Evaluation of Port of Miami Tunnel Segments

Carbonation and service life assessment made using on-site air permeability tests

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The $1 billion Port of Miami Tunnel is one of the largest construction projects currently underway in the United States. When completed, the project will provide direct access between the seaport and highways I-395 and I-95, reducing the number of cargo trucks on congested downtown Miami, FL, streets and aiding development in the region.

A key element of the project is the construction of a 3/4 mile (1.2 km) long twin-tube tunnel between Watson and Dodge Islands. The tunnel is being bored using a 42 ft (13 m) diameter earth pressure balance tunnel boring machine (EPB TBM), which concurrently installs segmental precast concrete lining rings. Each ring panel is composed of eight precast curved segments that are typically about 16 ft (4.9 m) long, 5.5 ft (1.7 m) wide, and 2 ft (0.6 m) thick.

The project is a public-private partnership governed under a concession agreement between the owner, Florida Department of Transportation (FDOT), and MAT Concessionaire, LLC (MAT). The agreement transfers the responsibility for designing, building, financing, operating, and maintaining the project to the private sector. The contract terms make it clear that durability and service life of the tunnel are of paramount importance, as the specified service life is 150 years.

During the design and construction phases, which MAT has subcontracted to Bouygues Civil Works Florida, FDOT makes payments to MAT based on achievement of contractual milestones. Once the construction phase is completed, FDOT will make payments contingent upon actual lane availability and service quality. The contract terms require that MAT returns the tunnel to FDOT in first-class condition at the end of the contract in October 2044.

Service Life Design

The service life of the tunnel will be limited by corrosion of the reinforcing bars in the precast concrete lining. The exterior face of the lining (extrados) will be affected by chloride ingress from seawater, and the interior face of the lining (intrados) will be affected by carbonation of the cover concrete. The design service life was predicted using three different models: Life-365,[1] DuraCrete/DARTS,[2,3] and the Sagües prediction model.[4] Analyses identified steel corrosion induced by chloride ingress at the extrados as the most severe deterioration mechanism.

Achieving the specified service life required the use of a low-permeability concrete made with locally available materials complying with FDOT specifications. The accepted mixture design comprises Type II portland cement, slag cement, and Class F fly ash (318, 397, and 79 lb/ft^3 [188, 236, and 47 kg/m^3], respectively) and has a water-cementitious material ratio (*w/cm*) of 0.32.

Fig. 1: A view of some of the 32 steel forms used for production of the tunnel lining segments

Fig. 2: Concrete was transported to each form using a vehicle equipped with a hopper and an auger. During and after filling, the steel form was vibrated for a total of 8 minutes to consolidate the mixture

Analyses of chloride ingress through the 3 in. (76 mm) extrados cover indicated, at a confidence level of 90%, a 140-year period before corrosion initiation. Taking the tunnel tail void grout into account, the confidence level was raised to 93%. Corrosion propagation would occur over an additional 10 years. Analyses conducted using the DuraCrete/DARTS model predicted that the carbonation front in the intrados cover would reach just one third of the cover depth at the same age. The results were accepted by FDOT as demonstrating that the segment lining design fulfilled the 150-year service life requirement.

Segment Fabrication

The precast segments were cast, cured, and fitted with rubber gaskets inside a dedicated prefabrication plant housing 32 steel forms (Fig. 1). After forms were cleaned and conditioned, a segment's reinforcing cage was placed inside the forms, supported on polymer wheels, to ensure the cover was at least 3 in. (76 mm).

Concrete was batched outside the plant and transported in a vehicle equipped with a maneuverable arm that housed an auger to move the concrete and discharge it from short height into the steel form (Fig. 2). The forms were vibrated for 8 minutes during and after the discharge of the concrete. The extrados were manually finished and then sprayed with a liquid curing compound (Fig. 3).

