

A Simple Chamber for Accelerated Carbonation Testing of Concrete

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Abstract

This paper describes an easily constructed accelerated carbonation test chamber suitable for evaluation of the carbonation rate into concrete specimens. The test chamber can be constructed at low cost using readily available materials. Very uniform test conditions were created within the chamber. Various Portland cement based trowel applied anti-carbonation coatings were applied to site cast and precast concrete substrates. The types of coatings included polymer additives of acrylic and styrene butadiene in both powdered and liquid form. Coatings were applied to both formed and exposed/cast surfaces. Depth of carbonation was measured using phenolphthalein solution.

Keywords: carbonation, coatings, precast, acrylic, SBR

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1.0 Introduction

There is a practical need to evaluate materials and coatings that reduce the rate of carbonation into concrete. Atmospheric carbon dioxide diffuses into the concrete surface and reacts with the calcium hydroxide and CSH in the surface layers of the concrete. The slowly advancing carbonation front results in reduction in the pH of the protective cover of concrete over the reinforcing steel and subsequently may result in conditions suitable for corrosion of the reinforcing steel. Increasing air pollution, and potential increases in atmospheric CO₂ and temperature due to greenhouse gas effects [1] may result in greater carbonation rates in the future.

While carbonation effects have been known for many years and the general quality of concrete has improved in recent years, there is still not a consistent design approach to reducing the carbonation penetration into concrete in codes of building practice. Part of this is due to the complex nature of the carbonation process when variables such as hydration, temperature, micro-cracking, pore structure change due to carbonation reaction and the normal heterogeneity of concrete are considered. It is also true that large environmental test chambers are expensive, and may be difficult to maintain. There is little description in the literature as to exactly how environmental conditions are generated for accelerated carbonation tests. One practical chamber was described by Dhir et al [2] with a sample capacity of 1.5 m³. This paper describes an easily constructed accelerated carbonation test chamber with 0.2 m³ capacity suitable for evaluation of the carbonation rate into concrete specimens and is useful in carbonation studies where atmospheric conditions are kept constant.

The custom built carbonation chamber was designed specifically for the evaluation of anti-carbonation coatings for a commercial application. The carbonation study was completed to evaluate the quality of coatings that needed to be both moisture vapour permeable but CO₂ inhibiting. This is a typical situation in building construction for instance where there is a need for vapour "breathability" of wall construction. Coatings, such as epoxy will nearly prevent the diffusion of CO₂, but due to low vapour permeability, can trap moisture in concrete. This may result in unacceptable moisture conditions for instance in the building envelope. If there is sufficient vapour pressure, breakdown of bond of impermeable coatings may occur. Water vapour breathable but CO₂ inhibiting sealers were evaluated by Igaune et al [3] who studied siloxanes, alkali silicates and others. Although water vapour permeability was not measured, the CO₂ barriers tended to also be liquid water impermeable with likely poor breathability.

In this study, various coatings were formulated and applied to samples of the site cast concrete and precast concrete for an industrial project. The process had elevated levels of atmospheric CO₂ and thus a high risk of corrosion of the embedded steel once the 40 mm concrete cover was carbonated. Because a high water vapour pressure gradient was also expected, barrier type coatings, such as epoxy or polyurethane, were risky due to potential debonding problems. Various Portland cement based trowel applied coatings were developed which were expected to have good water vapour transmission characteristics. These included cement based coatings modified with polymer additives of acrylic and styrene butadiene in both powdered and liquid form as well as a reactive crystalline coatings containing proprietary ingredients. Coatings were applied to both formed and exposed/formed surfaces. In addition, coatings were applied to precast concrete panel elements made and cured under more controlled conditions than the site cast materials. Following 1 and 2 months in the test chamber using a procedure similar EN 132925 [4], the depth of carbonation was measured by splitting the specimens and applying a pH indicating phenolphthalein solution.

2.0 Carbonation Test Chamber

The carbonation chamber apparatus consists of two separate chambers as shown in Figure 1. The chamber on the right is the environmental supply chamber where air is conditioned to a CO₂ content of 4%, relative humidity of 58 to 62% and temperature of 25 °C. The chambers are easily constructed using standard commercial 45 gallon (200 litre) drums or barrels. Gaskets and sealing clamps can be used to make a near air tight system.

