2	34.7	2.3	6.5
	Pier	5.07	2	20.0	1.4	7.1	30.0	2.1	7.1
145	Pier	5.05	3	15.0	0.0	0.0	28.8	2.8	9.9
	Pier	5.07	3	18.7	1.2	6.2	40.0	2.6	6.5
146	Abutment	4.97	3	17.0	2.0	11.8	29.7	3.1	10.3
147	Pier	4.32	3	8.3	1.2	13.9	52.3	3.3	6.3
	Abutment	4.97	3	20.0	2.0	10.0	30.1	2.6	8.7
148	Pier	4.24	2	9.0	0.0	0.0	51.3	14.5	28.3
	Abutment	5.06	3	19.3	0.6	3.0	29.8	1.4	4.6
149	Abutment	2.16	3	7.3	0.6	7.9	51.2	7.5	14.7
150	Abutment	2.24	2	6.0	0.0	0.0	43.7	2.6	5.9
151	Pier	1.91	3	6.3	1.2	18.2	40.6	2.0	5.0
	Pier	1.91	3	6.3	0.6	9.1	37.1	1.6	4.3
	Pier	1.91	4	6.3	1.5	24.0	53.9	5.7	10.6
	Pier	2.00	3	4.3	1.2	26.6	42.8	2.0	4.8
	Abutment	1.83	3	9.5	0.7	7.4	43.1	2.3	5.3
	Abutment	1.83	3	5.3	0.6	10.8	43.8	1.1	2.5
152	Pier	3.58	3	5.3	0.6	10.8	61.6	2.3	3.8
	Abutment	3.57	3	7.3	0.6	7.9	54.5	10.6	19.5
153	Pier	3.41	3	6.7	0.6	8.7	62.4	2.9	4.7
154	Pier	3.41	3	5.3	0.6	10.8	62.3	2.0	3.2
	Abutment	3.32	3	5.7	1.2	20.4	53.3	3.9	7.4