The freshly cast segments remained in the forms for at least 18 hours. They were then lifted from the forms and placed on an assembly where they were turned upside down and fitted with rubber gaskets. The segments were

Fig. 3: The finished extrados of each segment was sprayed with curing compound

then moved outside the facility, stacked in groups of eight, and stored until they were to be transported to the tunnel.

Before the segments were placed in storage, the sides and the intrados of each should have been sprayed with a curing compound to extend the curing period to a minimum of 72 hours, as required by the project specification (alternatively, the segments could have remained in their forms for 72 hours or they could have been moist cured). In the initial production lot, however, curing compound was not applied to 623 segments. The effects of this omission are discussed in this article.

Problem Statement

Rejection of the subject elements would have entailed significant environmental and financial losses. The initial argument against rejection was that the well-consolidated, low-permeability concrete mixture would benefit little from 54 hours of curing beyond the initial 18 hours. This opinion was supported by previous experience, technical review, and examinations of the completed units, which indicated there was no drying shrinkage cracking. Furthermore, DuraCrete/DARTS modeling predicted that carbonation depth after 150 years of exposure in the tunnel would be 0.95 and 1.4 in. (24 and 35 mm) for surfaces that received 72-hour and 18-hour curing, respectively (the model and software include a "curing factor" function that accounts for the length of moist curing). Segments that had been cured for 18 hours would therefore be expected to have carbonation depths that were less than half of the 3 in. (76 mm) cover.

Given the importance of ensuring absence of any damage affecting the 150-year required service life, however, it was necessary to obtain further evidence. A decision was made to conduct direct, nondestructive air permeability tests on the intrados of segments that had been in the forms for 18 and 72 hours (the latter curing occurred when segments were cast on a Friday and stripped on the following Monday). The air permeability of the segments could then be used to assess the segments' resistance to carbonation. Global Sustainable Solutions, LLC, associated with Materials Advanced Services Ltd., were retained to conduct the tests, analyze the results, and use the results to validate the service-life assessment made with the DuraCrete/DARTS model.

Experimental Investigation

Test method

The coefficient of air permeability was measured using the double-chamber vacuum cell method.[5] This well-proven method has been discussed in numerous publications[6-8] and is covered by Swiss Standard SIA 262/1-E:2003.[9] The principles of the test method include:

- A vacuum of about 30 mbar (0.44 psi) is created inside a two-chamber cell (Fig. 4), vacuum-sealed onto a concrete surface by means of a pair of concentric soft rings. After 35 to 60 seconds, Valve 2 is closed, isolating the inner