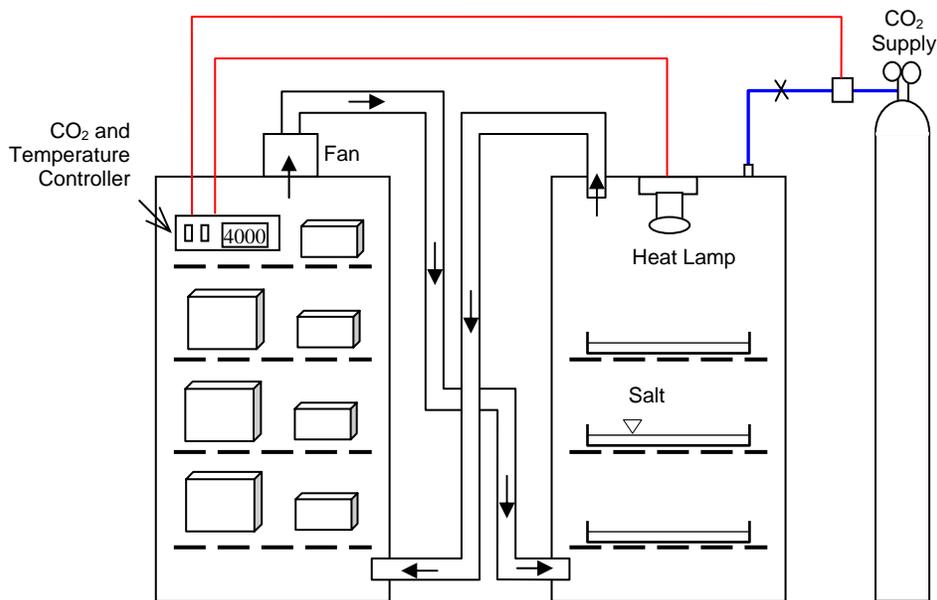


Figure 1: Schematic of Test Chamber

Relative humidity was controlled with multiple pans of saturated salt solution composed of NaNO₂ and water. Racks were made for the conditioning drum using cut sections of commercial wire shelf material and stacked one on top of another with large surface area flat pans containing the saturated salt solution in between. Various types of saturated salt solutions for humidity control in the laboratory are described in detail by Young [5]. Saturated salt solutions can absorb or liberate a large amount of water without changing their equilibrium vapour pressure but it is important to make sure the solution is fully saturated with excess solid below the solution surface and to recognize that the equilibrium relative humidity will be dependant upon temperature [5]. Periodic checks need to be made to make sure the solutions is not under-saturated or dried out.

Temperature was controlled using a 250 W heat lamp connected to a control loop and relay and the chambers were insulated to assist with temperature stability. Slight influence of daily ambient temperature effects can be seen in the average chamber temperature in Figure 2.

The CO₂ atmosphere was created using compressed CO₂ gas supply, solenoid valve, needle valve, CO₂ sensor and control loop. The EN 132925 [4] standard suggests the CO₂ should be supplied in

a premixed bottled form (1% CO₂ in air). In this experiment a 4% CO₂ atmosphere was chosen to shorten the test period to suit project requirements. An industrial gas mixture of 4% CO₂ in air was tried initially but cylinders were consumed at a rapid rate and a more cost effective solution was found to be pure CO₂ controlled to 4% using a sensor and solenoid valve system. The needle valve was useful in keeping the flow rate very low thus reducing swings in the CO₂ concentration in the atmosphere. The typical concentration of CO₂ over a 1 day period is shown in Figure 3. With a sensor accuracy of approximately +/-3% the estimated CO₂ concentration in the chamber is 4.0 +/-0.2 % CO₂. It is noted that if minor CO₂ leaks are occurring, then proper venting of the laboratory should be completed to avoid risk of injury.

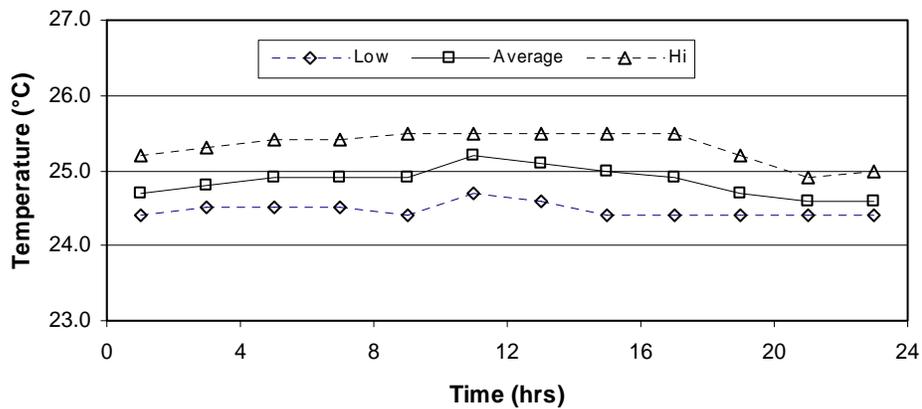


Figure 2: Typical chamber temperature during one day.

