

CARBONATION BEHAVIOUR OF CONCRETE EXPOSED TO NATURAL AND ACCELERATED CARBONATION CONDITIONS

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Abstract

Carbonation is both one of the primary deterioration mechanisms in reinforced concrete structures and a method for sequestration of environmental CO₂. Owing to rising atmospheric CO₂ concentrations, understanding concrete carbonation is of increasing importance. The response of concretes can be assessed under natural carbonation (at atmospheric CO₂ concentrations) or accelerated carbonation (in an environment with an artificially high concentration of CO₂). This work investigates the natural and accelerated carbonation behaviour of two concretes with water/cement ratios of 0.65 and 0.7. Specimens of each mix are exposed to either natural carbonation conditions or accelerated conditions following an initial period of natural exposure. For the concretes and exposure conditions tested, results show that estimated natural carbonation coefficients derived from accelerated tests are consistently lower than those measured in natural tests. Changes in the carbonation mechanism between natural and accelerated tests as well as errors in the formulation of carbonation equations are highlighted as possible sources of this discrepancy.

Keywords: Carbonation, durability, modelling.

INTRODUCTION

Carbonation describes the process of atmospheric CO₂ reacting with hydration products such as calcium hydroxide (Ca(OH)₂) in concrete. The physiochemical process of carbonation is considered to have two main phases: the diffusion of CO₂ through the concrete pore structure, and its chemical reaction within pores in the presence of pore water [1]. The diffused CO₂ dissolves in pore water to form carbonic acid, which then reacts with calcium compounds in concrete to form carbonates such as calcium carbonate (CaCO₃) [2]. The reaction therefore sequesters CO₂ while simultaneously reducing the alkalinity of the concrete, leaving embedded steel reinforcement vulnerable to corrosion.

Natural carbonation (NC) describes carbonation of concrete which occurs at ambient CO₂ concentrations of ~0.04 %, whereas accelerated carbonation (AC) describes carbonation occurring at artificially elevated CO₂ concentrations. Where NC can take many years to progress to a substantial extent within a given concrete specimen, AC tests can be used to rapidly produce measurable depths of carbonation in laboratory conditions. Using known conversions between AC and NC rates enables useful prediction of the NC behaviour in short time frames.

It is assumed that the rate of the carbonation reaction is much faster than the diffusion of CO₂ through the concrete [3]. As such, the overall carbonation rate is diffusion-controlled and can be described using one-dimensional diffusion equations. The following derivation is adapted from Kropp and Hilsdorf [4]. The carbonation process is modelled by Fick's first law of diffusion, Equation 1. The flux, F , of the CO₂ through the concrete (in mol/mm²/day) is given as:

$$F = -D \frac{\partial c}{\partial x} = D \frac{c}{x} \quad \text{Equation 1}$$

where x (mm) is the carbonation depth from the free face; D (mm^2/day) is the diffusion coefficient of CO_2 through concrete; and C (mol/mm^3) is the concentration of CO_2 , which has a value of c at the free surface of the concrete and is negligible at the carbonation front.

Defining a (mol/mm^3) as the mass of CO_2 required to carbonate a unit volume of the material, the mass of CO_2 delivered to a unit volume ($dV = Adx$) in a given time, dt , is equivalent to the mass which is required to carbonate the unit volume, as expressed in Equation 2:

$$FA dt = a A dx \quad \text{Equation 2}$$

which may be rearranged and integrated to give the familiar form of the carbonation equation, in which the carbonation depth is proportional to the square root of time:

$$x = K\sqrt{t} \quad \text{Equation 3}$$

where:

$$K = \sqrt{2Dc/a} \quad \text{Equation 4}$$

The constant carbonation coefficient, K ($\text{mm}/\text{day}^{1/2}$), captures the influence of many different material properties and environmental conditions and is therefore unique to each concrete and its test conditions. Many analytical carbonation models propose methods of estimating K to match the general form of Equation 4. These are explored elsewhere by the authors [5].

Effect of CO_2 concentration on K

A higher environmental concentration of CO_2 results in a faster rate of carbonation, due to a greater concentration gradient between the surrounding atmosphere and the carbonation front within the concrete driving the diffusion process. Based on Equation 4, the carbonation coefficient, K , for any given test is proportional to the square root of the CO_2 concentration, c . It follows that the ratio of carbonation coefficients in the same concrete for accelerated carbonation, K_{AC} , and natural carbonation, K_{NC} , can be described by Equation 5 (see also [6]–[8]).

$$\frac{K_{AC}}{K_{NC}} = \sqrt{\frac{c_{AC}}{c_{NC}}} \quad \text{Equation 5}$$

where c_{NC} and c_{AC} are the CO_2 concentrations in NC and AC conditions respectively.

