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Long-term permeability measurements on site-cast concrete box culverts

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HIGHLIGHTS

- Changes in transport properties of concrete cover were monitored for three years.
- Applicability of non-destructive tests on concrete cover was compared.
- Effectiveness of a new simplified method, WIST, was verified.
- Correlation between carbonation rate and air permeability was increased with age.
- Aged concrete water sorptivity and carbonation rate were not correlated.

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ABSTRACT

This study investigated the effect of age on transport property measurements of concrete cover. Changes in moisture contents, air permeability, and water sorptivity were monitored for three years by conducting non-destructive tests on surfaces of site-cast concrete box culverts and mock-up specimens. Furthermore, carbonation rates in the specimens were measured. The results revealed that transport properties measured by non-destructive tests were effective at detecting effects of cement types and curing periods on the carbonation progress. In particular, the air permeability coefficients of specimens with lower moisture contents at later ages showed high correlation with the carbonation rates.

1. Introduction

Deterioration of concrete structures is strongly related to the ingress of aggressive agents from the surrounding environment into the concrete and embedded steels [1–3]. Quality control of concrete cover in construction works is crucial to ensure durable concrete structures. Thickness and transport properties (permeability, diffusivity, and water sorptivity) of the concrete cover are two key parameters governing the durability of reinforced concrete structures. Non-destructive test methods measuring the thickness of concrete cover have already been established in some standard specifications [2–6]. Furthermore, the necessity for test methods estimating concrete cover quality has been discussed in the context of performance-based durability design. Although strength has traditionally been used as a good indicator of concrete quality, lower correlation between strength and permeability has been reported in some studies [1,3,7–9]. The lower correlation is often caused by quality differences between structures and specimens and between surface and inner concrete in the structures, aspects that depend significantly on construction process such as compaction, curing and finishing. This strongly increases the demand to develop non/semi-destructive test methods for on-site characterization of concrete transport properties rather than mechanical properties [1]. Numerous methods measuring air permeability and water sorptivitiy on site have been proposed [1,2,10–13]. Under

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identical and controlled environmental conditions, it has been reported that successful differentiation of the quality of concrete cover is possible. This can also support research and development pertaining to durability of concrete structures [14].

Measurements of transport properties are significantly affected by the internal moisture condition of concrete [15–22]. Laboratory tests have facilitated several preconditioning procedures to prepare uniform moisture distribution in specimens [23,24]. On site, the moisture content gradually decreases by drying with age and changes in accordance with weather conditions. However, it is difficult to artificially control the moisture condition of in-situ concrete structures for the purpose of taking measurements [25,26]. Although a modification method neutralizing the moisture effect on the measured transport properties has been proposed with additional measurements of electrical resistivity related to the moisture content on the surface of concrete structures [27,28], its accuracy and feasibility are still arguable.

In general, the use of on-site measurements is recommended after extended drying periods (i.e., at later ages) [20,21]. For example, Romer [20] monitored the changes in measured air permeability of 200 mm cubic specimens stored at controlled environmental conditions at 20 °C and 35%, 70%, or 90% relative humidity (RH) from the age of seven days to one year. Based on the recorded pressure increase curves during air permeability measurements, one month drying at low RH and three to four months drying at medium RH were needed in order to reliably calculate permeability coefficients. In addition, to avoid evaporative effects during measurements, moisture contents of 5.5% or less measured by the electrical impedance method were recommended [20]. This threshold of maximum moisture content was accepted in the 2013 version of the Swiss Standard SIA 262/1 [29]. Basheer and Nolan [21] investigated changes in air permeability and water sorptivity of concrete block specimens (450 × 200 × 500 mm) for 18 months. One surface of the specimens was fully exposed to weather conditions while another surface was partially exposed to the environment near a building [21]. For reliable measurements, the dried condition satisfying an RH below 80% of the near surface concrete was needed. However, conclusions on the effect of the moisture condition remain indefinite.

The aim of this study was to investigate the effect of drying with aging on on-site measurements of transport properties of concrete cover. For this purpose, the change in transport properties on site-cast concrete box culverts and mock-up specimens was monitored. Long-term measurements over three years were planned to extend the discussion from previous studies. Furthermore, the impacts of cement type and curing period on measured values were analyzed. The applicability of several non-destructive tests, including a new method, was discussed after undertaking comparative investigations. Part of the data on air permeability measurements over seven months were obtained from a previous publication [30]. This paper presents a continued and detailed investigation with additional measurements.

2. Materials and methods

2.1. Concrete

Typical ready-mixed concrete for box culverts was manufactured using ordinary Portland cement (OPC) in accordance with standard JIS R 5210 [31] and blast furnace slag Type-B cement (containing 30–60% slag in cement; also called BBC) in accordance with JIS R 5211 [32], sand and coarse aggregate with a maximum particle size of 25 mm. The mix proportions are provided in Table 1. The strength class of the concretes was 24 MPa, conforming to standard JIS A 5308 [33], and the required maximum water-to-cement ratio (W/C) was 0.55. The target slump for the mixes was 80 mm; a powdered superplasticizer was added on-site to increase the slump to 120 mm for the OPC and 150 mm for the BBC mixes. The measured compressive strengths of cylindrical OPC and BBC specimens after 28 days of water curing were 31.9 and 33.4 MPa, respectively, based on standard JIS A 1108 [34].

2.2. Structure

Two concrete box culverts, N-box and B-box types, were constructed in Gunma Prefecture, Japan, as parts of new highway structures. They were 35 m and 12 m long, respectively. The interior dimensions were 3.5 m high and 8.0 m wide for the N-box, and 3.5 m high and 4.0 m wide for the B-box culverts (The outline is shown in Fig. 1 and detailed geometry is presented in the Appendix A). The top and bottom slabs, and the walls had a thickness of 500, 700, and 600 mm, respectively, in case of the N-box culverts, and 400, 400, and 400 mm, respectively, in case of the B-box culverts. The manufactured ready-mixed concrete was delivered and cast on site, using boom concrete pumps. After removing the formwork at the age of approximately one week, the internal and external surfaces were sealed using plastic films for three months. The interior surfaces of the walls were targeted for measurements in this study. The average temperature and RH during a period of three years, measured at the nearest meteorological observatory, were 16.0 °C and 62.1%, respectively (see more details in the Appendix B).

