

SWISS REQUIREMENTS FOR THE CARBONATION RESISTANCE OF CONCRETE FOR THE EXPOSURE CLASSES XC3, XC4 AND XD1

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ABSTRACT. In the past, many reinforced concrete structures have shown cracking and spalling due to the carbonation of the concrete and subsequent corrosion of the reinforcement. The carbonation rate was high because of the use of concrete that was too porous (high porosity and high water/cement ratio, respectively) and due to an insufficient concrete cover of the reinforcement, very often not conforming to the national standards. Due to changes in the cement and concrete market, the durability of concrete came into the focus of research and standardisation. The overall goal is to establish a performance-based concept for requirements and testing. This paper will provide an overview of extensive Swiss research work on the carbonation resistance of concrete. The correlation between carbonation under accelerated conditions and carbonation at normal atmospheric levels of CO₂ with a variety of concrete mixes was investigated, as well as the influence of cement type, water/cement (w/c) ratio, curing, preconditioning (pre-treatment) and relative humidity. Furthermore, some results of CO₂ measurements at different locations in Switzerland, including a road tunnel, will be presented. Based on the results of these studies, a Swiss standard for an accelerated carbonation test (4% CO₂) was elaborated and published in 2013. Since then concrete producers have to check within the factory production control that they fulfil the limiting values for carbonation resistance (carbonation coefficient) defined by the Swiss concrete standard for the exposure classes XC3, XC4 and XD1. Both the test method (including precision) and the limiting values will be explained.

Keywords: Carbonation resistance, Accelerated carbonation test method, Natural and field exposure, Curing, Modelling.

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INTRODUCTION

In the 1950s and 1960s, corrosion due to carbonated concrete was a significant focus of practice and research. The insights gained at the time led to a requirement for more compact concretes (lower w/c ratios), for a control of the fresh concrete properties and for an increase of the concrete cover. This was ultimately reflected in the corresponding standards. In Switzerland and in Europe, the cement and concrete market is changing at a rapid rate (new cement types, concrete recycling). Whereas in 1995 the proportion of CEM I cements was still about 90% of total Swiss cement usage, in 2015 it was only about 10%. The CEM I cements were initially replaced by CEM II/A cements (mainly CEM II/A-LL) and in recent years increasingly with CEM II/B cements. The CEM II/A cement achieved a maximum of 73% of total usage in Switzerland in 2010.

Linked to these changes is the reduction of the clinker content (clinker factor) of the cements. This trend leads to potentially higher carbonation rates. The driving force behind these changes is the demand for sustainable construction and concrete structures. This is reasonable and necessary, but it requires a re-evaluation of the durability of concrete. In particular, it has to be checked whether the previous requirements for concrete composition (w/c ratio, cement content) are still adequate. These questions were the starting point for various research works in Switzerland, which are presented in summary below.

INFLUENCE OF THE CO₂ CONTENT ON THE CARBONATION OF CONCRETE

A comprehensive experimental study examined the influence of CO₂ content, concrete composition (cement type, w/c ratio) and curing on the rate of carbonation [1]. The aim of this work was to establish a basis for a rapid testing of the carbonation resistance of concretes.

Experimental

In the first phase of the project, studies were carried out with a natural CO₂ content and at 1, 10 and 100% CO₂. In the second phase, just 1% and 4% CO₂ were used for the accelerated carbonation. The results of the carbonation tests are presented below. The results of the further tests carried out (fresh concrete properties, compressive strength, gas permeability, water permeability, porosity, sodium/potassium/calcium content) are given in the final report. Some results were also published in [2].

The concrete mixes AGB11 and AGB12 (Table 1) were used for phase 1, the other concrete mixes for phase 2. The concrete specimens were cured according to table 2. Before the start of the rapid carbonation, they were pre-conditioned for 14 to 27 days in a climatic room (20°C, 70% RH). In phase 1B, after curing and before the carbonation test, the specimens were pre-dried in addition for 18 days at 60°C. The carbonation conditions are summarised in Table 3. Prisms (120 x 120 x 360 mm) were used for the tests. In Switzerland, this type of specimens is used for shrinkage measurements in accordance with the standard SIA 262/1 [3]. Special testing chambers have been developed for the accelerated carbonation, in which the CO₂ content and the relative air humidity can be varied [4]. While the increased CO₂ contents could be kept constant in the testing chambers, the natural CO₂ content in the climatic room fluctuated widely, as this room was also used for other work. When storing young concrete test specimens, the CO₂ content decreases, whereas it increases rapidly to over 1000 ppm when people are present (Figure 1).

