- Technical Report -

COMPARATIVE ANALYSIS OF THE VARIABILITY OF SURFACE AIR PERMEABILITY OF CONCRETE ROAD STRUCTURES IN THAILAND

Michael HENRY[*1], Koji MATSUMOTO[*2], Kota HORIUCHI[*3], Pakawat SANCHAROEN[*4]

ABSTRACT

This paper reports on the variability of surface air permeability data taken in-situ from concrete road structures in Thailand. The distributions of the air permeability results were found to be statistically the same for the four structures. However, the relationship between air permeability and moisture content revealed that variability in some structures may be due to concrete quality, while, for others, it may be more dependent on the moisture state. The spatial variations of the moisture content and air permeability showed good consistency, but the compressive strength exhibited a different distribution.

Keywords: maintenance, non-destructive testing, spatial variability, surface air permeability

1. INTRODUCTION

The life cycle management of existing concrete infrastructure relies on data on the actual structural condition for planning proper maintenance activities. Condition data may be acquired through visual or detailed inspection, the latter of which includes destructive and non-destructive testing of the structural concrete. For reinforced concrete (RC) structures, the surface concrete plays a crucial role in protecting the reinforcing steel against deterioration factors, such as water, chlorides, or carbon dioxide [1]. Consequently, evaluation of the surface concrete - especially its mass transfer resistance - can provide useful information for assessing the structural performance level, predicting future degradation, and determining the appropriate countermeasures for ensuring required performance.

Numerous non-destructive test (NDT) methods have been developed to evaluate the mass transport properties, or "penetrability," of surface concrete in-situ [2]. Among these, the Torrent air permeability test, which measures the air permeability of surface concrete using a two-chamber vacuum cell system [3], has become a popular method for characterizing concrete quality. The results of this test method have been found to correlate well with various deterioration factors [4], leading to the development of systems in Japan and Europe for verifying durability based on the surface concrete quality of new structures [5,6]. However, while extensive work has been reported on the use of the air permeability test for quality control of new structures, there are few examples of its application to aged concrete structures, with those cases mainly being concrete buildings [7].

To explore how surface air permeability data taken from existing infrastructure may be used to improve maintenance management, an investigation program was carried out targeting four RC road structures in Bangkok, Thailand. This paper presents an analysis of the variability of the surface air permeability results acquired during this investigation. First, the relationships between the surface air permeability, surface moisture content, and compressive strength, as measured by rebound hammer, are compared between structures. As the air permeability test is influenced by the surface concrete moisture state, it is necessary to consider this relationship when interpreting the air permeability results [8]. It is also useful to correlate the mass transfer resistance with the compressive strength to clarify any divergences between these properties for actual structures. Second, the spatial variability of the surface air permeability is examined and compared for two surfaces on one of the target structures. The spatial distribution can illuminate the non-homogeneity of the concrete properties across a structure, which may be useful to identify vulnerable areas and plan appropriate countermeasures to ensure required performance [9].

2. INVESTIGATION PROGRAM

2.1 Target structures and test locations

In this study, four concrete road structures - three RC walls and one RC column - were selected to gather in-situ data on surface concrete air permeability (Table 1). All structures are located in the greater metropolitan area of Bangkok, Thailand, and vary in age from 15 to 25 years. The structures are exposed to the tropical environmental conditions typical of Southeast Asia. No data on the material specifications, such as compressive strength or cement type, were available.

The test locations at each structure were chosen based on their accessibility and surface conditions such

---

[*1] Associate Professor, Faculty of Engineering, Hokkaido University, JCI Member
[*2] Associate Professor, Faculty of Engineering, Hokkaido University, JCI Member
[*3] Master student, Graduate School of Engineering, Hokkaido University
[*4] Researcher, Sirindhorn International Institute of Technology, Thammasat University (Thailand)

Table 1 Appearances and details of the target structures

Structure	Wall 1 (W1)	Wall 2 (W2)	Wall 3 (W3)	Column 1 (C1)
Appearance				
Description	RC wall supporting roadway ramp	RC wall supporting roadway ramp	RC wall supporting roadway ramp	RC column supporting elevated roadway
Age	~15 years	~25 years	~15 years	~15 years

Fig. 1 Localized damage at two test locations (Left: W1-3, Right: W2-1)

Table 2 Number of NDT measurements per structure and location

Structure	Wall 1			Wall 2	Wall 3		Column 1	
Location	1	2	3	1	1	2	North	East
Code	W1-1	W1-2	W1-3	W2-1	W3-1	W3-2	C1-N	C1-E
Surf. moist. content	16	16	10	30	18	30	40	58
Surface air perm.	8	8	5	15	9	15	20	29
Rebound number	31	31	0	86	45	54	130	195

that the NDT measurements could be reliably carried out. For Wall 1, data were taken at three locations spaced approximately 27 and 22 meters apart on the same wall face. For Wall 3, the two locations were spaced approximately 3.5 meters apart on the same wall face. Finally, for Column 1, testing was carried out on adjoining north and east faces of the column.