2.3. Specimens

Three mock-up specimens of the walls of the box culverts were prepared for each structure. The mock-up specimens for the N-box and B-box had a thickness of 600 mm and 400 mm, respectively. Both the height and width of the all mock-up specimens was 1500 mm (Fig. 2). Reinforcement bars were embedded in a manner similar to that for inner layers of the box culvert structures. They were supported by 400-mm-high footing. After removing the formwork at the age of one day, three curing conditions were applied: (i) no curing after mold removal (no-curing, specimens N-1d and B-1d); (ii) sealed curing without demolding until the ages of five and seven days for N-box and B-box specimens, respectively, based on minimum requirements in the standard specification published by the Japan Society of Civil Engineers (standard curing, specimens N-5d and B-7d); and (iii) sealed curing using plastic films for three months, under the same conditions as the structures (long-term curing, specimens N-3m and B-3m). Thereafter, two large surfaces of 1500 mm × 1500 mm, namely the modeled interior wall surfaces of the structures, were exposed to open air while the other side and top surfaces were continuously sealed to imitate one-dimensional moisture transport. The specimens were located under roofs to simulate the dry interior surface of the box culvert wall (i.e., without rainfall). Temporary roofs made of tarpaulin were used for the first eight months on-site and then the specimens were moved under a bridge girder for later measurements. Since degradation rarely progresses without water, the effect of rainfall needs to be discussed in future studies in the context of durability with the ingress of aggressive agents.

2.4. Measurements

Non-destructive and semi-destructive tests were performed to measure transport and other related properties of the concrete cover over a period of three years as shown in Table 2. The measurements were conducted at mid-height of the specimens and at a height of 1 m of the inner wall of the box culverts. Because of limitations by time, only selected measurements were applied

Table 1
Mix proportions of the tested concretes.

Cement	W/C	s/a*	W (kg/m^3)	C (kg/m^3)	S (kg/m^3)	G (kg/m^3)	Add.** (kg/m^3)
OPC	0.550	0.440	162	295	816	1029	2.803
BBC	0.525	0.430	159	303	795	1042	2.954

* Sand to aggregate ratio in volume.
** Air entraining and water reducing agent (09NL-P, Yamaso-Chemical Co., Ltd.).

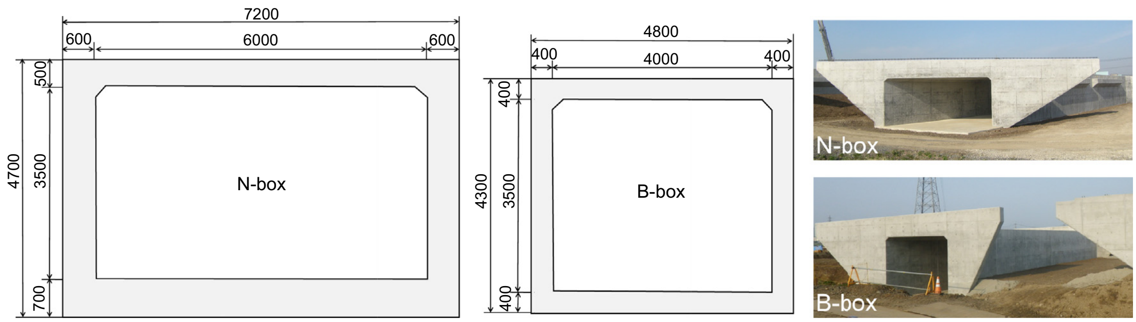

Fig. 1. Geometries of box culverts (N-box (left) and B-box (center)) and their overviews (right).

Fig. 2. Outline of specimens: under a tarpaulin until the age of eight months (left) and under a bridge girder thereafter (right).

Table 2
Measurement items and ages.

Age (months)	Moisture content		Air permeability	Water sorptivity			Carbonation depth
	Surface	Inner		SWAT	WIST	ASTM	
1.3	St., Sp.		St., Sp.		St., Sp.		
2.6	St., Sp.	Sp.	St., Sp.	St., Sp.	St., Sp.	Sp.	
7.4	St., Sp.		St., Sp.		St., Sp.		
13	St., Sp.		St., Sp.		St., Sp.		
27	Sp.		Sp.				Sp.
37	Sp.		Sp.		Sp.		
38	St.		St.		St.		
39	Sp.		Sp.	Sp.	Sp.		Sp.

St.: Measured for structures (box culverts), Sp.: Measured for mock-up specimens.

at certain ages. The moisture contents were measured non-destructively on the concrete surface by the electrical impedance method (CMEX II, Tramex Ltd., Ireland) at the ages of 1.3, 2.6, 7.4, 13, 27, and ~38 months. At the age of 2.6 months, the internal distribution of the moisture content across depth was additionally measured in small drilled holes in the specimens using the electrical resistivity method (HI-800, Kett Electric Laboratory, Japan). Regarding transport properties, air permeability was measured by the double chamber method (Permea-TORR, Materials Advanced Services Ltd., Argentina) [12] with moisture content measurements. Water sorptivity was measured by the surface water absorption test (SWAT, Maruto Testing Machine Company, Japan) [35] at the ages of 2.6 and ~38 months and the water intentional spraying test (WIST, JR Soken Engineering Co. Ltd., Japan) [36] with the measurements of moisture content and air permeability. Measurements by CMEX, HI-800, Permea-TORR, SWAT and WIST were conducted at 6, 3, 6, 4, and 8 locations per element at each age, respectively, and average values have been used in the discussion that appears later in this paper. To prevent mutual interference (e.g., vacuum by Permea-TORR and water supply by WIST and SWAT), different locations were selected for measurements.

Similar to the initial surface absorption test (ISAT) [19] and Autoclam sorptivity test [37], SWAT is a non-destructive test method to measure capillary suction. In SWAT measurements, the drop in water level by water absorption for a water cup of 80 mm diameter is automatically recorded with presser sensors. WIST is a new simple non-destructive test used to measure capillary suction using hand trigger spray bottles. WIST measurements offer an indicator of water absorption by repeatedly spraying water on the concrete surface till it is visually observed to flow over.