A.2. Geographical area II

Structure	Structural element	Service life (year)	Total number of extracted cores	Experimental carbonation depth			Experimental compressive strength		
				Mean value, $x_{cm}(t)$ (mm)	Standard deviation, σ_{xc} (mm)	$(COV)_{xc}$ (%)	Mean value (N/mm^2)	Standard deviation, σ_{fc} (N/mm^2)	$(COV)_{fc}$ (%)
201	Abutment	2.33	2	14.5	0.7	4.9	33.5	1.4	4.2
		2.33	2	14.5	0.7	4.9	33.5	1.4	4.2
202	Abutment	2.25	1	4.0			31.5		
203	Abutment	2.33	1	5.0			42.0		
204	Pier	2.83	2	7.5	0.7	9.4	45.8	0.4	0.8
	Pier	2.66	3	10.7	1.2	10.8	43.0	3.3	7.6
205	Pier	2.83	3	9.7	0.6	6.0	39.2	1.3	3.2
206	Abutment	4.00	3	10.0	2.0	20.0	29.8	1.8	5.9
207	Pier	2.25	3	10.0	0.0	0.0	37.3	1.6	4.3
	Pier	2.25	2	10.0	0.0	0.0	40.3	4.6	11.4
208	Abutment	2.38	1	2.0			45.3		
209	Pier	2.87	3	7.0	0.0	0.0	57.3	7.0	12.2
	Abutment	2.38	3	12.7	0.6	4.6	43.7	1.5	3.5
	Abutment	2.46	3	10.0	2.0	20.0	43.5	5.3	12.2
210	Pier	2.96	3	9.0	1.0	11.1	53.4	0.5	1.0
	Pier	2.96	6	10.8	3.2	29.4	47.9	2.9	6.1
	Pier	2.96	3	10.0	0.0	0.0	54.0	3.3	6.0
	Pier	2.96	3	10.3	0.6	5.6	45.2	6.9	15.4
	Pier	2.96	3	9.7	0.6	6.0	48.9	6.2	12.7
	Pier	2.96	3	10.7	0.6	5.4	44.6	7.6	17.0
	Abutment	1.54	3	6.3	1.5	24.1	44.2	2.5	5.7
	Abutment	2.46	3	8.7	0.6	6.7	45.9	2.1	4.6
211	Pier	2.96	3	7.3	1.5	20.8	55.3	2.0	3.7
	Abutment	2.96	3	7.3	0.6	7.9	38.8	1.1	3.0
212	Pier	3.63	3	15.3	0.6	3.8	46.0	1.1	2.4
	Pier	3.63	3	14.7	0.6	3.9	36.5	2.2	6.0
	Abutment	3.46	3	21.3	1.2	5.4	41.2	3.7	8.9
	Abutment	3.71	3	15.0	1.0	6.7	40.8	2.5	6.2
213	Pier	3.38	3	11.7	2.9	24.7	45.3	3.5	7.7
	Pier	3.38	3	8.7	1.2	13.3	37.2	1.3	3.4
	Pier	3.38	3	10.0	1.7	17.3	40.8	4.8	11.8
	Pier	3.38	3	8.7	1.2	13.3	42.0	4.6	10.9
	Pier	3.38	3	10.7	0.6	5.4	43.5	3.8	8.7
	Pier	3.38	3	8.7	0.6	6.7	46.5	3.9	8.4
	Pier	3.38	3	12.3	2.1	16.9	43.3	0.4	1.0
	Pier	3.38	3	12.3	2.1	16.9	41.2	2.7	6.6
	Pier	3.38	3	9.3	1.5	16.4	36.8	2.5	6.7
	Abutment	2.70	3	16.0	1.7	10.8	43.1	3.6	8.4
	Abutment	2.96	3	9.0	1.0	11.1	47.7	9.1	19.0
214	Pier	1.12	3	2.7	0.6	21.7	44.8	2.9	6.4
215	Pier	1.38	3	4.7	1.2	24.7	41.1	2.3	5.7
	Abutment	1.38	3	6.3	0.6	9.1	33.2	1.8	5.3
216	Pier	1.46	3	6.0	1.7	28.9	61.3	7.9	12.8
	Abutment	1.70	3	6.7	0.6	8.7	39.9	5.1	12.9
217	Pier	1.46	3	5.7	1.2	20.4	56.7	3.0	5.3
	Abutment	1.63	3	6.3	0.6	9.1	35.5	2.5	6.9
218	Pier	1.46	3	5.3	1.5	28.6	56.1	5.7	10.2
	Abutment	1.54	3	6.0	0.0	0.0	38.7	1.0	2.6
219	Abutment	3.67	5	10.6	0.5	5.2	37.4	5.4	14.5

(*continued on next page*)

A.2 (*continued*)