The carbonation coefficient measured in an AC test, K_{AC} , can therefore be converted to an estimate of NC coefficient. This is denoted as $K_{NC(AC)}$ to indicate that it has been back-calculated from AC results using Equation 6.

$$K_{NC(AC)} = \frac{K_{AC}}{\sqrt{c_{AC}/c_{NC}}} \quad \text{Equation 6}$$

The following work presents NC and AC testing of the same concretes. The resulting carbonation coefficients, calculated using the equations given, are compared.

Initial carbonation depth

The previous formulations are based on constant CO_2 conditions throughout the exposure period. However, it is not unusual for some initial carbonation to have occurred in a concrete before it

undergoes AC testing, due to prolonged exposure to NC during curing or preconditioning. To account for the resulting initial carbonation depth, x_0 , a linear shift is often applied to Equation 3, as in [9] and the Swiss standard SIA 262/1 [10]. This results in Equation 7:

$$x = x_0 + K_{AC}\sqrt{t} \quad \text{Equation 7}$$

where x_0 represents the initial carbonation depth prior to AC exposure; K_{AC} is the AC coefficient; and t is the duration of exposure to AC conditions.

To estimate K_{AC} , Equation 7 may be rearranged as:

$$K_{AC} = \frac{x - x_0}{\sqrt{t}} \quad \text{Equation 8}$$

METHODOLOGY

Two concrete mixes, given in Table 1, are exposed to NC at a concentration of 0.04% CO₂, and AC at 4% CO₂. The change in carbonation depth over time is monitored for both exposure conditions.

The two concrete mixes (mix B and mix C) were designed using the BRE method of design of normal concrete mixes [11], assuming bulk densities of the coarse and fine aggregates of 2700 kg/m³ and 2600 kg/m³ respectively. The coarse aggregate has a maximum particle size of 10 mm. The mixes selected have water/cement ratios of 0.65 and 0.7, and total cementitious contents of 269 kg/m³ and 290 kg/m³. In the B mix, a small amount of black dye was included to visually distinguish between the different concretes.

Table 1 Concrete mix proportions, kg/m³

	B	C
CEM IIA 32.5 R cement	269	290
Crushed limestone gravel	1274	1274
Sharp sand	678	657
Water	188	188
Black mortar dye	5	
water/cement	0.70	0.65

Two series of castings were carried out, with concrete mix B cast in Series 1, and concrete mixes B and C in Series 2. The B mix was cast in both cases to allow for the effect of alterations in the curing method on carbonation behaviour to be observed. The nomenclature used herein indicates the series and mix design of a particular specimen, such that 1-B indicates mix B cast in Series 1, and 2-C indicates mix C cast in Series 2.

Two prismatic 100 × 100 × 300 mm specimens of each concrete mix were cast in oiled polyurethane moulds and compacted using a vibrating table. The top surfaces of the specimens were skimmed using a trowel to achieve a flat finish, and all specimens were covered with polyethylene sheeting during the first 24-hour hardening period. The prisms were then removed from their moulds and transferred to a water tank for curing. 1-B specimens were cured in water at 20°C until an age of 28 days. 2-B and 2-C specimens were cured in water at 60°C for an initial 48 hours followed by 20°C until 28 days old. At the end of curing, all specimens were moved to laboratory conditions of 20°C and 50% relative humidity (RH) with 0.04% ambient CO₂.

Fresh and hardened state properties of the concretes, given in Table 2, were measured from standard characterisation test specimens cast at the same time as the prisms used for carbonation testing.

Table 2 Measured properties of standard specimens of each concrete

		1-B	2-B	2-C
Slump	[mm]	4	17	22
$f_{cube,mean}$, 28 days	[MPa]	27.5	21.3	20.3
$f_{ct,sp}$	[MPa]	2.64	2.21	2.07
$E_{C,0}$	[GPa]	32.49	28.20	27.17
Saturated surface dry density	[kg/m ³]	2340	2320	2260
Open porosity	[%]	12.76	14.18	14.31

One prism from each mix and series was held in NC test conditions in the laboratory for a total of 58 weeks. After 20 weeks in NC laboratory conditions, the second prism of each mix and series was transferred into a carbonation chamber with constant AC test conditions of 55% RH, 20°C and 4% CO₂ concentration for a period of 11 weeks of AC. The AC test prisms were sealed with paraffin wax on all faces except the top ("free") and bottom ("cast") faces to allow simulation of 1-D carbonation.