Furthermore, after non-destructive tests at 2.6 months, two concrete cores were taken from the specimens to conduct the water absorption test based on standard ASTM C 1585 [38]. Carbonation depth was measured by spraying a 1% alcoholic solution of phenolphthalein on five drilled holes at the ages of 27 and 39 months. Wet drilling was conducted on only one surface while the other was kept intact for long-term non-destructive tests without water supply.

3. Results and discussion

3.1. Carbonation depth

Carbonation rates of specimens were calculated from measured carbonation depths based on the following square root of time theory.

$$x = A\sqrt{t}$$

where x is the carbonation depth (mm) at time t (months) and A is the empirical coefficient which describes the carbonation rates (mm/$\sqrt{\text{months}}$). Fig. 3 shows measured carbonation depths and calculated trend lines based on the square root of time theory. The plotted carbonation depths were average values calculated from five measurements.

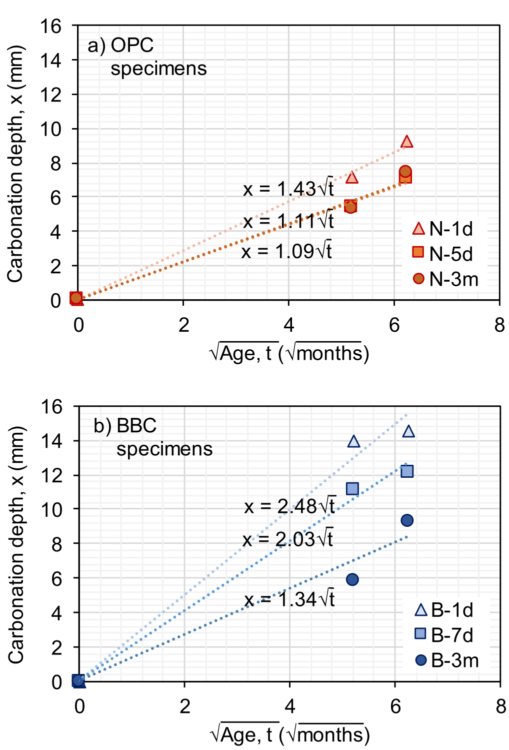

Fig. 3. Carbonation progress as per the square root of time theory for OPC (left) and BBC specimens (right).

The BBC specimens showed higher carbonation rates in open air compared with the OPC specimens, in agreement with previous findings [39–42]. In this study, the average rate for BBC was 1.6 times higher than that for OPC. Among the OPC specimens, the advantage of long-term over standard curing was not observed, while the "no-curing" regime increased carbonation rates (1.3 times higher than the others). On the other hand, in the case of the BBC specimens, curing conditions greatly changed the carbonation rates: long-term curing significantly reduced carbonation rates (0.8 times that of standard curing and 0.5 times that of no-curing).

3.2. Moisture content

The moisture content measured on the surface of the specimens and structures gradually decreased over time as shown in Fig. 4. The decreasing speeds were higher at earlier ages and for shorter curing times. In addition, the rate of decrease was slightly lower for the structures compared with the specimens. This result could be explained by less moisture evaporation inside the box structures. After 27 months, the measured moisture contents were almost constant, and the differences caused by curing conditions were reduced. Regarding the cement type, the moisture contents of the BBC specimens were always lower than those of the OPC specimens. At the end of the measurements, the moisture contents for BBC were around 0.7 times those for OPC.

The internal distributions of moisture contents measured in the specimens at the age of 2.6 months are shown in Fig. 5. As expected, the moisture contents decreased near the surface in all specimens. Sealing using plastic films was not completely able to prevent moisture evaporation because of on-site draft. Further, in the no-curing specimens (N-1d and B-1d), the decreases were significant up to 50 mm depth from the surface. Regarding the cement type, the moisture contents of the BBC specimens were always lower than those of the OPC specimens and they showed a relatively rapid decrease near the surface, in agreement with surface measurement results. The lower moisture contents of the BBC specimens could be additionally explained by the mixture proportion (smaller amount of unit water and lower W/C; see Table 1) and the used slag cement increasing the electrical resistivity of the concrete [43, 44].

3.3. Air permeability

The air permeability coefficients measured on the surface of specimens and structures gradually increased over time and the increases from 2.6 to 7.4 months were significant (Fig. 6). The differences in the air permeability coefficients under different curing conditions decreased over time. The increase in air permeability is associated with the increase in the open pore content caused by water evaporation [15,16,19–22] although aging usually causes finer pore structures due to cement hydration. The measured air permeability in the OPC specimens was typically lower than that in the BBC specimens. Fig. 7 shows the relationship between air permeability coefficients and moisture contents measured on the surface of specimens and structures. In the OPC specimens, the relationship was almost uniform for all specimens, so that the change in air permeability coefficients was completely explained by the changes in moisture content. However, in the BBC specimens, the relationship of the no-curing specimen (B-1d) suggested a large impact of the curing condition which caused its different behavior.

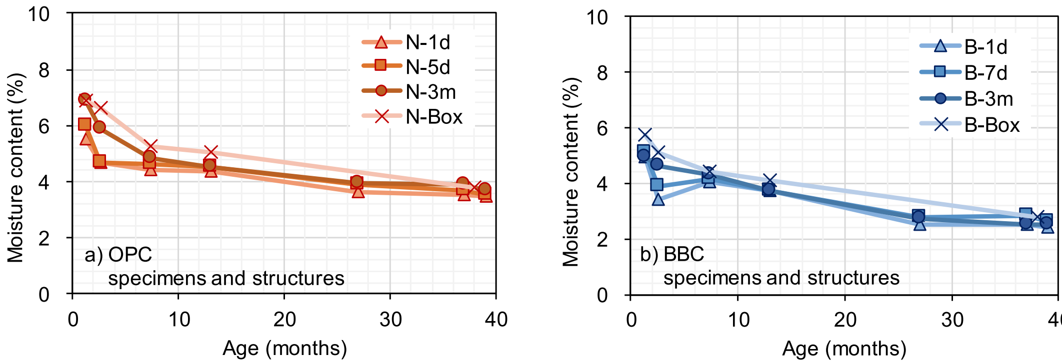

Fig. 4. Changes in moisture contents measured on the surface of specimens and structures.