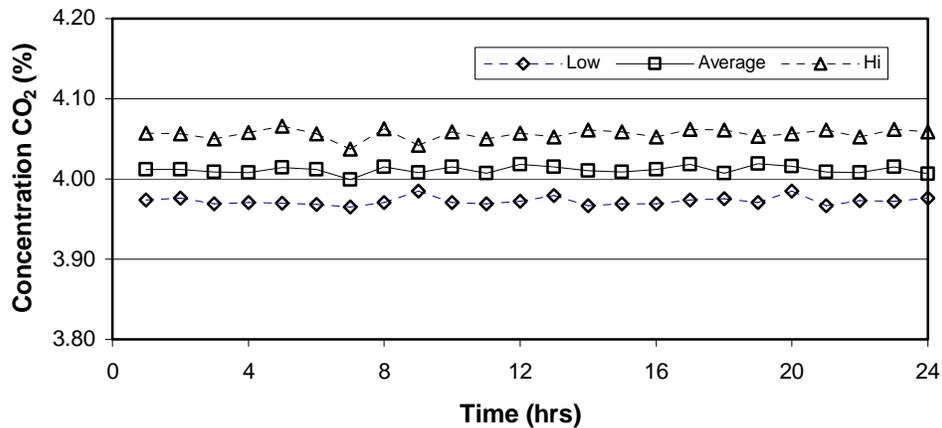


Figure 3: Typical chamber CO₂ concentration during one day.

Air was circulated between chambers using a low flow rate fan (110 Volt large computer style fan) and flexible ducting. Flow direction in Figure 1 was to take advantage of convective heat flow currents. The purpose of air flow was to create uniform atmosphere conditions and to avoid stratification of atmospheric conditions.

A commercially available atmosphere controller was used to regulate supply of CO₂ and control temperature as well as monitor relative humidity. The controller was capable of collection of 24 hrs of data on three channels and recorded high, low and average values each hour. The controller was designed for use in green house operations and thus needed to be customized by the manufacturer to include a 0 to 50,000 ppm (0 to 5%) CO₂ sensor as it normally contained a 0 to 5,000 ppm sensor.

Test samples were arranged randomly on racks contained within the test chamber (left side). Depth of carbonation was measured by splitting the samples and spraying with a phenolphthalein solution.

3.0 Preparation of Test Samples

Site cast concrete was brought to the lab after at least 3 months since time of cast and consisted of three panels of 40 to 50 mm thick. The concrete was a protective liner cast against a steel substrate intended for use in a high CO₂ atmosphere. Panels were sawcut into pieces approximately 100 x 100 mm. In addition, precast "hydro pressed" concrete paver slabs were obtained to act as a more uniform substrate not subjected to site variability of the cast samples. The concrete pavers were obtained from the same lot directly from the manufacturer so that the date of production was known. The samples were 1 month old at the time of application of the coatings.

Sample surfaces were sand blasted prior to application of coatings. Various coatings, as shown in Table 1 were applied to the saturated surface dry concrete substrate. Acrylic A1 and A2 were both liquid type with A1 having double the polymer content. Acrylic B is a liquid type and Acrylic C is a redispersible powder type. All polymer mixes had equal polymer contents except A2 which was half. Control samples were also sand blasted and presaturated so that they had similar surface and moisture conditions as coated samples. The acrylic and styrene butadiene (SBR) samples were given no moist curing in order to promote latex film formation. The proprietary/reactive coating was cured for 3 days. Following curing, samples were conditioned in lab air (50% rh and 23 °C) for 1 month prior to starting the accelerated carbonation test. After coating and curing, the 40 mm edges of the samples were coated with epoxy to create a one dimensional carbonation front.

4.0 Test Results

After one month in the test chamber, samples were removed and split into three pieces to create two separate carbonation depth readings for each sample. The dry surface was sprayed with a 1% solution of phenolphthalein in alcohol. Maximum and minimum depth of carbonation was measured and numerically averaged. A median depth was also determined. The median penetration was based equal carbonated and uncarbonated areas shallower and deeper than the median line respectively.

Results of depth of carbonation into the exposed/finished surface are shown in Table 1 and results of the formed surface are shown in Table 2. The "depth increase" in Table 1 is based on fact that samples were pre-carbonated when received on the exposed/cast face by approximately 5 mm. An example of a carbonated sample is shown in Figure 4.

Results for the precast slabs were not obtained after 1 month. Carbonation depth was found to be so minimal that samples were left in the chambers and data is not yet available.