Table 1 Designation and composition of the concrete mixes

MIX NO.	EXPOSURE CLASS	CEMENT		w/c ratio	AIR ENT-RAINING ADMIXTURE
		Type	Content, kg/m ³		
AGB11	XC4	CEM I 42,5 N	300	0.50	no
AGB12	XC4	CEM III/B 42,5 L-LH SR	300	0.50	no
AGB21	XC3	CEM I 42,5 N	280	0.60	no
AGB22	XD3, XF4	CEM III/B 42,5 L-LH-SR	320	0.45	yes
AGB24	XC4	CEM II/A-LL 42,5 N	300	0.50	no
AGB25	XD3, XF4	CEM II/A-LL 42,5 N	320	0.45	yes
AGB26	XC3	CEM II/B-LL 32,5 R	280	0.60	no
AGB27	XC4	CEM II/B-LL 32,5 R	300	0.50	no
AGB28	XD3, XF4	CEM II/B-LL 32,5 R	320	0.45	yes
AGB29	XC3	CEM II/B-M (T-LL) 42,5 N	280	0.60	no
AGB30	XC4	CEM II/B-M (T-LL) 42,5 N	300	0.50	no

Table 2 Curing conditions and pre-conditioning

ABBR.	CURING	PRE-CONDITIONING IN A CLIMATIC ROOM (20 °C, 70% RH)		AGE AT START OF TEST
NB 1d	1 d in the mould	27 d		28 d
NB 7d	1 d in the mould, 6 d in water	21 d		28 d
NB 28d	1 d in the mould, 27 d in water	14		42 d

Table 3 Carbonation conditions (ACC: Accelerated carbonation)

ABBR.	TEMP (average), °C	RELATIVE HUMIDITY (average), %	AVERAGE CO ₂ CONTENT (variation), ppm
Natural	20.2	69.0	0.032 (0.01 to 0.11)
ACC 1%	20.3	59.8	0.99 (0.95 to 1.05)
ACC 4%	20.6	61.8	4.02 (3.9 to 4.1)

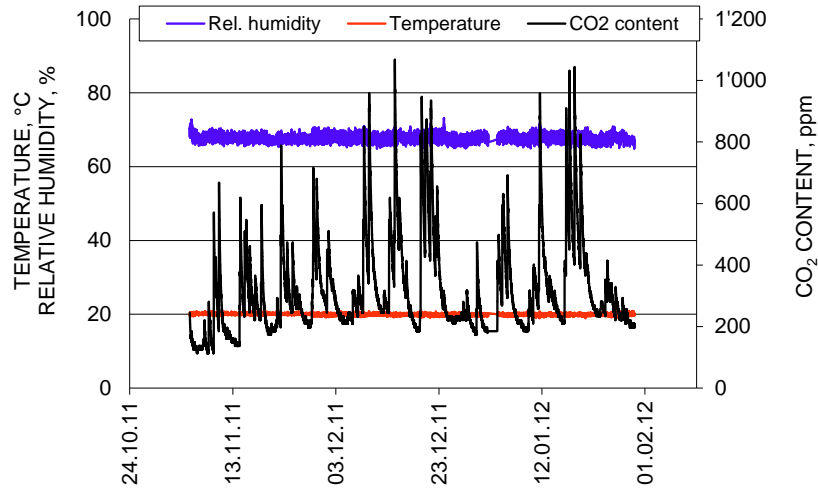


Figure 1 Temperature, relative humidity and CO₂ content over time

Influence of the CO₂ content

Figure 2 is used as an example to show the effect of the CO₂ content on the carbonation of the concrete AGB22 with a curing of 1 day. The accelerating effect of CO₂ can be taken into account according to equation 1. In Figure 3 all values, converted to 320 ppm CO₂, are compared.

$$K_{SN} = \frac{K_S}{\sqrt{\frac{[CO_2]_S}{[CO_2]_N}}} \tag{Eq. 1}$$

- K_{SN} Carbonation coefficient measured under accelerated conditions and converted to the natural or reference CO₂ content
- K_S Carbonation coefficient under accelerated carbonation conditions
- [CO₂]_N Natural CO₂ content (or reference content)
- [CO₂]_S CO₂ content for accelerated carbonation

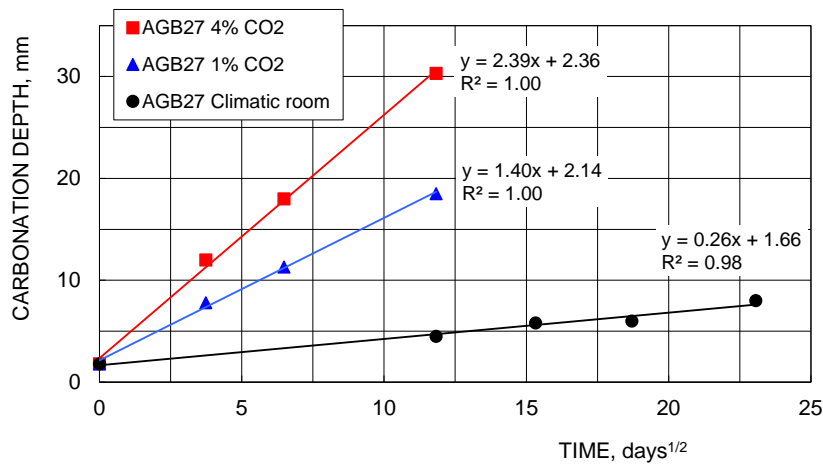


Figure 2 Carbonation of concrete mix AGB22 under natural and accelerated carbonation