The method outlined in BS 1881-210:2013 [12] was used to obtain the measurement of carbonation depth. After a given exposure time, 50 mm slices were split from specimens using a tensile splitting apparatus. The freshly split surface was sprayed with 1% phenolphthalein in ethanol solution to reveal the carbonation front. The recorded carbonation depth was calculated as the average of 5 digital calliper measurements taken at regular intervals along the exposed top-cast or bottom-cast faces. The remaining portion of the prism was then returned to its test conditions to continue carbonating.

RESULTS AND ANALYSIS

The average measured carbonation depths (μ) and standard deviations (σ) of measurements from NC tests for each of the concretes for the duration of NC exposure are given in Table 3.

Table 3 Carbonation depths of all concretes during NC exposure, mm

Mix	Face	0 days		139 days		242 days		405 days	
		μ	σ	μ	σ	μ	σ	μ	σ
1-B	Bottom	0.0	0.0	2.7	0.8	4.1	0.5	4.2	0.6
	Top	0.0	0.0	4.4	0.7	4.7	1.0	4.7	0.5
2-B	Bottom	0.0	0.0	3.7	0.7	4.6	0.5	5.2	0.6
	Top	0.0	0.0	4.5	0.9	5.8	1.1	6.4	0.6
2-C	Bottom	0.0	0.0	4.0	0.9	4.6	0.8	4.8	0.5
	Top	0.0	0.0	4.4	0.9	5.4	0.7	6.3	0.8

The same quantities for the AC tests for the duration of AC exposure are given in Table 4. Recall that at the start of the AC period (0 days) the specimens had previously been exposed for 20 weeks in NC conditions, hence the initial carbonation depth is non-zero.

Table 4 Carbonation depths of all concretes during AC exposure, mm

Mix	face	0 days		35 days		49 days		63 days		77 days		88 days	
		μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
1-B	Bottom	2.4	0.8	13.5	1.2	15.3	2.4	14.5	2.9	15.2	2.2	14.9	0.9
	Top	4.0	1.7	24.1	6.8	31.7	4.9	31.9	5.6	33.2	5.4	50.9	2.8
2-B	Bottom	3.5	0.3	13.2	3.0	16.5	0.7	20.5	4.9	20.0	1.3	21.3	3.4
	Top	4.5	1.0	17.3	2.5	25.3	1.6	27.0	5.5	28.7	5.5	27.9	3.4
2-C	Bottom	3.9	0.7	15.2	1.9	21.5	2.0	23.0	2.4	24.1	3.9	23.4	2.9
	Top	4.3	0.7	17.3	1.8	22.1	2.9	25.3	3.2	26.9	0.8	27.6	0.7

Natural carbonation

Figures 2(a)-(c) show the carbonation model from Equation 3 fit to the experimental data for the NC tests using a nonlinear least squares regression. Error bars indicate one standard deviation of the measured carbonation depth away from the mean value. The results for the free and cast faces of each specimen have been separated as they show distinctively different carbonation depths, with the top face carbonating at a faster rate than the bottom face in all cases.