Table 1: Depth of Carbonation – Exposed/Cast Surface

Treatment	Coating Type	Median Carbonation Depth (mm)	Depth Increase (mm)	Carbonation Relative to Control
Control	-	11.0	6.0	1.00
C1	SBR	8.5	3.5	0.58
C2	acrylic B	8.0	3.0	0.50
C3	acrylic A1	11.0	6.0	1.00
C4	acrylic C	11.0	6.0	1.00
C5	acrylic A2	11.3	6.3	1.05
C6	proprietary/reactive	8.8	3.8	0.63

Table 2: Depth of Carbonation -Formed Surface

Treatment	Coating Type	Median Carbonation Depth (mm)	Carbonation Relative to Control
Control	-	7.8	1.00
C1	SBR	7.3	0.94
C2	acrylic B	7.7	0.99
C3	acrylic A1	4.5	0.58
C4	acrylic C	6.5	0.83
C5	acrylic A2	7.5	0.96
C6	proprietary/reactive	4.5	0.58

5.0 Discussion

The test chamber was simple to construct and easy to operate. The entire cost of materials for the chamber was approximately \$2500 USD including the controller yet environmental conditions were very uniformly throughout the test. There is some limitations to the range of relative humidity produced by salt solutions, however, several salt solutions are available for different set points [5]. Simple commercial humidifiers and dehumidifiers could also be employed. The humidity obtained in this test (60%) was slightly less than that described by Young [5] for NaNO₂ and this may be due to the purity of the salt or the slow loss of moisture with leakage of air from the chambers.

Generally, the acrylic and SBR coatings showed little resistance to carbonation and there was little differentiation possible between coating types. Microcracks and weak porous regions around aggregates are two possible reasons for the high variability. Acrylic A2, with only half the polymer content, showed least resistance to carbonation and this may indicate that there was insufficient polymer film in any of the polymer coatings to substantially affect carbon dioxide diffusion. Further study is needed to determine if higher polymer content would reduce carbonation but still allow sufficient water vapour diffusion. Water vapour diffusion was not completed in this study but is planned for future studies.



Figure 4: Example of Carbonated Sample

There was considerable variation in the maximum and minimum carbonation depths between samples and within individual samples with the same surface treatment. It is interesting to note that the method of splitting samples prior to spraying with indicator will naturally find the weakest path (bond failures at the aggregate paste interface can be seen in Figure 4). If a sample contains substantial microcracks or a thick transition zone around aggregates, then greater depth would be expected along this permeable pathway. Sawcutting the sample to avoid this problem was attempted for comparison, however, very poor colouration was obtained likely due to smearing of high pH dust across the sawcut surface thus obscuring the CO_2 front.

Because of the variability in depth readings, the median depth technique tended to smooth out some of the errors associated with high variability of the maximum and minimum depths. Even so, there is difficulty in determining which coating was best at reducing carbonation rate. The most prominent trends in the data are that the Control samples tend toward that greatest depth of penetration and the samples coated with the cement based reactive/proprietary coating tended toward the least penetration. The thick build epoxy that covered the edge of the sample was a very effective barrier to carbonation but would not provide the necessary breathability to water vapour required under the construction conditions.

A simple calculation was made to compare the difference in rates of carbonation of the coated and uncoated samples based on the median average data. An approximate formula assumes that the rate of carbonation follows a square root of time function in accordance with Fick's first law. If it is further assumed that the samples are carbonated under uniform conditions similar to the test chamber then it can be determined that it will take the reactive/proprietary coated samples between 2.5 and 3 times longer to be fully carbonated than the Control (uncoated samples). However actual rates of carbonation may be substantially different due to variation in the concrete substrate

quality, the influence of microcracks and transition zone porosity, difference in the effect of actual CO₂ concentrations inside the industrial project, and the degree of saturation concrete.

6.0 Concluding Remarks

A simple and inexpensive test chamber was developed that can be quickly assembled and is useful for carbonation studies of concrete.

Due to the high variability in maximum and minimum values it is difficult to draw firm conclusions about the effectiveness of the various coatings. The samples coated with the cement based reactive/proprietary coating tended toward the least penetration. The thick build epoxy was an very effective barrier to carbonation but would not provide the necessary breathability to water vapour required under the construction conditions.

7.0 References

1. Yoon, I., Lee, C., and Seol, J., "Prediction of Carbonation Depth of Concrete Structures Considering Atmospheric Change," *Proceedings of the 4th International Conference on Concrete Under Severe Conditions: CONSEC'04*, Seoul, 2004, pp. 189-204
2. Dhir, R.K., Jones M.R., and Munday, J.G.L., "A Practical Approach to Studying Carbonation of Concrete", *Concrete*, October, 1985, pp. 32-34
3. Igaune, S., Lagxdins, E., Vitina, I., Setina, Y., "Effects of Various Coatings on Carbonation and Sulphation of Concrete" *Proceedings of the 3rd International Conference on Concrete Under Severe Conditions: CONSEC'01, Vancouver, 2004*, pp.1892-1899
4. European Standard EN 13295:2004 "Products and systems for the protection and repair of concrete structures – test methods – Determination of resistance to carbonation".
5. Young, J.F., Humidity Control in the Laboratory Using Salt Solutions-A Review," *Journal of Applied Chemistry*, **17**, 241-245 (1985)