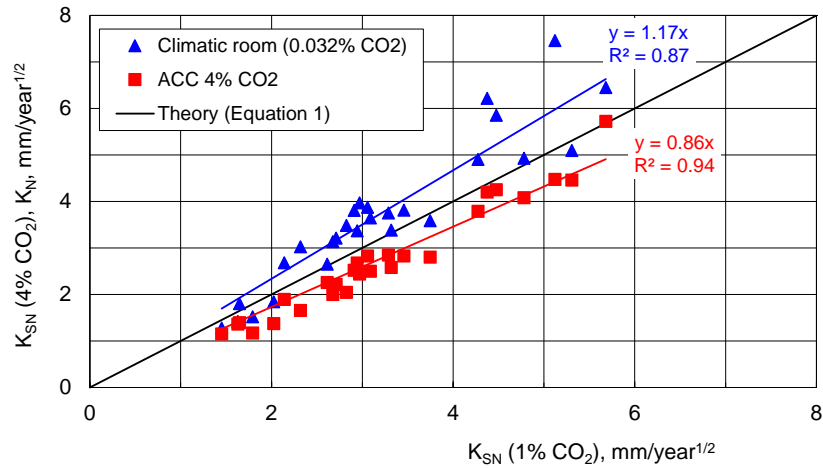


Figure 3 Carbonation coefficient under natural K_N (0.032 % CO_2) and accelerated conditions K_{SN} (4 % CO_2 , converted to 0.032 % CO_2) vs. K_{SN} (1 % CO_2 , converted to 0.032 % CO_2)

If the carbonation coefficient is determined under accelerated, as well as natural conditions, the effective acceleration can be calculated with the ratio K_{SN}/K_N (equation 2).

$$K_{Rel} = \frac{K_{SN}}{K_N} \tag{Eq. 2}$$

K_{Rel} Relative carbonation coefficient

If $K_{Rel} = 1$, the effect of the elevated CO_2 content corresponds exactly to the theoretical acceleration. If $K_{Rel} < 1$, the effect of the CO_2 content is weaker than the theoretically expected value. K_{Rel} cannot be greater than 1, if the reference value is the lowest studied or observed CO_2 content. This is mostly the natural content. The results of this study, as well as of some other research work, are shown in Figure 4.

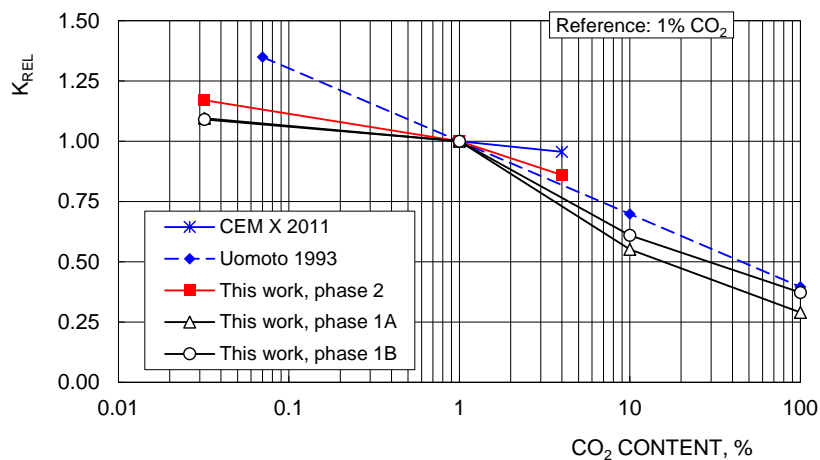


Figure 4 Relative carbonation coefficient (K_{rel} acc. to Eq. 2) as a function of CO_2 [1].
CEM X 2011 = [5]; Uomoto 1993 = [6].

Table 4 Influence of the CO₂ content on the relative carbonation coefficient [1]

CO ₂ CONT. , VOL. -%	RELATIVE CARBONATION COEFFICIENT		
	Phase 1A	Phase 1B	Phase 2
0.032	1.10	1.09	1.17
1.0	1.00	1.00	1.00
4.0	-	-	0.86
10	0.55	0.61	-
100	0.29	0.37	-
Ratio "0.032" to "4"	-	-	1.36
Ratio "0.032" to "100"	3.77	2.93	-
	3.35		

Influence of curing

The influence of the duration of curing is clearly dependent on the type of cement (Figure 5). On average, the effect is scarcely dependent on the CO₂ content (Table 5). The dependency from Gehlen [7] used for the modelling of the carbonation resistance classes is outside of this range. In the Swiss standard [3], a curing duration of 3 days has been fixed, since the curing of concrete is often not as long as it should be. The duration of 3 days is a compromise between several requirements and aspects (e.g. slowly reacting cements).