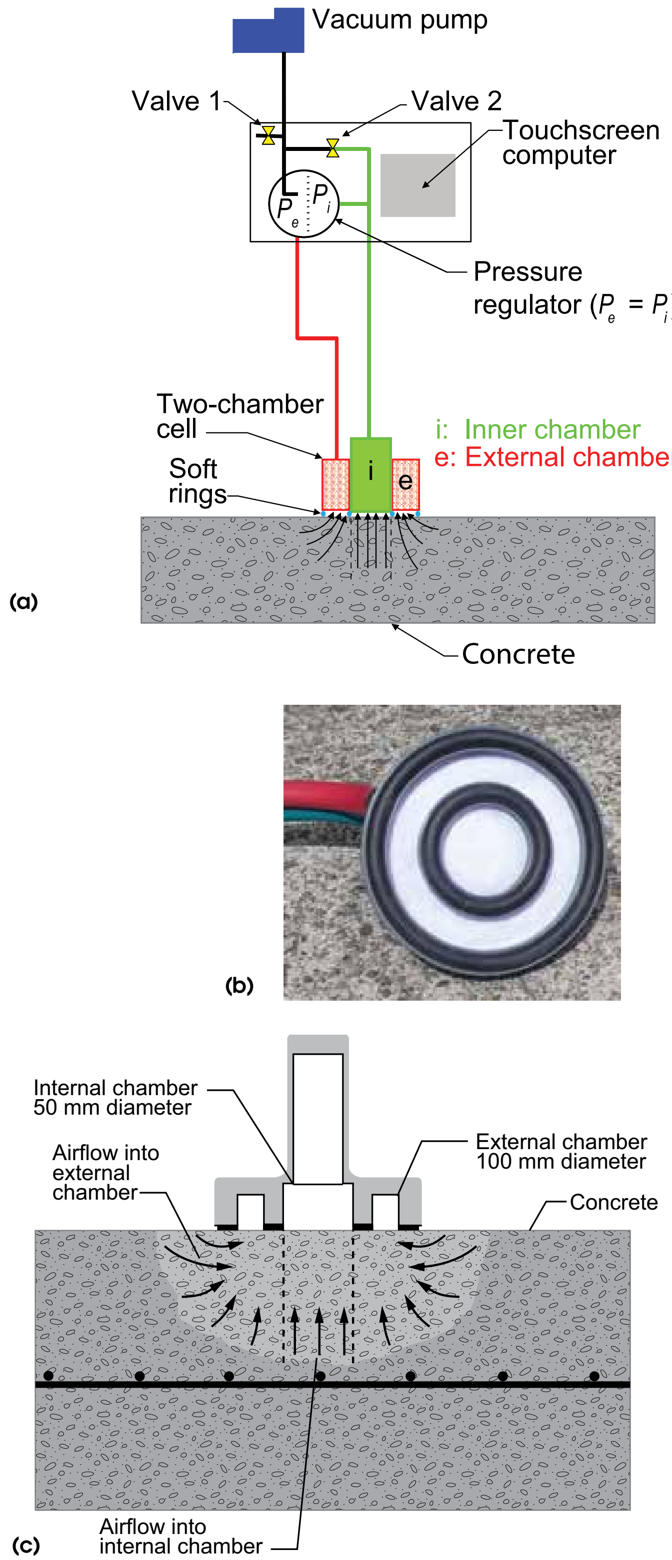

Fig. 4: A double-chamber vacuum cell was used to determine the coefficient of air permeability: (a) schematic of test setup; (b) detail of vacuum cell showing soft concentric rings and air hoses; and (c) schematic showing how the external chamber acts as guard ring ensuring unidirectional flow to the inner chamber

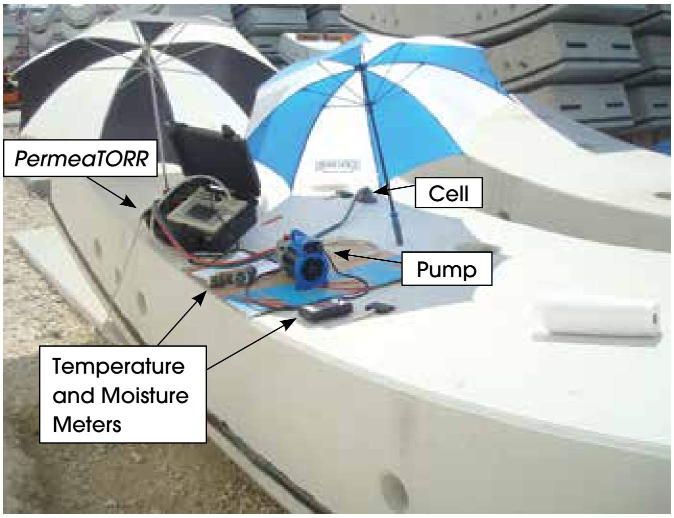

Fig. 5: During air permeability tests, the instrumentation was shielded from direct sunlight. As this image also shows, the formed surfaces of the segments were almost completely free of any "bugholes," indicating a well-consolidated concrete