Structure	Structural element	Service life (year)	Total number of extracted cores	Experimental carbonation depth			Experimental compressive strength		
				Mean value, $x_{cm}(t)$ (mm)	Standard deviation, σ_{xc} (mm)	$(COV)_{xc}$ (%)	Mean value (N/mm^2)	Standard deviation, σ_{fc} (N/mm^2)	$(COV)_{fc}$ (%)
220	Pier	3.08		7.7	0.5	6.7	40.8	9.0	22.2
221	Pier	4.42	3	14.7	4.6	31.5	41.0	6.4	15.6
	Pier	4.42	6	16.0	5.4	33.5	32.8	6.8	20.7
	Abutment	4.17	6	7.0	1.5	22.1	42.9	2.2	5.0
	Abutment	4.17	5	12.2	1.1	9.0	41.8	2.4	5.8
222	Abutment	4.42	5	10.8	3.6	33.0	36.7	3.6	9.7
223	Pier	3.92	6	10.3	1.9	18.0	32.1	2.9	8.9
	Pier	3.92	5	11.8	2.0	17.4	29.7	3.1	10.4
	Abutment	3.83	5	6.8	1.6	24.2	36.0	1.4	3.9
	Abutment	3.83	5	9.6	0.9	9.3	40.4	7.1	17.5
224	Pier	2.42	3	13.3	1.2	8.7	30.8	6.3	20.5
225	Abutment	3.42	6	11.0	0.9	8.1	43.9	2.5	5.7
226	Abutment	3.42	5	10.0	0.0	0.0	32.4	1.9	6.0
	Abutment	3.42	4	10.0	0.0	0.0	42.0	6.1	14.6
227	Abutment	3.33	2	10.0	1.4	14.1	26.0	1.4	5.4
		3.33	2	12.5	0.7	5.7	32.5	1.4	4.4
228	Wall	1.83	2	11.0	1.4	12.9	20.3	1.8	8.7
		1.83	4	8.5	2.4	28.0	24.5	1.1	4.4
229	Abutment	2.08	2	8.5	3.5	41.6	26.8	1.8	6.6
		2.17	2	8.0	0.0	0.0	34.0	0.0	0.0
230	Abutment	2.25	2	14.5	2.1	14.6	25.3	1.1	4.2
		2.33	2	12.5	2.1	17.0	39.0	3.5	9.1
	Abutment	3.41	3	12.3	2.5	20.4	32.3	2.3	7.1
231	Abutment	3.50	3	13.3	4.2	31.2	33.8	1.0	3.1
232	Abutment	3.50	2	14.5	0.7	4.9	27.3	3.9	14.3
		3.50	2	8.5	0.7	8.3	40.8	8.1	20.0
233	Abutment	4.13	3	14.0	7.8	55.8	25.8	6.4	24.9
234	Pier	3.67	3	8.7	1.2	13.3	43.3	1.6	3.7
235	Pier	3.41	2	11.0	0.0	0.0	36.8	1.1	2.9
	Abutment	3.67	3	11.3	1.5	13.5	28.7	3.2	11.2
	Abutment	3.75	2	14.5	0.7	4.9	21.5	1.4	6.6
236	Pier	3.83	1	5.0			48.5		
237	Pier	3.83	2	5.0	1.4	28.3	40.8	2.5	6.1
238	Pier	2.41	2	10.0	0.0	0.0	40.0	2.1	5.3
239	Pier	3.00	3	8.7	0.6	6.7	41.0	3.1	7.6
240	Pier	3.56	3	3.7	1.2	31.5	61.3	5.0	8.1
	Abutment	3.61	3	12.0	0.0	0.0	46.1	4.9	10.7
241	Pier	2.31	3	7.3	1.5	20.8	57.6	4.2	7.2
	Abutment	2.27	3	11.7	3.5	30.1	41.8	5.2	12.4
242	Pier	1.88	3	5.7	1.2	20.4	57.1	2.8	4.9
	Abutment	1.96	3	9.0	2.0	22.2	47.5	4.4	9.4
	Abutment	2.21	2	2.5	0.7	28.3	46.9	10.8	23.0
243	Abutment	1.40	3	6.7	1.5	22.9	58.2	4.3	7.3
244	Pier	2.89	2	8.0	1.4	17.7	68.4	0.2	0.3
	Abutment	3.15	2	9.0	1.4	15.7	57.4	3.7	6.5
	Abutment	3.15	3	15.0	0.0	0.0	34.4	8.7	25.3
245	Pier	1.89	3	7.0	1.0	14.3	50.3	5.7	11.2
	Abutment	2.02	3	10.7	1.5	14.3	50.6	2.3	4.6

A.2 (*continued*)

Structure	Structural element	Service life (year)	Total number of extracted cores	Experimental carbonation depth			Experimental compressive strength		
				Mean value, $x_{cm}(t)$ (mm)	Standard deviation, σ_{xc} (mm)	$(COV)_{xc}$ (%)	Mean value (N/mm^2)	Standard deviation, σ_{fc} (N/mm^2)	$(COV)_{fc}$ (%)
246	Pier	2.22	1	4.0			51.0		
	Pier	2.30	3	6.0	1.0	16.7	52.4	1.8	3.5
	Abutment	2.13	2	2.5	0.7	28.3	49.1	4.1	8.3
		2.22	2	2.0	1.4	70.7	61.9	6.9	11.1
247	Pier	1.49	3	3.7	0.6	15.7	57.8	7.7	13.3
	Pier	1.59	3	2.7	0.6	21.7	62.2	4.2	6.7
	Pier	2.30	3	4.3	1.2	26.6	63.7	5.3	8.3
	Pier	2.41	2	2.5	0.7	28.3	67.8	1.1	1.6
	Pier	2.73	1	3.0			33.5		
	Pier	2.88	3	3.0	0.0	0.0	54.1	6.4	11.8
	Pier	2.92	3	3.3	1.5	45.8	60.2	3.1	5.2
	Pier	2.92	3	3.7	1.2	31.5	59.7	4.3	7.2
	Pier	2.98	3	4.3	0.6	13.3	59.3	2.5	4.3
	Abutment	1.65	3	6.7	0.6	8.7	41.9	4.9	11.6