Visual inspection of the test locations revealed two instances of localized deterioration. As shown in Figure 1, spalling and delamination of the surface concrete was found spanning several meters at the third test location of Wall 1 (W1-3). At Wall 2, similar delamination of the surface concrete was observed; subsequent removal of the damaged concrete revealed corrosion of the reinforcing steel.

2.2 In-situ NDT measurement

The investigation was carried out over three days at the end of February, 2019. Environmental conditions were dry, and no rainfall occurred during this period.

At each test location, the positioning of the reinforcing steel was first identified using ground penetrating radar. The surface moisture content was then measured, followed by the surface air permeability and the rebound number. The number of measurement points for each NDT method per structure and location are summarized in Table 2.

(1) Surface moisture content

The surface moisture content (m) was evaluated using a standard moisture meter that measures moisture content by electrical impedance. The reported values are the arithmetic mean of two measurements taken in tandem with each air permeability test.

(2) Surface air permeability

The surface air permeability (kT) was measured using PermeaTORR equipment following Torrent's double chamber method [1,3]. The data are assumed to follow a log-normal distribution, so the geometric mean is adopted for comparison of the air permeability results between structures [10].

(3) Rebound number (compressive strength)

A rebound hammer was used to obtain rebound numbers from the concrete surfaces. The compressive strength (f'$_c$) was then calculated following the JSCE (Japan Society of Civil Engineers) standard [11], as shown in Eq. 1.

$$f_c' = -18 + (1.27 \times RN) \qquad \text{Eq. 1}$$

Where f'$_c$: concrete compressive strength (MPa); and RN: rebound number.

The variability of the strength results has been reported previously [12], so only the relevant statistics and spatial distributions will be employed here for comparative analysis with the air permeability.

3. RESULTS AND DISCUSSION

3.1 Descriptive statistics and distribution of surface air permeability

Table 3 summarizes the descriptive statistics of the surface air permeability measurement results, and Figure 2 shows the normalized distribution of the results by structure following the classification scale

Table 3 Descriptive statistics for surface air permeability kT by structure

Structure	Total no. of measurements	($\times 10^{-16}$ m^2)				
		Geometric mean	Standard deviation*	Median	Maximum	Minimum
Wall 1	21	7.183	0.688	8.100	18.000	2.000
Wall 2	15	5.951	0.965	5.300	27.000	0.740
Wall 3	24	9.269	0.947	9.800	139.000	1.600
Column 1	49	7.944	1.293	8.100	88.000	0.530

**Note: calculated using the natural logarithm of kT values [11]*

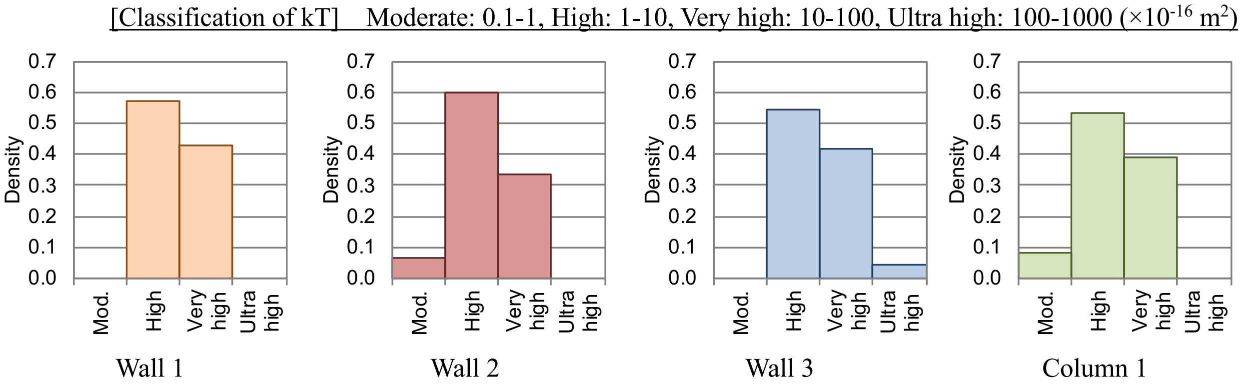


Figure 2 Distribution of surface air permeability kT by structure

proposed by Torrent and Frenzer [1]. It can be seen that, for all four structures, more than 50% of the resul ts are assessed as "High" permeability, and the geometric means and medians for all structures also correspond to "High" permeability. Furthermore, more than 90% of each structure's results fall within either the "High" or "Very high" classification. Although the standard deviations vary between structures, it appears that the mass transfer resistance of the four structures are similar based on their air permeability distributions.