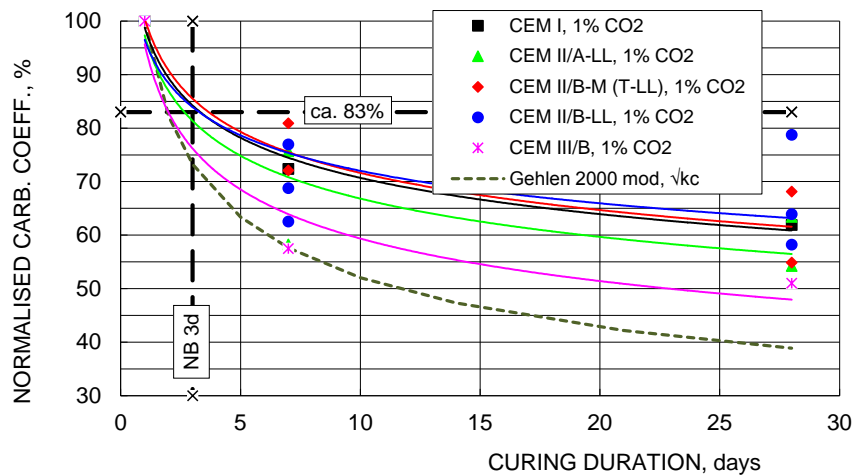


Figure 5 Normalised carbonation coefficient as a function of curing duration [1]

Table 5 Relative Effect of Curing on Carbonation

CO ₂ Content, Vol. -%	Relative effect of curing		
	NB 1d	NB 7d	NB 28d
0.032	1.00	0.69	0.63
1.0	1.00	0.69	0.63
4.0	1.00	0.69	0.63

SWISS TESTING STANDARD FOR CARBONATION RESISTANCE

Based on the research work, a testing standard was developed for determining the carbonation resistance with 4 vol.-% CO₂. Testing details can be found in [1,2]. Equation 3 is used for calculating the carbonation coefficient from the accelerated carbonation test.

$$K_{N,ACC} = c \cdot K_{SN} = a \cdot b \cdot c \cdot K_S = 2.60 \cdot K_S \quad \text{Eq. 3}$$

$K_{N,ACC}$	Carbonation coefficient from the accelerated carbonation test converted to 400 ppm CO ₂ , and corrected with the correction factor c, mm/year ^{1/2}
K_{SN}	Carbonation coefficient measured under accelerated conditions and converted to the reference CO ₂ content of 0.04 vol.-% (400 ppm), mm/year ^{1/2}
K_S	Carbonation coefficient under accelerated carbonation condition, mm/day ^{1/2}
a	Conversion factor for time: 1 day to 1 year: $(365/1)^{1/2} = 19.10$
b	Conversion factor for CO ₂ : $(0.04/4.0)^{1/2} = 0.10$
c	Correction factor (see Table 4) 1.36

Concrete producers have to test the concrete for the exposure classes XC3, XC4 and XD1 in accordance with this testing standard (valid since 01.08.2013) and to demonstrate that they meet the required carbonation resistance (see next chapter).

A Swiss round robin test with 18 laboratories [8] and 4 concrete mixes demonstrated the high reliability of the test procedure given in [2] (Figure 6). The results of a smaller RRT [] are included in this Figure.

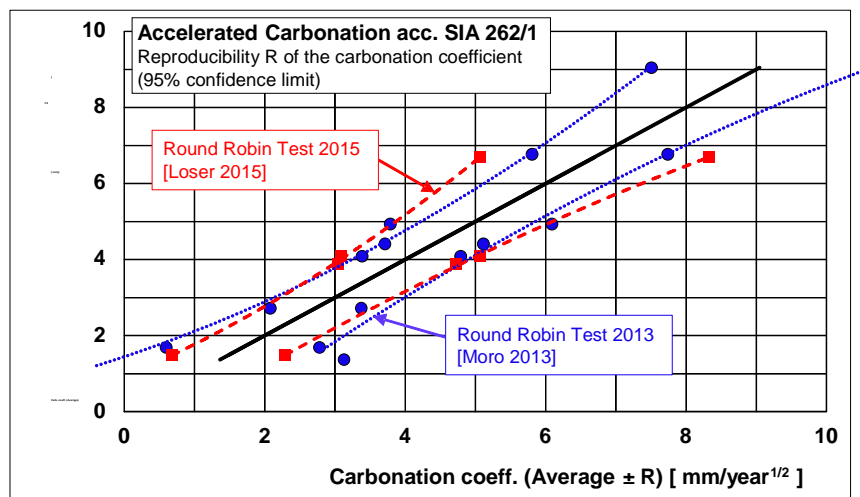


Figure 6 Average carbonation coefficient vs. carbonation coefficient $\pm R$ (reproducibility). Data taken from [8,9].