A.3. Geographical area III

Structure	Structural element	Service life (year)	Total number of extracted cores	Experimental carbonation depth			Experimental compressive strength		
				Mean value, $x_{cm}(t)$ (mm)	Standard deviation, σ_{xc} (mm)	$(COV)_{xc}$ (%)	Mean value (N/mm^2)	Standard deviation σ_{fc} (N/mm^2)	$(COV)_{fc}$ (%)
301	Abutment	3.78	3	14.0	1.7	12.4	32.9	2.2	6.5
302	Abutment	3.10	3	12.7	1.2	9.1	28.1	2.3	8.2
303	Pier	3.03	3	11.3	1.2	10.2	32.6	4.9	15.0
	Abutment	3.02	3	12.3	2.5	20.4	38.8	0.4	1.0
304	Abutment	2.28	3	10.7	0.6	5.4	30.8	5.0	16.2
305	Abutment	3.79	3	7.7	1.5	19.9	34.8	5.8	16.6
306	Abutment	1.75	3	3.0	0.0	0.0	39.6	4.0	10.2
307	Abutment	1.05	3	1.7	0.6	34.6	46.6	2.9	6.2
308	Pier	3.72	3	14.3	0.6	4.0	37.3	5.4	14.4
	Abutment	3.80	3	14.7	0.6	3.9	37.3	2.9	7.9
309	Pier	3.71	3	13.0	1.0	7.7	33.2	2.2	6.6
	Abutment	2.79	3	9.0	0.0	0.0	38.3	3.3	8.7
	Abutment	3.45	3	20.3	3.1	15.0	35.8	2.9	8.2
310	Abutment	3.79	3	14.0	1.7	12.4	35.2	2.6	7.4
311	Abutment	3.47	3	10.7	0.6	5.4	33.6	7.3	21.7
312	Abutment	2.14	3	14.3	0.6	4.0	30.0	8.8	29.5
313	Abutment	3.49	3	10.7	1.2	10.8	36.3	1.0	2.8
314	Abutment	3.43	3	8.0	0.0	0.0	41.1	4.4	10.7
315	Abutment	2.74	3	6.7	1.5	22.9	33.8	4.5	13.4
316	Abutment	3.09	3	7.3	0.6	7.9	28.0	1.4	5.0
317	Abutment	3.33	3	10.3	1.5	14.8	25.0	3.1	12.5
318	Pier	2.59	3	10.0	1.0	10.0	40.2	9.8	24.4
	Abutment	2.89	3	12.7	0.6	4.6	26.3	2.3	8.6
319	Pier	2.23	3	10.7	0.6	5.4	38.3	1.6	4.2
	Pier	2.25	3	6.7	0.6	8.7	35.7	2.6	7.2

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A.3 (*continued*)