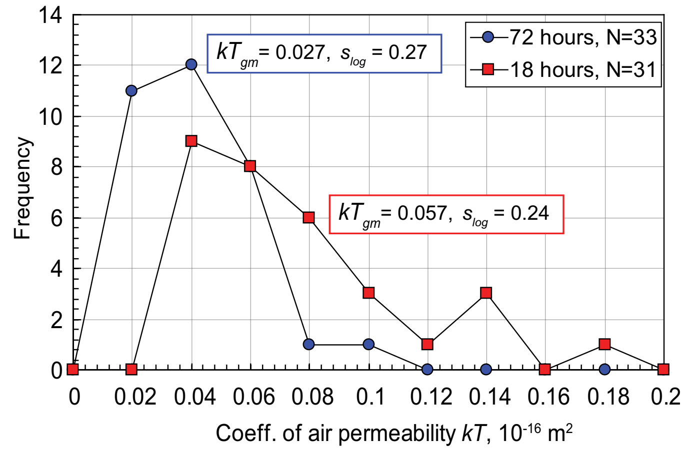

Fig. 6: Frequency distribution and statistical parameters of test results

chamber from the vacuum pump. Air flows through the cover concrete into the inner chamber, raising its pressure P_i. The external chamber of the cell maintains unidirectional airflow into the inner chamber by acting as a guard ring. This is accomplished by means of a pressure regulator, which continuously maintains the pressure of the external chamber at that of the inner chamber ($P_e = P_i$); and

- The rate of pressure rise ΔP_i (measurement starts at t_o = 60 seconds) is directly linked to the coefficient of air permeability of the cover concrete. The coefficient of permeability to air kT, in units of 10^{-16} m^2, can be computed via suitable modeling.[6,10] The latest, automatic version of the instrument PermeaTORR[6] was used for this investigation, allowing a measurement in 6 minutes or less.

Sampling and testing

Ten precast segments were selected for the tests. Five segments had been cured for 18 hours in the forms, while the remaining five had been cured 72 hours in the forms. The segments were chosen so as to have about the same age of 4 months at the time of testing.

The selected segments were placed in an open space in the storage yard, with the intrados surfaces up, and were covered with a tarpaulin for at least 2 days prior to the initiation of the tests. This action was taken to protect the segments from rain, as additional water could have saturated the surface pores, thus influencing the flow of air and accuracy of test results.

At least six kT measurements were conducted on points well-distributed on the intrados of each segment. Over two full days of testing, 33 and 31 measurements were taken on the segments with 72-hour and 18-hour curing, respectively.

To ensure consistency and accuracy of readings, the instrument was calibrated per Reference 7 before starting the measurements and following lengthy pauses in the testing. Also, care was taken to protect the instrument from direct exposure to Miami's sun (Fig. 5).

The moisture content of the concrete surface layers—known to influence the measurements of gas permeability significantly—was measured using an impedance-based instrument, CMEX 1210, manufactured by Tramex Ltd. Based on extensive experience, Reference 7 states that gas permeability measurements are not significantly influenced by moisture content when the moisture content is 5.5% or less. The moisture values recorded at the 64 points evaluated in our test series ranged between 4.5 and 5.9%, with just two measurements exceeding 5.5%. This indicates that the conditions were adequate for measuring kT.

The concrete surface temperature was measured using an infrared thermometer. Values ranged from 68 to 118°F (20 to 48°C).

Test results

Figure 6 presents the frequency distributions of the test results obtained on the segment surfaces that had been cured for 18 and 72 hours. It is immediately obvious that the test results do not follow a normal distribution, confirming the conclusions of other researchers that kT results fit a log-normal distribution (that is, the logarithms of kT are normally distributed).[7,8] Therefore, the distributions of test results are better characterized by the geometric mean kT_{gm} and by the standard deviation of the logarithms s_{LOG} (both indicated in Fig. 6).

The statistical "t-test," applied to the logarithms of the kT values obtained for the two sets of data, indicates that 18-hour curing resulted in a statistically significant increase in the "mean" value of the permeability, compared to the 72-hour curing (significance level of 1×10^{-6}).

Because all segments were about the same age when tested; built with the same concrete mixture; and subjected to the same controlled precast manufacturing procedures, except the curing, the differences in observed *kT* values must be attributed to the difference in curing.