SWISS REQUIREMENTS FOR THE CARBONATION RESISTANCE

As part of the research project [1], the results of various long-term studies were analysed. The following procedure can only be used when the carbonation depths were measured under laboratory (indoor) and outdoor conditions at the same time and over an extended period of time. The CO₂ contents should be similar. There are only very few such publications available.

At first it is assumed that the \sqrt{t} law is valid under laboratory or indoor conditions (time exponent $b = 0.5$). In order to assess the influence of the type of exposure, the carbonation depths of the (unweathered/sheltered and weathered) outdoor storage are compared to the carbonation depths in the laboratory. The relationship between “outdoor storage” and “laboratory storage” carbonation depths can be described by equation 4.

$$\frac{d_{KA}}{d_{KL}}(t) = \frac{K_A t^{b(A)}}{K_L t^{0.5}} = \frac{K_A}{K_L} t^{b(A)-0.5} \tag{Eq. 4}$$

- d_{KA} Carbonation depth under outdoor conditions, mm
- d_{KL} Carbonation depth under laboratory conditions, mm
- K_A Carbonation coefficient under outdoor conditions, mm/year^{b(A)}
- K_L Carbonation coefficient under laboratory conditions (normal CO₂ content), mm/year^{0.5}
- $b(A)$ Time exponent for outdoor conditions
- t Time, years

Figures 7 and 8 show the results of the analysis of data from Wierig [7]. The following conclusions can be drawn:

- The ratio K_A/K_L , i.e. the relative carbonation coefficient, is between 70 and 100% for the sheltered outdoor storage. The lower the w/c ratio, the lower this ratio is.
- The exponent ‘ $b(A) - 0.5$ ’ is around -0.10. The time exponent $b(A)$ is therefore around 0.40 (= -0.10 + 0.50). The influence of the w/c ratio is minimal.

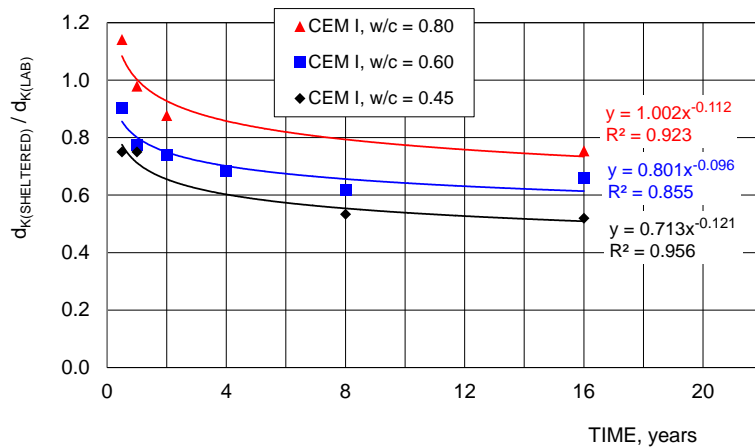


Figure 7 Ratio d_{KA} (outdoor sheltered) to d_{KA} (laboratory) as a function of time. Data taken from [10].

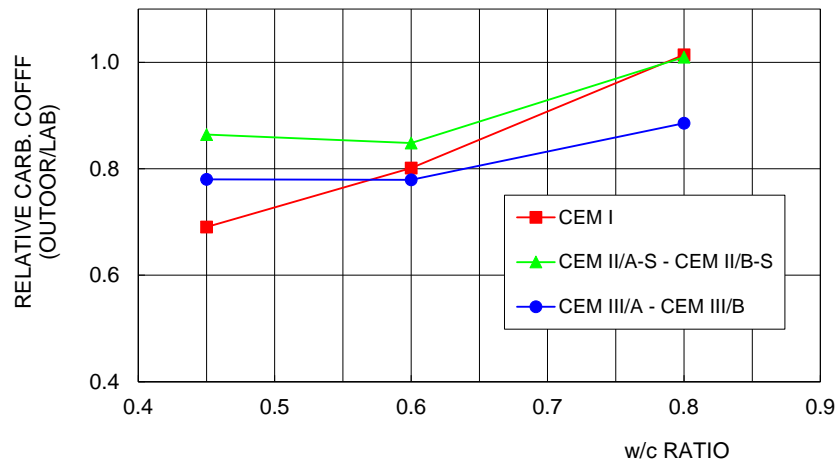


Figure 8 Influence of the exposure condition and the w/c ratio on the normalised carbonation coefficient [1]. Data taken from [10].