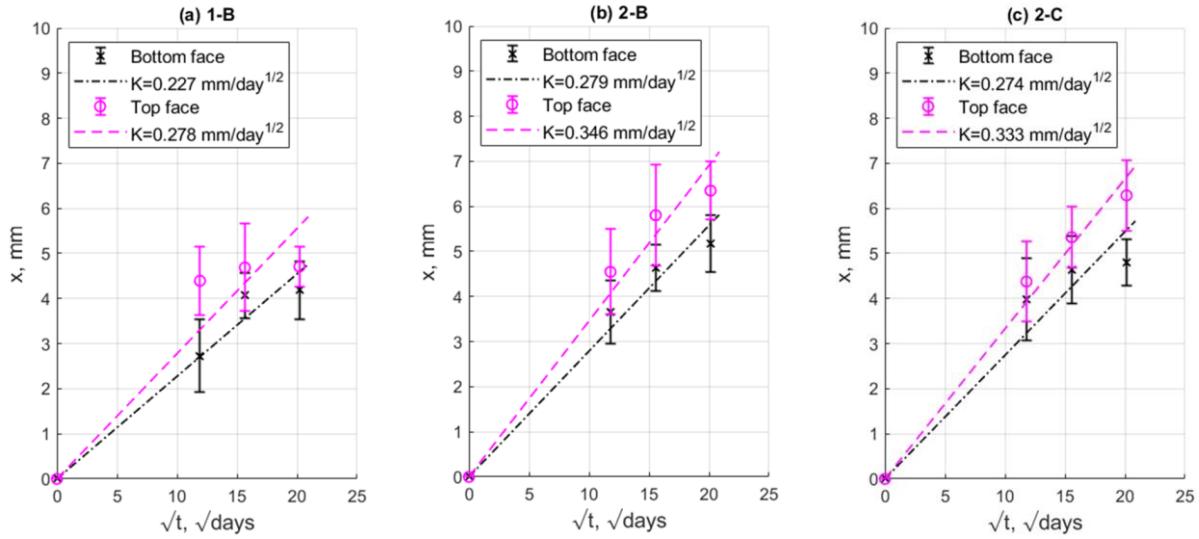


Figure 1 NC carbonation of concrete mixes (a) 1-B, (b) 2-B and (c) 2-C

The estimated carbonation coefficients, K_{NC} , are given in Table 5. 95% confidence intervals indicate the range of K_{NC} with which there is 95% certainty the true value is contained. The coefficient of determination, R^2 , is also given as an indicator of the goodness of fit of Equation 3 to the data.

Table 5 Estimates of NC carbonation coefficient, K_{NC} , mm/day

Mix	Face	K_{NC}	95% confidence interval		R^2
1-B	Bottom	0.23	0.18	0.27	0.96
	Top	0.28	0.18	0.37	0.87
2-B	Bottom	0.28	0.24	0.32	0.97
	Top	0.35	0.29	0.40	0.97
2-C	Bottom	0.27	0.20	0.35	0.92
	Top	0.33	0.29	0.37	0.98

The NC results support the applicability of Equation 3, as the carbonation depth is proportional to the square root of time. A variety of carbonation resistances have been observed in these NC tests, ranging from $K_{NC} = 0.23 \text{ mm}/\text{day}^{1/2}$ (1-B bottom face) to $K_{NC} = 0.35 \text{ mm}/\text{day}^{1/2}$ (2-B top face).

Accelerated carbonation

Figures 2 (a)-(c) show the fit of the carbonation model (with an offset for the initial carbonation depth as proposed in Equation 7) to the results of the specimens subjected to AC (following an initial NC period). Again, the error bars indicate one standard deviation in the measurement of carbonation depth and the top and bottom casting faces have been separated due to consistent differences between their carbonation rates for the same material.