To put this difference in perspective, Fig. 7 presents the values of kT_{gm} and s_{LOG} of the segments tested. At the top of the chart, a classification of the permeability based on *kT*, as originally proposed in Reference 10, is shown. It can be seen that the results of both sets fall predominantly within the same "Low" permeability class. It is also worth mentioning that the permeability classifications, based on *kT* ratings per SIA 262/1-E:2003, correspond quite well to the permeability classifications based on charge passed per ASTM C1202-12, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration" (Fig. 8).

Assessment of Service Life

An estimate of the expected penetration depth of the carbonation front was made by applying Parrott's Model.[11,12] Although the model strictly applies to a different test method for permeability, comparative results show that it provides equivalent results when *kT* values are used

$$d = A \cdot kT^{g} \cdot t^{n}/c^{f} \tag{1}$$

where *d* is the carbonation depth, in mm; *kT* is the coefficient of air permeability measured on the structure, in 10^{-16} m^2, corrected for eventual differences in relative humidity of the environment where the tests were performed and where the structure is actually exposed; *t* is the concrete age, in years; and *c* is the CaO content in the hydrated cementitious material matrix of the cover concrete, expressed as mass per unit volume of cement matrix, kg/m^3. Default values are provided as a function of the relative humidity (affecting the degree of hydration) and type of cementitious material[11,12]; *A* is a constant of 64, based on empirical correlations; *n* is the expected "law" of progress of carbonation front. While usually assumed as 0.5, *n* is a function of the relative humidity of the exposure environment *r* (%) and is given as $n = 0.02536 + 0.01785r - 0.0001623r^2$. The maximum value of *n*, 0.52, corresponds to a relative humidity of 55%. The other exponents *g* and *f* are equal to 0.4 and 0.5, respectively, also based on empirical correlations.

Parrott's model has been calibrated and validated by its author, using data from concrete specimens stored outdoors for 16 years and from buildings and bridges with ages of over 50 years.[11] For the prediction of carbonation, a pessimistic scenario was chosen, assuming a relative humidity of 55% and an extremely low unit CaO content of 379 lb/yd^3 (225 kg/m^3). Under these conditions, the carbonation depth is calculated from Eq. (1) as

$$d = 64\,(kT)^{0.4}\,(150)^{0.52} / (225)^{0.5} \approx 60\,(kT)^{0.4} \tag{2}$$

For the data set for segments cured for 72 hours, with the measured kT_{gm} of 0.027×10^{-16} m^2, *d* will be 14 mm (0.6 in.). For segments cured for 18 hours, with the measured kT_{gm} of 0.057×10^{-16} m^2, *d* will be 19 mm (0.75 in.).

For final validation of the predictions, a further estimate of the carbonation depth was made using data obtained in Switzerland and Japan on several old structures ranging in age from 12 to 60 years.[13-17] For these structures, site measurements of *kT* and carbonation depth (based on the phenolphthalein method on cores drilled from the same spots) were performed.

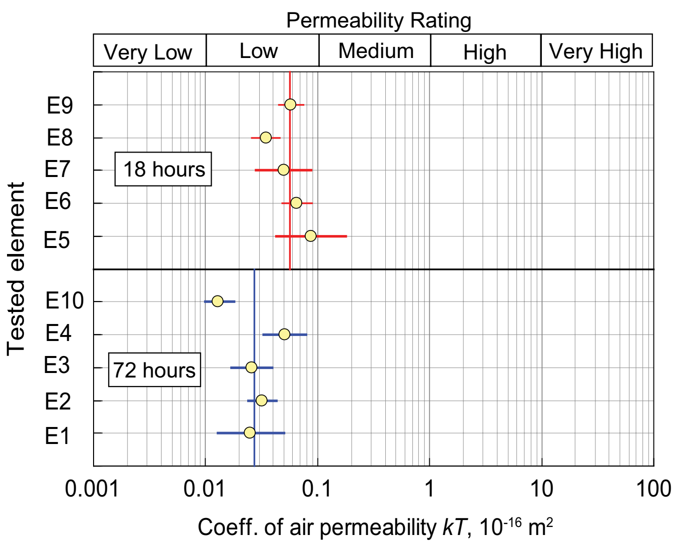

Fig. 7: Summary results for tested segments cured for 18 and 72 hours. Circles represent kT_{gm} values, and horizontal line segments represent ± s_{LOG}. Vertical lines correspond to overall kT_{gm} of the data sets for the five elements in each curing category