Based on these results, equation 5 was derived and used for calculating the limiting values for the carbonation coefficient (carbonation resistance).

$$d_{K,Max} \leq r_K K_{SN} t^{0.40} = 0.80 K_{SN} t^{0.40} = K_{Max} t^{0.40} \quad \text{Eq. 5}$$

$d_{K,Max}$	Maximum allowable carbonation depth [mm]. $d_{K,Max}$ can be set as e.g. 80% of the minimum concrete cover (c_{min}) according to SIA 262 [11].
r_K	Factor for considering the influence of the relative humidity [-]
K_{SN}	Carbonation coefficient from testing according to SIA 262/1 [3], appendix I [mm/year ^{0.40}]. Reference for CO ₂ content: 400 ppm.
K_{Max}	Maximum allowable carbonation coefficient [mm/year ^{0.40}]
t	Time (service life), [years].

For fixing the limiting values for K_{Max} , in principle several further influences can be taken into consideration:

- 1) The two- and three-dimensional diffusion of CO₂ leads to significantly deeper carbonation in corner and edge areas. According to our studies, the interaction coefficient with a cover of 20 mm is about 1.2 [1].
- 2) The maximum carbonation depth can be greater than the average value up to a factor of 1.2 or more [1].
- 3) The corrosion of the reinforcement can start already if the carbonation depth determined by phenolphthalein has reached 80% of the concrete cover of the reinforcement [1].
- 4) The CO₂ content is constantly increasing worldwide. In the “unpolluted” air on the Jungfrauoch at 3580 metres above sea level it has increased over the last 10 years by appr. 2 ppm per year. At the end of 2014 it reached appr. 400 ppm [12].
- 5) The end of the service life has not been reached when the carbonation depth has reached the reinforcement. It then still takes a certain time until the corrosion of the reinforcement leads to cracks in the concrete (and later on to spalling), i.e. the time it takes until a certain critical corrosion attack has been reached can be further taken into account. For conventional concrete the critical corrosion loss is between 10 and 100 μm [1].

The aim of being able to fix a single limiting value for a service life of 50 years and both exposure classes XC3 and XC4 (and XD1) made it necessary that the mentioned influences could only partially be taken into account. The limiting values, valid since 2013, are listed in Table 6. The concrete cover is given in [11].

Table 6 Limiting values for carbonation resistance according to [13]

PARAMETER	SERVICE LIFE, YEARS	EXPOSURE CLASS	
		XC3	XC4
Concrete cover c_{min} , mm		25	30
Limiting values for K_{max}	50	5.0 mm/year ^{1/2}	5.0 mm/year ^{1/2}
	100	4.0 mm/year ^{1/2}	4.5 mm/year ^{1/2}

CORRELATION BETWEEN CARBONATION UNDER NATURAL AND ACCELERATED CONDITIONS

Experience has shown that the carbonation rate is at its greatest within a humidity level of between about 50 and 70%. Completely water saturated concrete practically does not carbonate, as the diffusion speed of CO₂ in the pore solution is about 3 to 4 times lower than in dry or scarcely moist concrete. Very dry concrete does not carbonate, since free water, necessary for the carbonation reaction, is not available.

Within another research project [14] concrete mixes with CEM II/A-LL (300 kg/m³) with a w/c ratio of 0.65, 0.60 and 0.50 without and with partial replacement of the cement with limestone filler were studied with the accelerated carbonation test method (NB 1d.). Figure 9 shows that the carbonation coefficient decreases with increasing relative air humidity. The w/c ratio has a strong influence. This finding can be explained by the different adsorption isotherms of the concrete mixes. Figure 9 also contains the curve from Gehlen [7] used for the modelling of the carbonation resistance classes. It does not cover the behaviour of less carbonation resistant concrete mixes as they are often used for buildings.

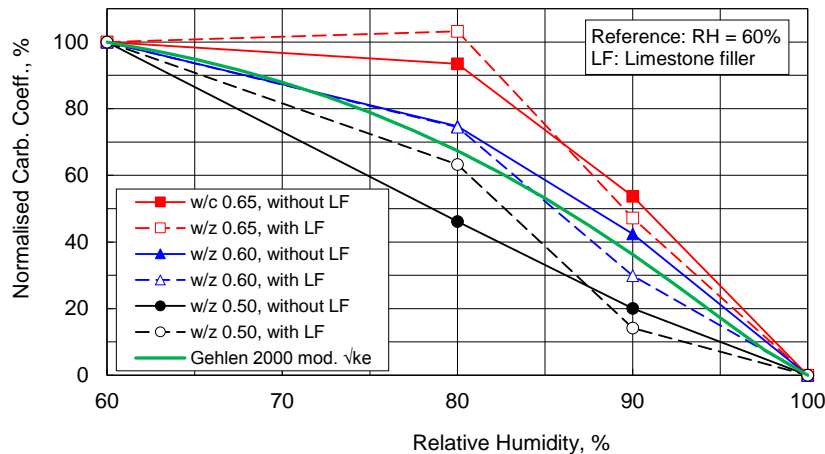


Figure 9 Influence of relative air humidity and the water/cement ratio on the normalised carbonation coefficient [14]. Gehlen 2000 = [7].