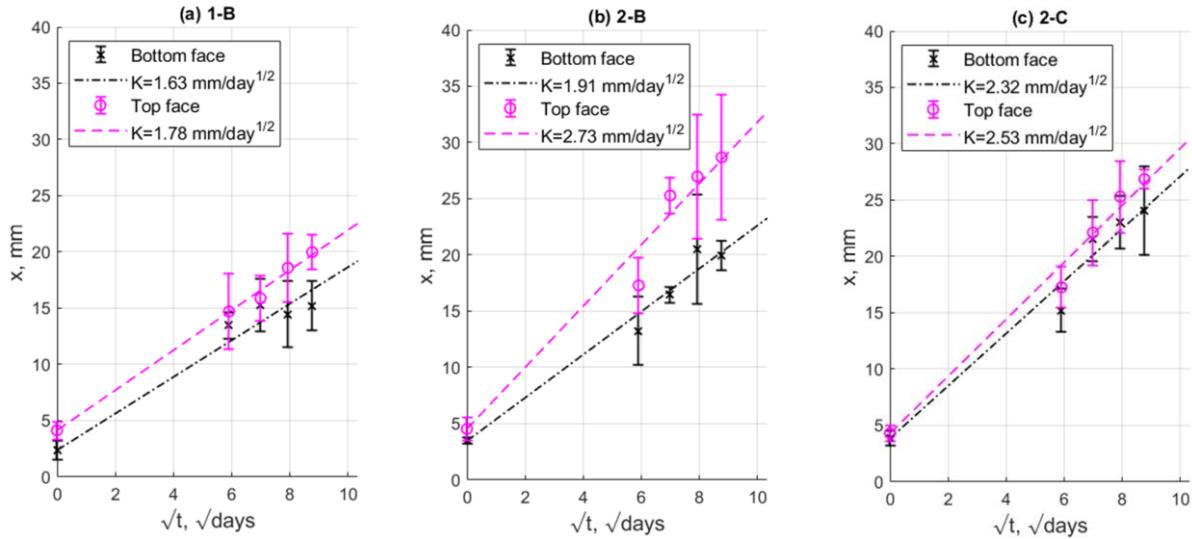


Figure 2 AC carbonation of concrete mixes (a) 1-B, (c) 2-B and (d) 2-C

The estimated carbonation coefficients, K_{AC} , are given in Table 6. These are achieved by fitting Equation 7 to the results for average carbonation depth evolution using linear least squares regression. The value of x_0 is fixed as the initial carbonation depth measured at the start of AC. R^2 values indicate goodness of fit of this model to the data.

Table 6 Estimates of carbonation coefficient, K_{AC} , $\text{mm}/\sqrt{\text{day}}$

Mix	Face	K_{AC}	95% confidence interval		x_0	R^2
1-B	Bottom	1.63	1.38	1.88	2.38	0.94
	Top	1.78	1.70	1.86	4.15	1.00
2-B	Bottom	1.91	1.68	2.14	3.48	0.97
	Top	2.73	2.37	3.08	4.54	0.96
2-C	Bottom	2.32	2.06	2.59	3.85	0.97
	Top	2.53	2.32	2.74	4.30	0.98

A variety of carbonation resistances have been observed across the mixes, ranging from $K_{AC} = 1.63 \text{ mm/day}^{1/2}$ (1-B bottom face) to $K_{AC} = 2.73 \text{ mm/day}^{1/2}$ (2-B top face) in AC test conditions of 4% CO₂. In all cases, the R^2 value is close to 1, indicating that Equation 7 is a good fit to the data.

Effect of casting orientation on carbonation behaviour

In both the NC and AC tests, the carbonation coefficient, K , of the bottom face (which was cast against the formwork at the bottom of the specimen) is lower than that of the top face (which was the free face after casting). The carbonation rate into the top face is found to be consistently faster. It is difficult to make definitive conclusions, although casting differences may be a factor. The bottom face was cast against the plastic moulds coated in mould release oil, and vibrated for a longer total period, whereas the top face was not in contact with release oil, was finished using a trowel to achieve a flat surface and was sprayed with water during the initial 24 hr setting period. Vibration of the specimens may also have been a contributing factor if this had caused air to rise within the specimens, resulting in a higher porosity at the top face which could cause a lower resistance to carbonation observed here.

Effect of curing differences on carbonation behaviour

The curing of Series 2 differed from Series 1, as Series 2 specimens were initially stored in a high temperature water bath. Since both series included the mix B, the effect of this on the resultant concrete

properties can be directly observed. When comparing the properties of concrete 2-B to 1-B, Table 2 shows that the period of hot curing results in a loss of strength and stiffness, and an increase in open porosity. There is also an apparent reduction in the carbonation resistance attributable to the hot water curing, seen as an increase in the carbonation coefficients of 2-B compared to 1-B in both NC and AC conditions. This is consistent with the findings of Tang et al. [13] that durability and strength of concrete is lost when curing temperature exceeds a critical value, since the porosity of the resultant concrete is increased.

Effect of CO₂ concentration on carbonation behaviour

The CO₂ concentrations of the AC and NC tests were measured as 4% and 0.04% respectively. The NC carbonation coefficient measured indirectly from the AC test is therefore calculated by applying Equation 9:

$$K_{NC(AC)} = \frac{K_{AC}}{\sqrt{4\%/0.04\%}} = \frac{K_{AC}}{10} \quad \text{Equation 9}$$

Figure 3 shows the relationship between the NC carbonation coefficient predicted from the AC test, $K_{NC(AC)}$, and the measured NC carbonation coefficient, K_{NC} . The error bars indicate the 95% confidence intervals of each estimate of K . The red line indicates the theoretical case where $K_{NC(AC)} = K_{NC}$. For the concretes assessed here, the NC coefficient obtained from the accelerated test, $K_{NC(AC)}$ is an underestimate compared to the true NC coefficient K_{NC} .