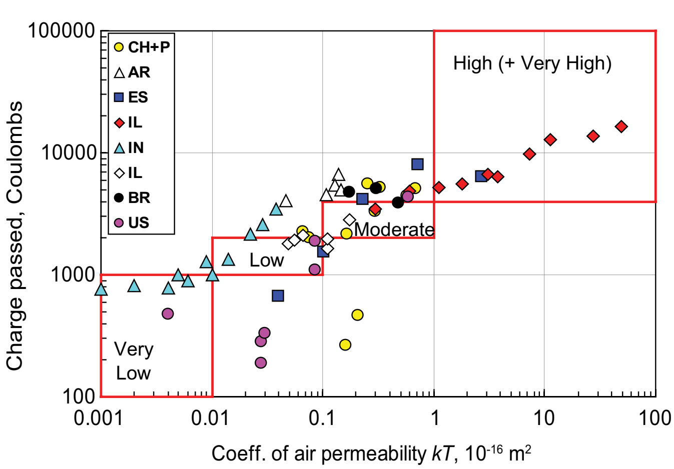

Fig. 8: Comparison of charge passed per ASTM C1202 and *kT* values per SIA 262/1-E,[9] from Reference 8. The data were taken from numerous sources. Permeability classes for the two test standards are also shown

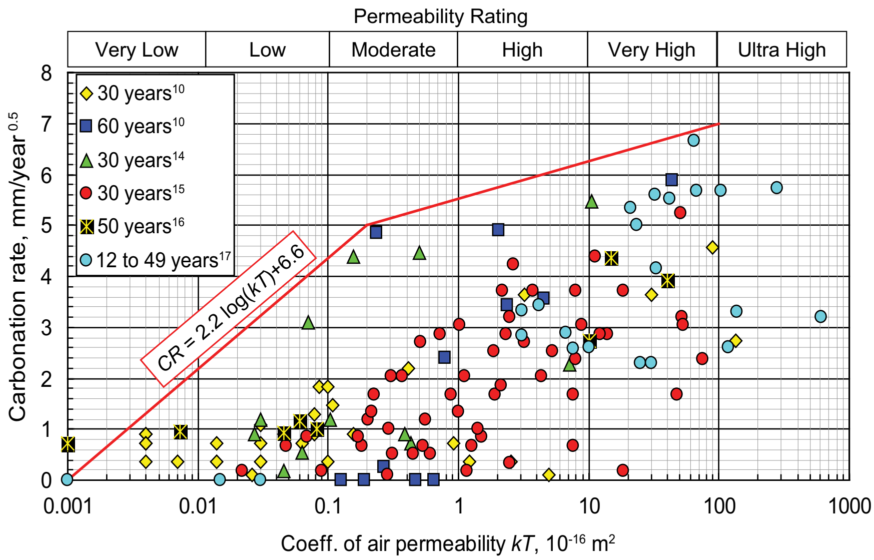

Fig. 9: Carbonation rate versus air permeability measured on old structures in Switzerland and Japan[13-17]

Table 1:
Predicted carbonation depth at 150 years by analytical and *kT*-based methods

Curing time, hours	Predicted carbonation depth at 150 years, in. (mm)		
	Analytical	Based on *kT* site measurements	
	DuraCrete/DARTS	Parrott	Old structures data
72	0.95 (24)	0.56 (14)	1.5 (38)
18	1.4 (35)	0.75 (19)	1.9 (48)