One-way ANOVA (analysis of variance) was carried out to deteremine whether the surface air permeability results are statistically the same across the four structures. The natural logarithms of the measurement data were used for this analysis, as these tend to follow the normal distribution. The ANOVA result confirmed that none of the measurement result distributions possess significantly different means from the other structures' distributions.

3.2 Relationship between surface air permeability and surface moisture content

Although statistical analysis verified that the four structures share similar surface air permeability distributions, this result neglects the effect of the concrete moisture state on the surface air permeability measurement. While it is recommended that the air permeability test be carried out when concrete is in the dry state, this may not be feasible for structures in service. Torrent and Frenzer suggested carrying out electrical resistivity measurement as a means for capturing the moisture state of the concrete [1]. Kurashige et al. expanded on this idea by proposing that the concrete quality be examined in tandem with either the electrical resistivity or the surface moisture content to consider the effect of the concrete moisture state on the surface air permeability [8].

During the investigation period, the surface concrete of the target structures was in the dry state, resulting in electrical resistivity values that were too high to measure. For this reason, the surface moisture content, which represents the moisture state for a depth of approximately two centimeters from the surface, was adopted to further examine the variability of the surface air permeability.

The relationships between the surface air permeability and the surface moisture content are shown in Figure 3. For Wall 1, Wall 2, and Wall 3, the surface air permeability values fall within a range of surface moisture contents, and do not vary with an increase or decrease in the surface moisture content. Consequently, the variability of the surface air permeability results may be more dependent on the variability of the surface concrete quality, rather than the moisture state, which varies comparatively less. On the other hand, for Column 1, the surface air permeability displays a tendency to decrease as the surface moisture content increases, and vice versa. This result suggests that the variation in the air permeability results for this structure is not due to variability of the surface concrete quality, but, instead, due to the surface moisture state of the concrete.

3.3 Relationship between surface air permeability and compressive strength

The descriptive statistics for the compressive strength results are given in Table 4. Wall 1, Wall 3, and Column 1 were found to have relatively similar mean compressive strength values, whereas Wall 2 was comparatively weaker. The standard deviations, however, were nearly identical for all structures.

Figure 4 shows the relationship between the geometric means of the air permeability results and the arithmetic means of the compressive strength results