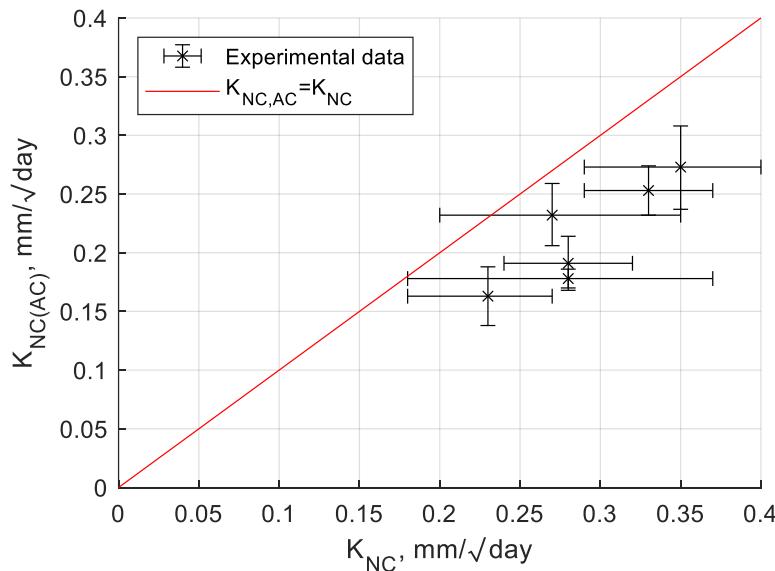


Figure 3 $K_{NC(AC)}$ vs K_{NC}

Elsewhere in similar experiments, Hunkeler [7] also compared results from AC and NC tests, where an initial carbonation depth x_0 was present due to NC exposure prior to commencement of the AC tests. In their work, K_{AC} was also obtained using Equation 8 and converted to an estimate of $K_{NC(AC)}$ using Equation 9. Hunkeler defines the relative carbonation coefficient, K_{rel} as the ratio of the NC carbonation predicted from the AC test, and the measured NC carbonation coefficient, given in Equation 10.

$$K_{Rel} = \frac{K_{NC(AC)}}{K_{NC}} \quad \text{Equation 10}$$

A value of $K_{Rel}=1$ indicates that the estimate of K_{NC} from the AC test, $K_{NC(AC)}$ is accurate, and that this test may therefore be used to predict NC behaviour. The values of K_{rel} for the experiments conducted here are given in Table 7.

In all cases, the value K_{Rel} is significantly less than 1, indicating an error in the estimate of $K_{NC(AC)}$ of up to 36%. Even accounting for the 95% confidence interval for the estimate of K , not presented here for simplicity, there is consistently a lower predicted NC coefficient from all AC tests than was measured in corresponding NC tests. This is in agreement with the findings of Hunkeler [7], [14], and consistent also with Leemann and Moro [15], who all used the same equations to determine K_{AC} and K_{NC} .

Table 7 K_{Rel} values obtained from experimental data

	Face	K_{Rel}
1-B	Bottom	0.72
	Top	0.64
2-B	Bottom	0.69
	Top	0.79
2-C	Bottom	0.85
	Top	0.76

Underprediction of carbonation coefficient in natural conditions is unconservative. If true carbonation coefficients are higher than those estimated by AC tests, this may result in prescription of concretes which do not satisfy durability requirements in real conditions.

It is suggested by Hunkeler that the consistent underprediction of $K_{NC(AC)}$ from AC tests is due to the effect of the CO₂ being weaker than expected [7], but no physical explanation for this phenomenon is given. The apparent error is accounted for in the Swiss standard SIA 262/1 when predicting true NC coefficients from AC tests by applying a correction factor [10]. Possible explanations for this apparent incompatibility include: changes to the carbonation mechanism between AC and NC tests; or errors in estimation of K_{AC} from the experimental data.

Changes to the carbonation mechanism at different concentrations

The validity of Equation 6 relies on the carbonation mechanism remaining unchanged with changing concentration of CO₂. However, it has been observed that high concentrations of CO₂ can lead to formation of phases of calcium carbonate (CaCO₃) which are not normally formed under NC conditions, such as vaterite [16], and an opportunity for other compounds which do not normally carbonate to do so, such as magnesium hydroxide (Mg(OH)₂) [4], [17]. This implies that the value of a in Equation 4 is also concentration dependent. The porosity of the resulting phases of AC tests may also be different to the porosity after NC exposure. The overall effect is that Equation 5 does not remain valid, as was observed by Van Den Heede et al. [18]. To minimise the effect of this on the comparability of AC and NC carbonation coefficients, it is often recommended to keep CO₂ concentrations in accelerated tests low [16]. It has been shown that at a concentration of 3% CO₂ the carbonation products are similar to those formed in natural carbonation [19] and this is widely accepted to extend to values of 4% [15], which are recommended by numerous standards for AC tests [10], [12]. It is therefore unlikely that this is responsible for the discrepancy between $K_{NC(AC)}$ and K_{NC} measured in the experimental series although further experimental work would be required to make firm conclusions.