The results (Fig. 9) show that an absolute upper limit for the carbonation rate *CR*, in units of mm/year$^{1/2}$, can be established as

$$CR = 2.2\log(kT) + 6.6 \quad (3)$$

At 150 years, for the data set for segments cured for 72 hours, with $kT_{gm} = 0.027 \times 10^{-16}$ m^2 and $CR = 3.1$ mm/year$^{1/2}$, *d* will therefore be 38 mm (1.5 in.). For the data set for segments cured for 18 hours, with $kT_{gm} = 0.057 \times 10^{-16}$ m^2 and $CR = 3.9$ mm/year$^{0.5}$, *d* will be 48 mm (1.9 in.).

Table 1 summarizes the predicted carbonation depths at 150 years according to the Duracrete/DARTS model and the two methods based on the *kT* measurements. Parrott's model values are about 45% lower than the predictions made using the analytical DuraCrete/DARTS model.

The estimates based on the old structures data are significantly higher than those obtained with the other two methods. The factors that may affect those estimates include:

- The carbonation depth has been calculated using Eq. (3), which overestimates *CR*;
- The air permeability values in Fig. 9 were measured on concrete at 30 and 60 years of age, compared with the tunnel segments, which were tested at 4 months;
- The large majority of data in Fig. 9 correspond to structures where ordinary portland cement was used as binder. In the tunnel segments, a ternary blend was used; and
- The exposure conditions for a bridge are different from those in a tunnel—the latter will possibly experience higher CO_2 concentrations and no wetting.

Despite different results provided by three methods (not unexpected when predicting an extended service life), the projected carbonation depths at 150 years are well below the 3 in. (75 mm) cover depth, confirming the durability of the structure for both segment sets.

Summary

The coefficient of air permeability was measured on the intrados of two sets of precast segments produced for the Port of Miami Tunnel. The tests were conducted by applying the PermeaTORR, a nondestructive test instrument complying with Swiss Standard SIA 262/1-E:2003. Analyses of these results support the following conclusions:

- The segments cured for only 18 hours showed coefficient of air permeability values *kT* that were significantly higher, in statistical terms, than those for segments cured for 72 hours. However, the difference was not significant in practical terms, as both sets of results fall predominantly within the same "Low" permeability class;
- An assessment of the service life by Parrott's model, based on measured *kT* values, indicates carbonation depths at 150 years of 0.56 in. (14 mm) and 0.75 in. (19 mm) for the elements cured for 72 and 18 hours, respectively;
- A validation based on carbonation depth and *kT* values measured on old buildings yielded values of 1.5 in. (38 mm) and 1.9 in. (48 mm), for 72- and 18-hour curing, respectively;
- The estimated carbonation depths confirm the assessment made with the DuraCrete/DARTS model predicting the carbonation depth well below the 3 in. (75 mm) cover depth at 150 years; and
- Because the predicted carbonation depths are much smaller than the 3 in. (76 mm) cover depth, the

durability of the intrados against carbonation-induced corrosion can be ensured.

Findings from this investigation, and other evidence produced by the construction company, led to the acceptance of the 623 segments that had been produced using 18-hour curing of the intrados. Although this assessment supports the argument that it should be possible to omit the application of curing compound to the intrados, the construction company chose to produce subsequent segments with the originally specified curing method.

The investigation shows the validity and usefulness of measuring the air permeability of the cover concrete on site as a quality control tool and realistic assessment of service life based on hard data obtained from the end product.

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Note: Additional information on the ASTM standard discussed in this article can be found at www.astm.org.

Selected for reader interest by the editors after independent expert evaluation and recommendation.

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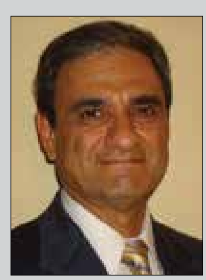

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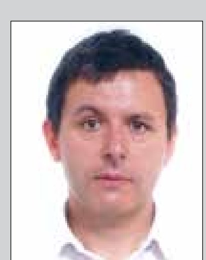

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