Specimens of same concrete mixes were stored for up to 2 years also under natural conditions in a climatic room (20°C, 70% RH) and in the Stevenson Screen in Wildegg (temperature and RH average 2012: 10.3 °C, 75 % RH). Figure 10 shows the influence of the relative humidity

(RH) and of the storage conditions on the carbonation coefficient. The results of the outdoor storage in the Stevenson Screen are similar to those of the rapid carbonation at 80% RH. The results from the climatic room and the accelerated carbonation tests are in good agreement. Further, it was found, that the time exponent b under sheltered outdoor conditions remained at 0.50, i.e. no decrease to 0.40.

In the light of these new results, the assumptions for the calculation of the limiting values for carbonation resistance (see Eq. 5) must be questioned critically.

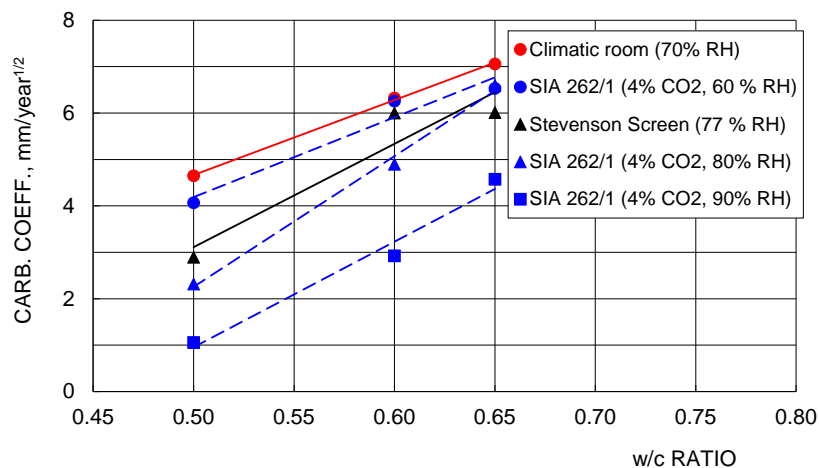


Figure 10 Influence of the exposure conditions and the water/cement ratio on the normalised carbonation coefficient [14]

ONGOING RESEARCH

In 2014, a new research programme, funded by the Federal Roads Office and cemsuisse, was launched with the goals detailed in Table 7. All these topics are of fundamental importance for a correct long-term modelling. WP 1 and 2 are intended to provide answers to the questions raised in the previous chapter.

Table 7 Goals of the ongoing research

WORKING PACKAGE (WP)	INFLUENCE ON	NEED FOR RESEARCH
1 Influence of RH on the carbonation rate	Carbonation coefficient, factor r_K	Measurements of various concrete mixes (e. g. slow reaction concrete)
2 Time exponent b	Carbonation rate over time	Long-term field studies under sheltered outdoor conditions (5 to 10 years)
3 Actual CO ₂ content in natural air and in tunnels	Carbonation coefficient	Monitoring of CO ₂ at different locations and in two Swiss road tunnels
4 Influence of RH on the corrosion rate of the reinforcement	Corrosion time until cracks and spalling appear	Corrosion rate measurements on different reinforced concrete specimens

In the Swiss midlands, the average CO₂ content already significantly exceeds the reference value of 400 ppm. In Wildegg the average CO₂ content during the summertime is around 400 ppm and in the winter season around 550 ppm (Figure 11). The average value from June 2014 to June 2015 was 492 ppm (± 76 ppm). This causes an increase in the carbonation coefficient of around 11% (see equation 1). As part of WP 3, in addition to Wildegg further monitoring systems were installed in summer 2015 at several locations in Switzerland. Preliminary results in the ca. 3.18 km long road tunnel Belchen, a part of the motorway between Basle and Lucerne, show again much higher CO₂ contents (Figure 12). The CO₂ content depends not only on the day time and day of the week, but also on the location of the measurement in the tunnel. The location Q2 is about 700m from the entrance to the tunnel, Q6 about 2300m.