Structure	Structural element	Service life (year)	Total number of extracted cores	Experimental carbonation depth			Experimental compressive strength		
				Mean value, $x_{cm}(t)$ (mm)	Standard deviation, σ_{xc} (mm)	$(COV)_{xc}$ (%)	Mean value (N/mm^2)	Standard deviation σ_{fc} (N/mm^2)	$(COV)_{fc}$ (%)
320	Pier	2.90	4	12.8	3.2	25.1	30.8	1.1	3.5
	Abutment	2.24	3	10.7	1.2	10.8	26.8	5.2	19.6
	Abutment	2.99	2	13.5	2.1	15.7	31.5	1.4	4.5
321	Pier	2.16	3	10.0	2.6	26.5	39.6	1.4	3.5
	Abutment	2.16	3	11.7	1.5	13.1	27.4	5.5	20.0
	Abutment	2.49	3	9.7	2.5	26.0	41.1	10.1	24.5
322	Abutment	3.59	3	21.7	3.1	14.1	21.3	2.0	9.4
323	Abutment	1.59	3	6.0	1.0	16.7	30.8	1.6	5.1
324	Pier	1.09	3	10.3	0.6	5.6	29.4	0.1	0.5
325	Pier	2.59	3	12.7	0.6	4.6	31.4	4.4	14.0
	Abutment	2.66	3	14.3	4.0	28.2	28.8	0.3	0.9
326	Pier	3.17	3	14.7	0.6	3.9	29.8	4.7	15.9
	Abutment	3.16	3	12.3	0.6	4.7	30.0	0.4	1.4
327	Abutment	3.58	3	16.7	1.5	9.2	20.9	0.4	1.8
328	Abutment	3.42	3	14.3	0.6	4.0	21.3	1.5	7.1
329	Pier	3.25	3	17.0	1.7	10.2	26.4	2.1	8.0
	Pier	3.25	3	18.7	4.0	21.7	18.1	2.7	14.9
330	Abutment	3.00	3	10.3	2.1	20.1	29.2	2.2	7.7
331	Pier	3.41	1	11.0			33.5		
332	Pier	3.17	3	6.7	0.6	8.7	35.7	2.6	7.2
	Abutment	3.08	3	16.3	1.5	9.4	24.8	4.0	16.1
	Abutment	3.67	3	16.0	1.7	10.8	28.4	1.0	3.7
333	Wall	3.25	3	9.7	0.6	6.0	22.8	1.5	6.4
		3.25	3	10.7	1.5	14.3	27.5	2.0	7.2
334	Wall	3.84	3	17.7	1.5	8.6	24.8	0.7	2.7
		3.84	3	11.0	2.0	18.2	31.6	3.8	12.1
335	Abutment	1.31	3	6.7	0.6	8.7	30.8	2.4	7.8
	Abutment	1.39	3	5.3	0.6	10.8	33.8	0.4	1.3
336	Wall	3.43	3	9.7	0.6	6.0	26.3	1.8	6.7
337	Pier	3.02	3	16.3	3.2	19.7	32.1	1.4	4.3
	Pier	3.60	3	15.3	0.6	3.8	29.0	2.0	6.8
	Pier	3.69	3	15.3	0.6	3.8	24.3	1.1	4.5
	Abutment	3.17	3	13.3	2.9	21.7	33.2	6.8	20.6
		3.77	3	13.3	1.5	11.5	28.2	2.5	9.0
338	Wall	3.68	3	11.0	1.0	9.1	23.2	1.4	6.1
		3.68	3	10.0	2.6	26.5	29.7	0.3	1.0
		3.68	3	13.7	2.1	15.2	31.3	2.8	9.1
		3.68	3	13.0	2.6	20.4	40.8	3.8	9.2
339	Wall	4.69	3	15.3	2.5	16.4	31.0	1.4	4.5
		4.69	3	17.0	3.0	17.6	29.8	3.4	11.4
		4.69	3	16.0	1.0	6.3	37.8	2.0	5.3
		4.69	3	14.7	0.6	3.9	35.4	1.1	3.2
		4.69	3	6.7	2.9	43.3	35.1	1.7	4.9
340	Wall	3.19	3	14.3	3.2	22.4	24.0	4.1	17.1
		3.19	3	13.0	2.6	20.4	37.0	2.1	5.8
341	Abutment	1.52	3	6.0	1.7	28.9	39.1	3.1	7.9
342	Wall	1.52	3	5.7	1.2	20.4	31.8	5.1	15.9
343	Wall	1.60	3	10.7	0.6	5.4	32.1	1.2	3.8
		1.60	3	9.7	0.6	6.0	34.3	1.0	3.0

A.3 (*continued*)