An alternative explanation for differences in the carbonation mechanisms of AC compared to NC is highlighted by Meier et al. [20], whereby the water liberated in the carbonation reaction acts to retard the carbonation process. The rate of diffusion of carbonic acid through pore water is slower than the rate of diffusion of CO₂ through air in the pores. As demonstrated by Visser [21], this means that in a concrete with a fine pore structure, the water produced by the carbonation reaction cannot dissipate quickly enough and the rate of carbonation in AC tests is therefore slowed. In concretes with a high porosity, the carbonation front dries quickly, and therefore the carbonation coefficients are found to be related by Equation 9 [21]. Visser derives a model to account for the drying of the concrete and shows that when this effect is factored into the value K_{AC} , Equation 6 holds true for even fine OPC concretes. The concretes used in this experimental series have high porosity, most similar to the fly ash concrete

in [21]. Therefore, it is unlikely that a slow drying of the carbonation front is having a responsible for the entire discrepancy between $K_{NC(AC)}$ and K_{NC} measured, but this factor should be considered.

Errors in estimation of accelerated carbonation coefficient, K_{AC} , from the AC test

An alternative explanation for the discrepancy between $K_{NC(AC)}$, and K_{NC} , is that the value of K_{AC} from which $K_{NC(AC)}$ is calculated is inaccurate. In the experimental data presented here, and the results of Hunkeler [7], and Leeman and Moro [15], there is an initial carbonation depth in the carbonation tests. The porosity of carbonated material is lower than uncarbonated, providing a barrier which protects the internal concrete from carbonation. Therefore, a pre-existing carbonated layer may have significant impact on subsequent calculated carbonation coefficient in the AC test. This suggests that the inclusion of an initial carbonation depth as a linear term in Equation 7 may be a source of error when then calculating $K_{NC(AC)}$ (Equation 9).

CONCLUSIONS

Natural carbonation (NC) and accelerated carbonation (AC) experiments were carried out on two concretes across two casting series. The progress of the carbonation front in both the bottom (cast) and top (free) faces was measured over time. A range of carbonation coefficients were achieved, calculated by fitting Fickian diffusion equations to the experimental data.

It was observed that the carbonation through the bottom face was consistently slower than the top face. This suggests some influence of surface conditions on the carbonation rate. More research is required to establish the physical meaning behind this.

Theoretically, with AC CO₂ concentrations of 4%, the ratio of K_{AC}/K_{NC} should be equal to the square root of the ratio of CO₂ concentrations, $\sqrt{c_{AC}/c_{NC}}$, allowing a prediction of $K_{NC(AC)}$ to be made from results of AC tests. It was observed that, for the concretes here studied, the predicted NC coefficients estimated from their AC tests, $K_{NC(AC)}$, were consistently lower than measured NC coefficients, K_{NC} . It is suggested that the discrepancy between predicted and measured carbonation coefficients for natural conditions may be attributed to differences in the carbonation mechanism at different concentrations, or to errors in the estimation of K_{AC} in the presence of initial carbonation depth.

Overall, it is suggested by these findings and elsewhere [22] that there is a lack of understanding as to why the carbonation coefficient from NC conditions is not consistently well predicted directly from AC tests, resulting in the need for correction factors with no physical interpretation. More work is required to draw firm conclusions.

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REFERENCES

- [1] V. G. Papadakis, C. G. Vayenas, and M. N. Fardis, “Fundamental modeling and experimental investigation of concrete carbonation,” *ACI Mater. J.*, vol. 88, no. 4, pp. 363–373, Jul. 1991, doi: 10.14359/1863.
- [2] F. P. Glasser, J. Marchand, and E. Samson, “Durability of concrete - Degradation phenomena involving detrimental chemical reactions,” *Cem. Concr. Res.*, vol. 38, no. 2, pp. 226–246, Feb.