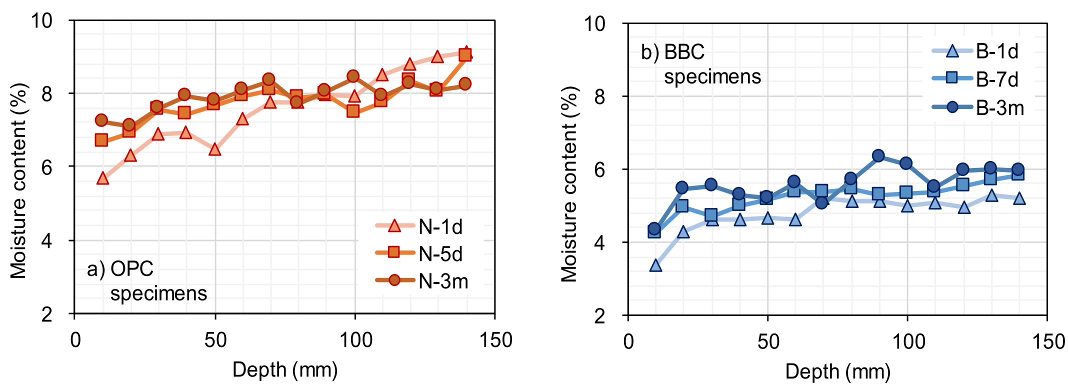

Fig. 5. Distribution of moisture contents over specimen depth after 2.6 months.

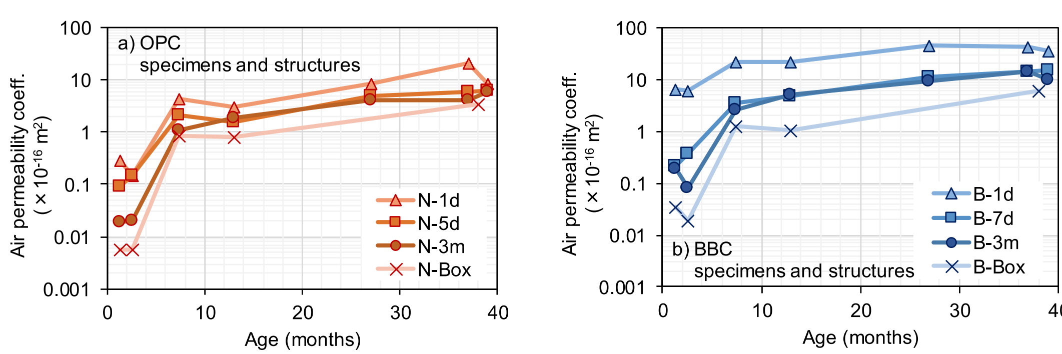

Fig. 6. Changes in air permeability coefficients measured on the surface of specimens and structures.

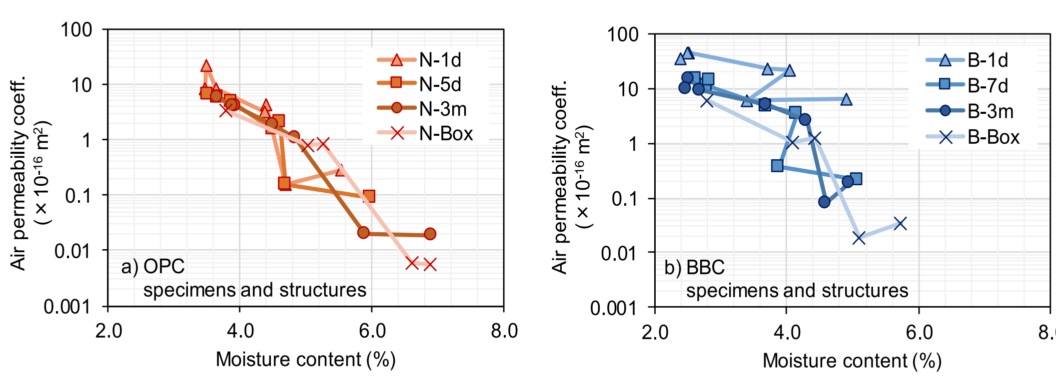

Fig. 7. Relationship between moisture content and air permeability measured on the surface of specimens and structures.

Fig. 8 illustrates the relationships between air permeability coefficients at 2.6 and 39 months (shown in Fig. 6) and the carbonation rates obtained from Fig. 3. The approximate lines for both the OPC and BBC specimens at the same measurement ages indicate high correlation coefficients. These coefficients show that the air permeability coefficient is a good indicator for predicting carbonation progress regardless of curing condition and cement type. The correlation increases with air permeability at later ages because air permeability measurements during sealed curing after 2.6 months overestimated the carbonation resistance of the OPC concrete. These results highlight the importance of drying conditions after curing is complete for accurate measurements of air permeability, although the measurements at the early age (e.g., 2.6 months), regulated by the Swiss Standard SIA 262/1 [29], also showed practically reasonable trends. As per Fig. 6, taking measurements after 6 months (3 months drying after curing) seems prudent to obtain more accurate results. In addition, quantitative/absolute evaluation using the measured air permeability (kT) should consider the drying stages.

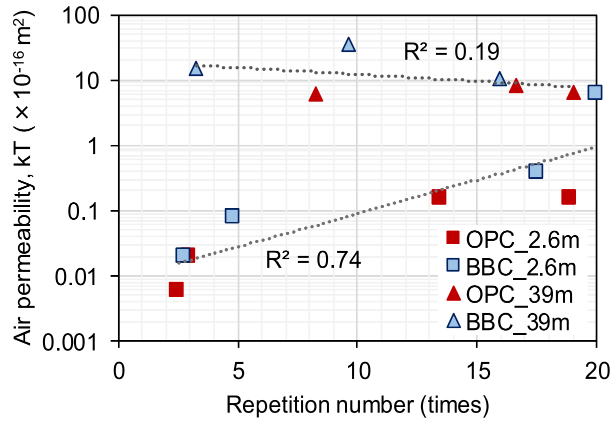

Fig. 10. Relationship between the repetition number by WIST and air permeability after 2.6 and 39 months.