Structure	Structural element	Service life (year)	Total number of extracted cores	Experimental carbonation depth			Experimental compressive strength		
				Mean value, $x_{cm}(t)$ (mm)	Standard deviation, σ_{xc} (mm)	$(COV)_{xc}$ (%)	Mean value (N/mm^2)	Standard deviation σ_{fc} (N/mm^2)	$(COV)_{fc}$ (%)
		1.60	3	9.3	0.6	6.2	32.6	0.5	1.6
		1.60	3	5.3	0.6	10.8	29.7	1.5	4.9
		1.60	3	8.3	3.2	38.6	25.0	5.1	20.3
		1.60	3	3.7	1.2	31.5	45.2	2.1	4.6
		1.60	3	7.0	1.0	14.3	31.3	1.8	5.6
		1.60	3	5.0	0.0	0.0	34.7	1.5	4.4
		1.60	3	6.7	1.5	22.9	34.3	5.9	17.3
		1.60	3	8.0	1.7	21.7	24.0	0.9	3.8
		1.60	3	8.0	1.0	12.5	25.4	3.9	15.4
344	Abutment	0.73	3	2.7	0.6	21.7	45.6	0.8	1.8
345	Abutment	0.22	3	4.3	0.6	13.3	33.3	1.3	4.0
346	Abutment	0.30	3	2.0	0.0	0.0	43.3	0.4	1.0
347	Abutment	0.47	3	3.3	0.6	17.3	35.6	1.2	3.5
	Abutment	0.56	3	2.7	0.6	21.7	37.3	0.9	2.4
348	Pier	0.93	2	2.5	0.7	28.3	62.3	3.2	5.1
	Pier	0.26	2	2.5	0.7	28.3	61.0	0.0	0.0
349	Tunnel	0.17	3	2.7	0.6	21.7	48.8	4.5	9.2
		0.17	3	5.3	0.6	10.8	30.6	1.5	4.9
		0.18	3	5.7	0.6	10.2	39.3	3.8	9.8
		0.18	3	4.3	0.6	13.3	38.6	1.6	4.2
		0.19	3	5.7	1.5	27.0	39.9	2.5	6.2
		0.20	3	4.7	0.6	12.4	41.6	0.9	2.3
		0.21	3	3.0	0.0	0.0	41.3	4.2	10.2
		0.21	3	6.7	0.6	8.7	37.9	2.6	6.7
		0.22	3	5.3	0.6	10.8	38.8	7.7	19.8
		0.23	3	4.0	1.0	25.0	42.2	5.7	13.5
		0.23	3	4.0	1.0	25.0	47.3	7.6	16.1
350	Pier	2.21	3	4.3	0.6	13.3	52.6	2.9	5.5
	Abutment	2.13	3	4.0	0.0	0.0	37.7	2.4	6.3
	Abutment	2.21	3	1.7	0.6	34.6	49.2	2.6	5.2
351	Abutment	1.83	3	4.7	0.6	12.4	44.5	7.7	17.2
352	Abutment	1.95	3	4.7	0.6	12.4	44.3	4.5	10.2
353	Wall	1.71	3	3.0	0.0	0.0	43.1	4.6	10.6
		1.71	3	3.3	0.6	17.3	54.8	4.1	7.5
		1.71	3	4.3	0.6	13.3	43.6	1.7	3.9
354	Abutment	1.49	3	4.3	0.6	13.3	43.7	14.9	34.1
	Abutment	1.70	3	3.3	0.6	17.3	44.5	4.1	9.2
355	Abutment	1.54	3	3.7	1.5	41.7	38.5	4.6	11.8
	Abutment	1.62	3	5.0	0.0	0.0	44.8	3.8	8.6
356	Abutment	1.58	3	7.0	1.0	14.3	39.8	3.3	8.2
	Abutment	1.70	3	3.3	0.6	17.3	37.9	3.7	9.7
357	Abutment	1.38	3	3.3	0.6	17.3	46.3	2.6	5.7
	Abutment	1.61	3	2.3	0.6	24.7	43.6	2.6	5.9
358	Abutment	1.35	2	5.0	0.0	0.0	43.0	1.4	3.3
359	Abutment	1.27	3	2.0	0.0	0.0	53.6	2.5	4.7
360	Abutment	0.98	3	2.3	0.6	24.7	51.3	3.7	7.2
	Abutment	1.05	2	1.0	0.0	0.0	43.3	7.8	18.0
361	Abutment	1.95	3	6.7	0.6	8.7	35.0	3.7	10.6

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