- 2008, doi: 10.1016/j.cemconres.2007.09.015.
- [3] S. Chatterji, K. A. Snyder, and J. Marchand, "Depth profiles of carbonates formed during natural carbonation," *Cem. Concr. Res.*, vol. 32, no. 12, pp. 1923–1930, Dec. 2002, doi: 10.1016/S0008-8846(02)00908-0.
- [4] J. Kropp and H. K. Hilsdorf, *Performance Criteria for Concrete Durability*. RILEM, 1995.
- [5] J. C. Forsdyke and J. M. Lees, "An analysis of existing models for carbonation coefficient applied to tests under natural conditions," in *fib Symposium 2021: Concrete Structures: New Trends for Eco-Efficiency and Performance*, 2021.
- [6] E. I. Moreno, "Carbonation coefficients from concrete made with high-absorption limestone aggregate," *Adv. Mater. Sci. Eng.*, vol. 2013, no. Article ID 734031, p. 4, 2013, doi: 10.1155/2013/734031.
- [7] F. Hunkeler and T. F. B. Ag, "Swiss Requirements for the Carbonation Resistance of Concrete for the Exposure Classes XC3 , XC4 and XD1," in *9th International Concrete Conference 2016, Environment, Efficiency and Economic Challenges for Concrete*.
- [8] K. Sisomphon and L. Franke, "Carbonation rates of concretes containing high volume of pozzolanic materials," *Cem. Concr. Res.*, vol. 37, no. 12, pp. 1647–1653, Dec. 2007, doi: 10.1016/j.cemconres.2007.08.014.
- [9] L. Czarnecki and P. Woyciechowski, "Prediction of the reinforced concrete structure durability under the risk of carbonation and chloride aggression," *Bull. Polish Acad. Sci. Tech. Sci.*, vol. 61, no. 1, pp. 173–181, Mar. 2013, doi: 10.2478/bpasts-2013-0016.
- [10] Swiss Society of Engineers and Architects (SIA), "SIA 262/1:2019 Construction en béton – Spécifications complémentaires." Norme Suisse (SN), 2019.
- [11] B. K. Marsh, D. C. Teychenné, R. E. Franklin, and H. C. Erntry, *Design of normal concrete mixes*, Second Edi. Construction Research Communications Ltd, Building Research Establishment (BRE), 1997.
- [12] British Standards Institution, "BS 1881-210:2013 Testing hardened concrete Part 210 : Determination of the potential carbonation resistance of concrete - Accelerated carbonation method." 2013.
- [13] Y. Tang, H. Su, S. Huang, C. Qu, and J. Yang, "Effect of Curing Temperature on the Durability of Concrete under Highly Geothermal Environment," *Adv. Mater. Sci. Eng.*, vol. 2017, 2017, doi: 10.1155/2017/7587853.
- [14] F. Hunkeler and L. Lammar, "Anforderungen an den Karbonatisierungswiderstand von Betonen."
- [15] A. Leemann and F. Moro, "Carbonation of concrete: the role of CO₂ concentration, relative humidity and CO₂ buffer capacity," *Mater. Struct.*, vol. 50, no. 1, 2017, doi: 10.1617/s11527-016-0917-2.
- [16] Fédération Internationale du Béton (fib), "fib bulletin 34 - Model Code for Service Life Design." Lausanne, 2006.
- [17] T. Powers, *A hypothesis on carbonation shrinkage*. Skokie Ill.: Portland Cement Association Research and Development Laboratories, 1962.
- [18] P. Van Den Heede, M. De Schepper, and N. De Belie, "Accelerated and natural carbonation of concrete with high volumes of fly ash: Chemical, mineralogical and microstructural effects," *R. Soc. Open Sci.*, vol. 6, no. 1, 2019, doi: 10.1098/rsos.181665.
- [19] M. Auroy *et al.*, "Comparison between natural and accelerated carbonation (3% CO₂): Impact on mineralogy, microstructure, water retention and cracking," *Cem. Concr. Res.*, vol. 109, pp. 64–80, 2018, doi: 10.1016/j.cemconres.2018.04.012.
- [20] S. A. Meier, M. A. Peter, A. Muntean, and M. Böhm, "Dynamics of the internal reaction layer arising during carbonation of concrete," *Chem. Eng. Sci.*, vol. 62, no. 4, pp. 1125–1137, 2007, doi: 10.1016/j.ces.2006.11.014.
- [21] J. H. M. Visser, "Accelerated carbonation testing of mortar with supplementary cementing materials - Limitation of the acceleration due to drying," *Heron*, vol. 57, no. 3, pp. 231–247, 2012.
- [22] S. von Greve-Dierfeld *et al.*, *Understanding the carbonation of concrete with supplementary cementitious materials: a critical review by RILEM TC 281-CCC*, vol. 53, no. 6. 2020.