3.4. Water sorptivity

Water sorptivity was measured by three tests: surface water absorption test (SWAT) [35], water intentional spraying test (WIST) [36], and water absorption test based on standard ASTM C 1585 [38]. Fig. 9 shows the relationship between the air permeability coefficients and the amount of water absorption for 6 min measured by SWAT at the ages of 2.6 and 39 months. The results indicate high correlations. At the age of 2.6 months, the SWAT measurements were less sensitive for concrete with low permeability. Thereafter, at the age of 39 months, the correlation coefficient decreased because the water absorption of the specimens with longer curing became higher than that of shorter-cured specimens. A possible cause for this observation is the change in the surface layer properties including micro cracking caused by drying shrinkage or carbonation because SWAT measurements cannot prevent the "skin effect," unlike the double chamber method used for air permeability measurements [12].

The repetition numbers measured using WIST showed high correlation with air permeability coefficients measured after 2.6 months, as noted in Fig. 10. This verified the effectiveness of the WIST technique as a simplified method for evaluating transport properties of concrete cover. However, the correlation coefficients decreased significantly over time. At the age of 39 months, the repetition numbers did not explain the curing effects and they showed a trend opposite to the one obtained for air permeability measurements. The decrease in the correlation coefficients could be attributed to quality changes in the surface layer associated with shrinkage and carbonation because WIST evaluates the quality of

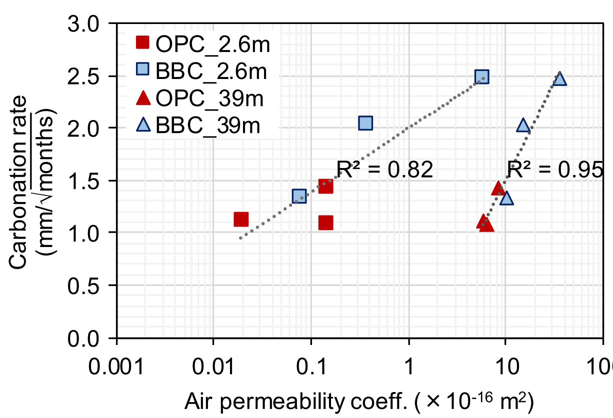

Fig. 8. Relationship between air permeability and carbonation rate of specimens after 2.6 and 39 months.

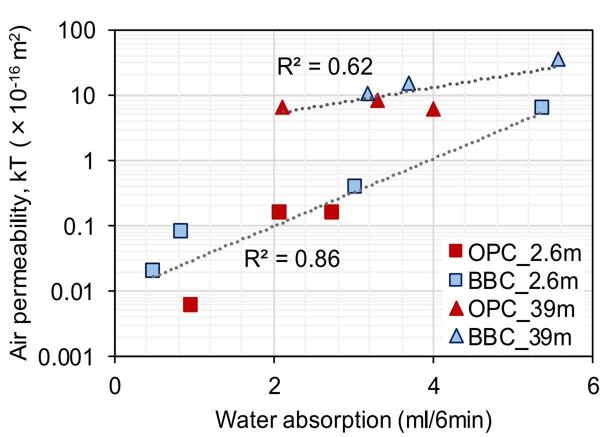

Fig. 9. Relationship between water sorptivity by SWAT and air permeability after 2.6 and 39 months.

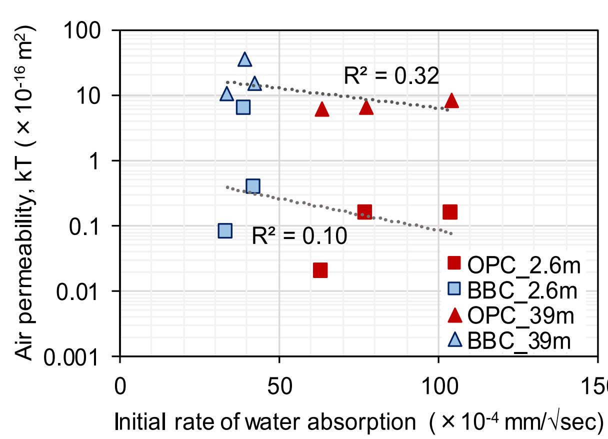

Fig. 11. Relationship between the initial rate of water absorption after 2.6 months determined by standard ASTM C 1585 and air permeability after 2.6 and 39 months.

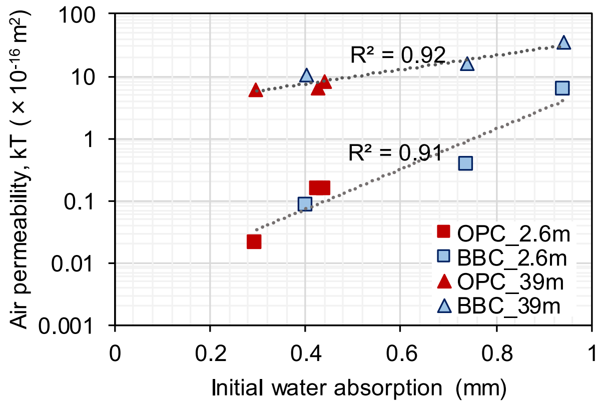

Fig. 12. Relationship between initial water absorption after 2.6 months determined by standard ASTM C 1585 and air permeability after 2.6 and 39 months.

a thin layer within a few millimeters. The results suggest a limitation of applying WIST to aged concrete structures.

The initial rate of water absorption of cylindrical samples, that is, the slope of the line best fitted to water absorption against the square root of time until 6 h, measured for the specimens at the age of 2.6 months, did not show significant correlation with the air permeability coefficients measured on the surface (see Fig. 11). In the case of the OPC specimens, the water absorption rates increased with increasing air permeability because of shorter curing time. In the case of the BBC specimens, the curing effect was not clearly observed, and the measured absorption rates were much lower than those of the OPC specimens. Simultaneously, the initial water absorption, that is, the y-intercept of the slope of the initial absorption rate, showed higher correlation with air permeability coefficients (see Fig. 12). The results clearly point to the potential effects of the curing condition and cement type on specimens prepared with the same W/C on the initial water absorption.