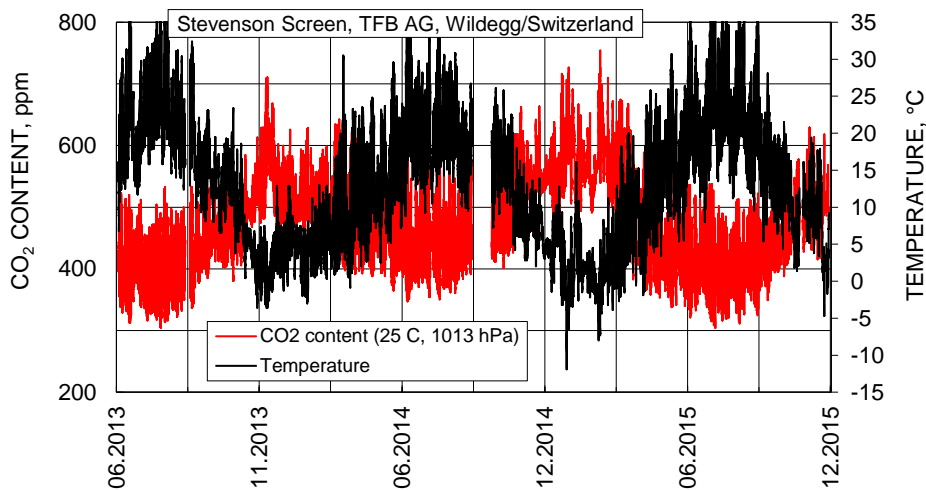


Figure 11 CO₂ content (normalised to standard conditions) of air in Wildegg

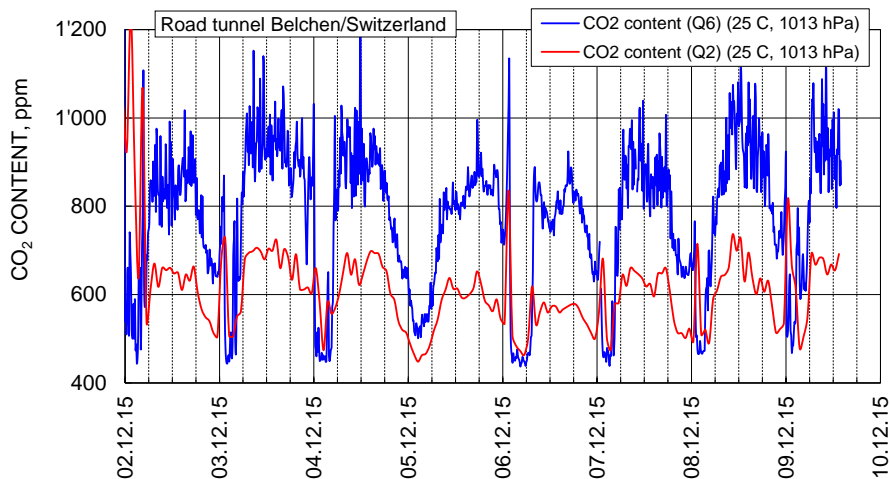


Figure 12 CO₂ content (normalised to standard conditions) in the road tunnel Belchen/Switzerland at the two locations Q2 and Q6

WP 4 focuses primarily on the question of whether the reinforcement corrosion under XC3 conditions is sufficiently small so that no cracking or spalling of the concrete can occur for 50 or 100 years. If this can certainly be excluded with some safety margin, then the requirements on concrete for XC3 could be dropped.

For old, reinforced and pre-carbonated test specimens that have been stored for several years in the Stevenson Screen (sheltered outdoor storage), the corrosion loss in summer 2015 was around 1 $\mu\text{m}/\text{year}$ or lower (Figure 13).

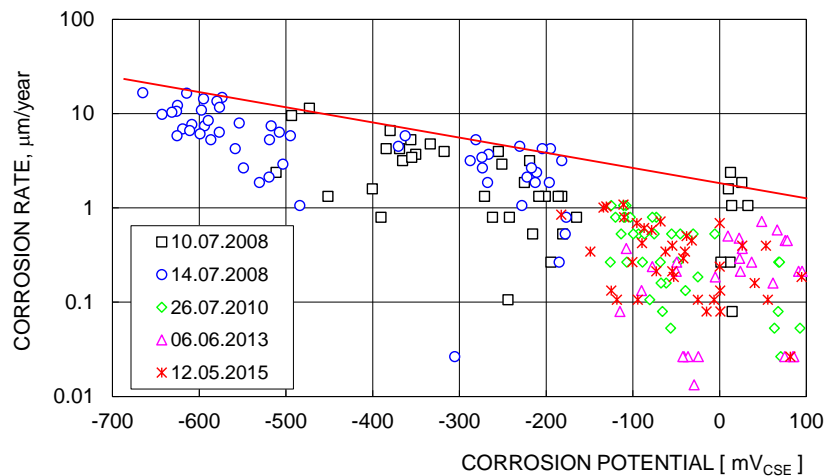


Figure 13 Dependence of the corrosion rate, calculated from the macroelement current between common and stainless steel reinforcement, on the corrosion potential. On 14 July 2008, the specimens were soaked with water. Since then they have been stored in a Stevenson Screen in Wildegg, where the yearly average RH lies between 75-80%.

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