4. Conclusions

This study monitored changes in moisture contents, air permeability, and water sorptivity of concrete cover of site-cast concrete box culverts and mock-up specimens over a period of three years using non-destructive tests on concrete surfaces. Furthermore, carbonation and water absorption rates in the specimens were measured using drilling. The following conclusions are drawn based on the above-mentioned measurements:

(1) The carbonation rates of the specimens were affected by cement type and curing period, which is in agreement with many previous reports. The BBC concrete with slag cement showed higher carbonation rate in open air compared with the OPC concrete with normal cement. The average rate for BBC was 1.6 times higher than that for OPC. The curing periods had significant impact on the carbonation progress of the BBC concrete.
(2) As many previous studies have reported, the air permeability and water sorptivity coefficients measured using non-destructive tests on the surfaces of specimens and structures increased as the moisture content decreased over time. The long-term measurements in this study indicated that it took approximately two years to observe stable values, while significant changes were observed just after curing was complete.
(3) The measured air permeability and water sorptivity coefficients showed high correlation with the carbonation rates in the specimens. The correlation with air permeability coefficients increased over time; hence, later measurements after drying are recommended. On the contrary, the correlation with water sorptivity coefficients decreased over time. This decrease was explained by changes to surface quality caused by shrinkage and carbonation. Water sorptivity measurements at early ages (e.g., after 3 months) are recommended but the measurements at longer ages (e.g., after 3 years) are not. For early age measurements, in particular, WIST showed an advantage given its simplicity. The age threshold should be studied in more detail in future studies.
(4) The water absorption rate measured on the drilled core from the specimens did not show high correlations with other measured values. Simultaneously, the initial water absorption was a good indicator as it showed high correlation with the air permeability coefficient.

The authors are in the process of performing detailed analyses using mercury injection and other methods to further clarify the mechanism of transport property changes in concrete under various conditions. These future results will help interpret the above-mentioned phenomena more comprehensively.

Conflict of interest

None.

Acknowledgements

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Appendix A

Fig. A.1 shows the detailed geometries of the N-box and B-box culverts.

Appendix B

Fig. B.1 shows the daily average temperature and relative humidity measured at the nearest meteorological observatory during this study. Temperature was measured at the Tatebayashi Meteorological Observatory, which is located approximately 3 km away from the site in the same city, and the relative humidity was measured at the Kumagaya Meteorological Observatory, which is located approximately 15 km away from the site. For the first three months, detailed changes in temperature and relative humidity were recorded on the site every 10 min as shown in Figs. B.2 and B.3.

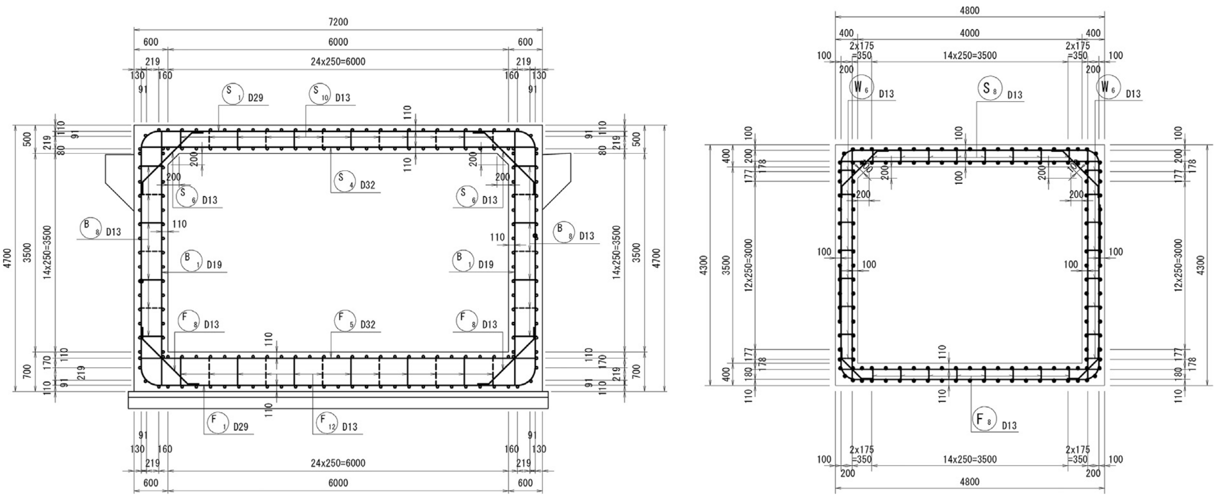

Fig. A.1. Detailed geometry of box culverts: N-box (left) and B-box (right).

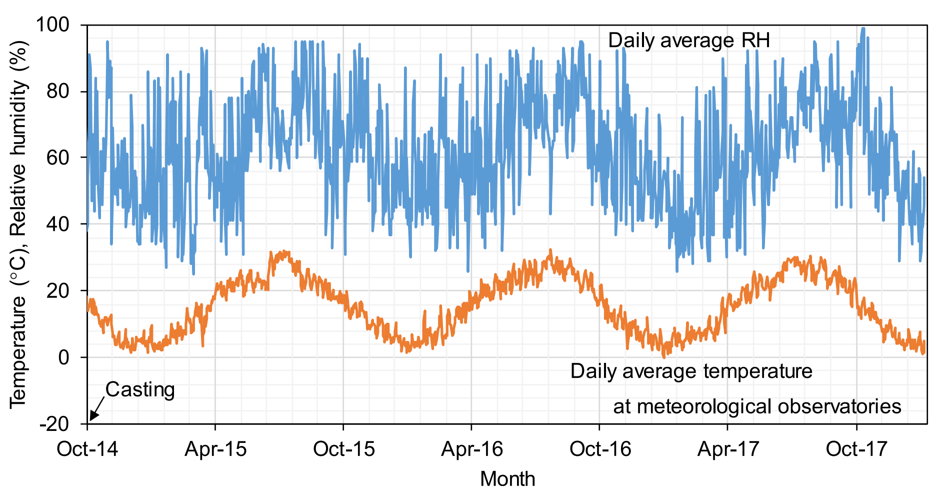

Fig. B.1. Daily average temperature and relative humidity measured at the nearest meteorological observatory.

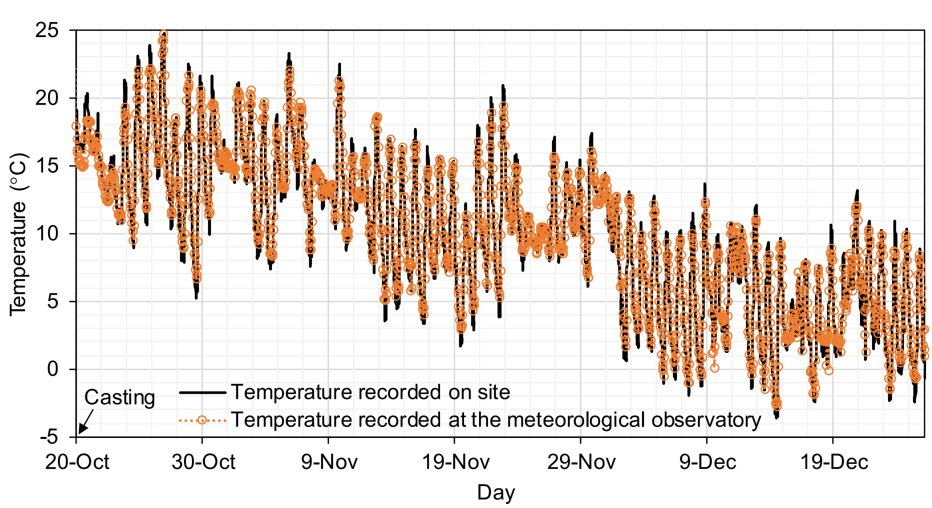

Fig. B.2. Detailed temperature changes for the first three months from October 20, 2014.

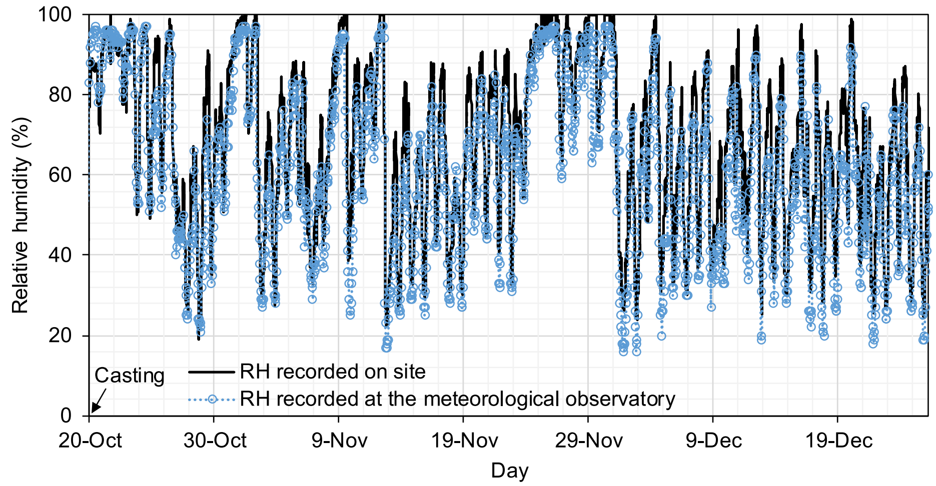

Fig. B.3. Detailed relative humidity changes for the first three months from October 20, 2014.

References

[1] M. Alexander, A. Bentur, S. Mindess, Durability of Concrete: Design and Construction, CRC Press, 2017.
[2] RILEM TC 230-PSC, Performance-Based Specifications and Control of Concrete Durability, RILEM State-of-the-Art Reports, 2015.
[3] RILEM TC 189-NEC, Non-Destructive Evaluation of the Penetrability and Thickness of the Concrete Cover, RILEM State-of-the-Art Reports, 2007.
[4] D.M. McCann, M.C. Forde, Review of NDT methods in the assessment of concrete and masonry structures, NDT E Int. 34 (2) (2001) 71–84.
[5] H.-W. Song, V. Saraswathy, Corrosion monitoring of reinforced concrete structures-A, Int. J. Electrochem. Sci. 2 (2007) 1–28.
[6] M.R. Shaw, S.G. Millard, T.C.K. Molyneaux, M.J. Taylor, J.H. Bungey, Location of steel reinforcement in concrete using ground penetrating radar and neural networks, NDT E Int. 38 (3) (2005) 203–212.
[7] G. Nganga, M. Alexander, H. Beushausen, Practical implementation of the durability index performance-based design approach, Constr. Build. Mater. 45 (2013) 251–261.
[8] A. Abbas, M. Carcasses, J.P. Ollivier, The importance of gas permeability in addition to the compressive strength of concrete, Mag. Concr. Res. 52 (1) (2000) 1–6.
[9] S. Okazaki, T. Yagi, T. Kishi, T. Yajima, Difference of sensitivity due to curing condition on strength and permeability, Cem. Sci. Concr. Technol. 60 (2006) 227–234.
[10] L. Basheer, J. Kropp, D.J. Cleland, Assessment of the durability of concrete from its permeation properties: a review, Constr. Build. Mater. 15 (2) (2001) 93–103.
[11] K. Yang, P.A.M. Basheer, Y. Bai, B.J. Magee, A.E. Long, Development of a new in situ test method to measure the air permeability of high performance concretes, NDT E Int. 64 (2014) 30–40.
[12] R.J. Torrent, A two-chamber vacuum cell for measuring the coefficient of permeability to air of the concrete cover on site, Mater. Struct. 25 (6) (1992) 358–365.
[13] A.E. Long, G.D. Henderson, F.R. Montgomery, Why assess the properties of near-surface concrete?, Constr Build. Mater. 15 (2) (2001) 65–79.
[14] L. Coppola, D. Coffetti, E. Crotti, Innovative carboxylic acid waterproofing admixture for self-sealing watertight concretes, Constr. Build. Mater. 171 (2018) 817–824.
[15] A. Abbas, M. Carcasses, J.-P. Ollivier, Gas permeability of concrete in relation to its degree of saturation, Mater. Struct. 32 (1) (1999) 3–8.
[16] W. Kubissa, M.A. Glinicki, Influence of internal relative humidity and mix design of radiation shielding concrete on air permeability index, Constr. Build. Mater. 147 (Suppl. C) (2017) 352–361.
[17] J. Castro, D. Bentz, J. Weiss, Effect of sample conditioning on the water absorption of concrete, Cem. Concr. Comp. 33 (8) (2011) 805–813.
[18] C. Hall, Water sorptivity of mortars and concretes: a review, Mag. Concr. Res. 41 (147) (1989) 51–61.
[19] R.K. Dhir, P.C. Hewlett, Y.N. Chan, Near-surface characteristics of concrete: assessment and development of in situ test methods, Mag. Concr. Res. 39 (141) (1987) 183–195.
[20] M. Romer, Effect of moisture and concrete composition on the torrent permeability measurement, Mater. Struct. 38 (5) (2005) 541.
[21] P.A.M. Basheer, É. Nolan, Near-surface moisture gradients and in situ permeation tests, Constr. Build. Mater. 15 (2–3) (2001) 105–114.
[22] R. Torrent, R. Moro, A. Jornet, Coping with the effect of moisture on air-permeability measurements, in: RILEM International Workshop on Performance-based Specification and Control of Concrete Durability, Zagreb, Croatia, 2014, pp. 489–498.
[23] C. Andrade, A. Bettencourt-Ribeiro, N.R. Buenfeld, M. Carcasses, N.J. Carino, F. Ehrenberg, C. Ewertson, E. Garbocczi, M. Geiker, O.E. Gjorv, A.F. Goncalves, H. Graf, H. Grube, H.K. Hilsdorf, R.D. Hooton, J. Kropp, S. Modry, C. Molin, L.O. Nilsson, J.P. Ollivier, C.L. Page, L.J. Parrott, P.E. Petersson, F.R. Rodriguez, M. Rodhe, M. Salta, N. Skalny, A.M.G. Seneviratne, L. Tang, F. Tauscher, R. Torrent, D. Whiting, Preconditioning of concrete test specimens for the measurement of gas permeability and capillary absorption of water, Mater. Struct. 32 (217) (1999) 174–176.
[24] M. Carcassès, A. Abbas, J.-P. Ollivier, J. Verdier, An optimised preconditioning procedure for gas permeability measurement, Mater. Struct. 35 (1) (2002) 22–27.
[25] P.A.M. Basheer, É.A. Nolan, W.J. McCarter, A.E. Long, Effectiveness of in situ moisture preconditioning methods for concrete, J. Mater. Civ. Eng. 12 (2) (2000) 131–138.
[26] R. Dhir, I. Shaaban, P. Claisse, E. Byars, Preconditioning in situ concrete for permeation testing. Part 1: initial surface absorption, Mag. Concr. Res. 45 (1993). 113-113.
[27] R. Torrent, G. Frenzer, A method for the rapid determination of the coefficient of permeability of the "covercrete", in: International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE), 1995, pp. 985–992.
[28] I. Kurashige, M. Hironaga, A nondestructive evaluation technique for assessing quality of surface concrete based on air permeability change characteristics considering its moisture content dependent, Cem. Sci. Concr. Technol. 65 (1) (2011) 225–232.
[29] SIA 262/1, Norme Suisse: "Construction en béton – Spécifications complémentaires", Annexe E: Perméabilité à l'air dans les Structures (2013) 31-33. (in German and French) (English translation is available atn www.m-a-s.com.ar).
[30] Y. Yokoyama, Y. Sakai, K. Nakarai, T. Kishi, Change in surface air permeability of concrete with different mix designs and curing, Cem. Sci. Concr. Technol. 71 (1) (2018) 410–417.
[31] JIS R 5210, Portland cement (2009).
[32] JIS R 5211, Portland blast-furnace slag cement (2009).
[33] JIS A 5308, Ready-mixed concrete (2014).
[34] JIS A 1108, Method of test for compressive strength of concrete (2006).
[35] A. Hosoda, K. Hyashi, Evaluation of covercrete quality by surface water absorption test, in: 4th International Symposium on Life-Cycle Civil Engineering, IALCCE 2014, Tokyo, Japan, 2014, pp. 1229–1234.
[36] S. Nishio, Simple evaluation of water permeability of cover-concrete using a water spray method, Quart. Rep. of RTRI 58 (1) (2017) 36–42.
[37] P.A.M. Basheer, F.R. Montgomery, A.E. Long, Clam' tests for measuring in-situ permeation properties of concrete, Nondestruct. Test. Eva. 12 (1) (1995) 53–73.
[38] ASTM C1585, Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes (2013).
[39] P. Sulapha, S.F. Wong, T.H. Wee, S. Swaddiwudhipong, Carbonation of concrete containing mineral admixtures, J. Mater. Civ. Eng. 15 (2) (2003) 134–143.
[40] G.J. Osborne, Durability of Portland blast-furnace slag cement concrete, Cem. Concr. Comp. 21 (1) (1999) 11–21.
[41] E. Gruyaert, P. Van den Heede, N. De Belie, Carbonation of slag concrete: effect of the cement replacement level and curing on the carbonation coefficient – effect of carbonation on the pore structure, Cem. Concr. Comp. 35 (1) (2013) 39–48.
[42] L. Parrott, Some effects of cement and curing upon carbonation and reinforcement corrosion in concrete, Mater. Struct. 29 (3) (1996) 164–173.
[43] P.I.I. Banea, Study of Electrical Resistivity of Mature Concrete (Master thesis) uuid: a927e4b3-5e8e-47f2-8273-090428108d83, TU Delft, 2015.
[44] R.B. Polder, Test methods for on site measurement of resistivity of concrete — a RILEM TC-154 technical recommendation, Constr. Build. Mater. 15 (2) (2001) 125–131.