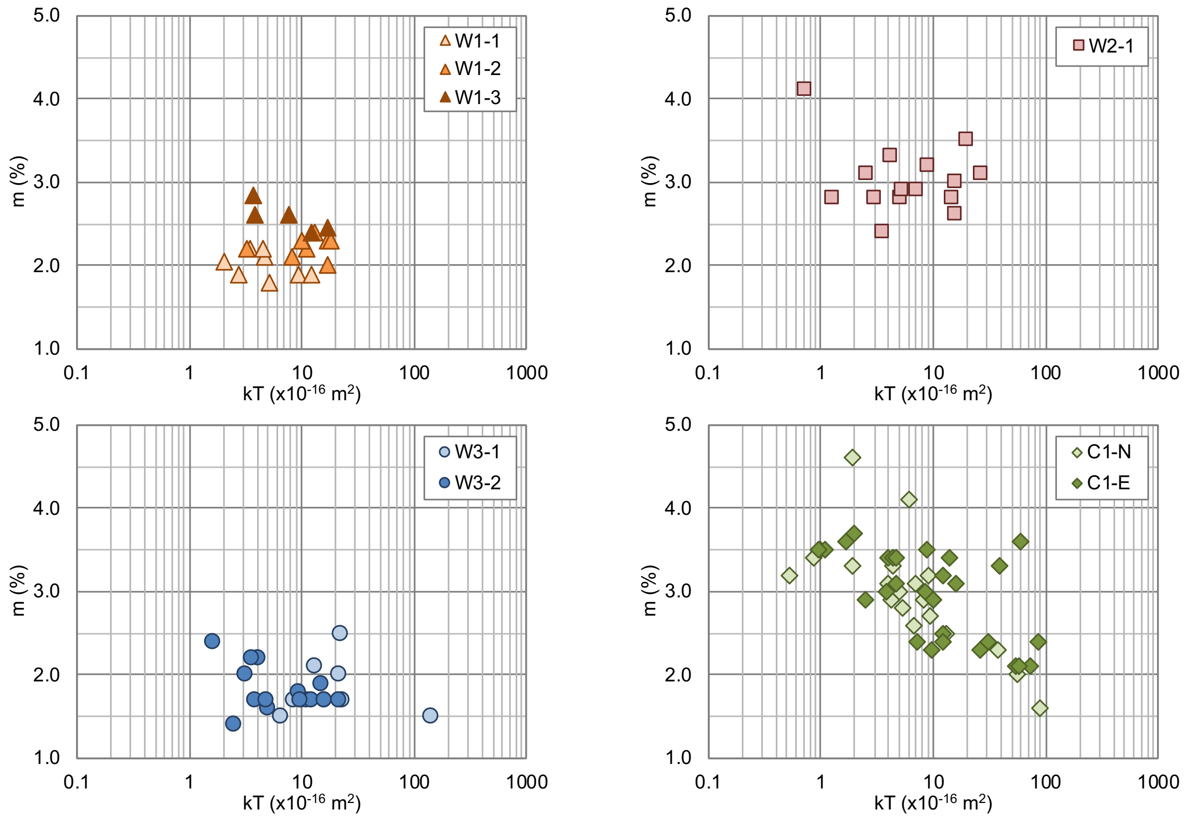


Fig. 3 Surface air permeability kT vs. surface moisture content m by structure and location
(Top left: Wall 1, Top right: Wall 2, Bottom left: Wall 3, Bottom right: Column 1)

Table 4 Descriptive statistics for compressive strength f'$_c$ by structure

Structure	Total no. of measurements	(MPa)				
		Arithmetic mean	Standard deviation	Median	Maximum	Minimum
Wall 1	62	47.9	5.1	49.3	54.4	35.3
Wall 2	86	38.2	5.0	39.2	50.6	25.2
Wall 3	99	51.1	5.0	51.9	60.7	37.9
Column 1	325	50.5	4.9	50.6	60.7	37.9

from each structure. Although each data possess their own variability, the means can be used to represent each data set. While higher compressive strength was expected to lead to lower surface air permeability [10], the opposite trend was found for the aggregated results. Both air permeability and compressive strength are dependent on the overall variability of the actual concrete quality; however, the rebound hammer is less sensitive to environmental factors [13], so it is considered that the differing surface moisture contents between structures led to the contrary relationship. This is further supported by the measurement variability, as the standard deviation of the compressive strength is very similar across all structures, despite the differing surface moisture content distributions. However, the variability of the surface air permeability is dependent on the moisture state, which may led to the relationship found in Figure 4.

3.4 Comparison of the spatial distributions of the NDT results

Finally, the spatial variability of the three NDT measurement results is examined for Column 1. Test areas were demarcated on the east (190cm×190cm) and north (190cm×110cm) faces of the column base, and measurement points were set on both test surfaces (Figure 5). Surface moisture content and surface air permeability were measured two or three times at each point, and compressive strength was measured 15 times at each point (except for one point with only 10 measurements). Contour plots were then constructed using the respective mean values of each NDT result at each point to examine the spatial variability.

The results are presented in Figure 6. On the east face, the surface moisture content is higher at the bottom, and tends to decrease when moving outwards towards the upper corners. The moisture content on the north face also decreases towards the upper left corner, but increases towards the upper right and bottom left corners. The surface air permeability distributions of the two faces are more similar, with lower values on the bottom and right sides, and increasing when moving towards the upper left. For the compressive strength, distinct peaks are seen at the centers of three quadrants

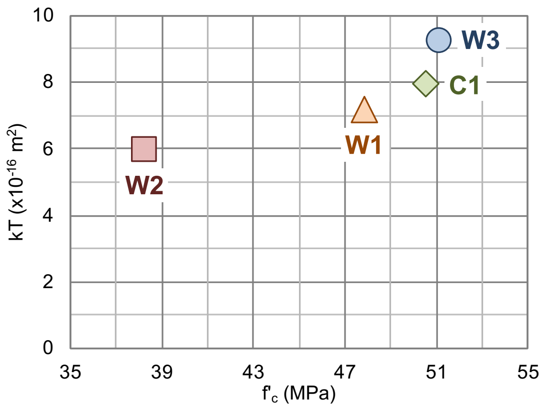
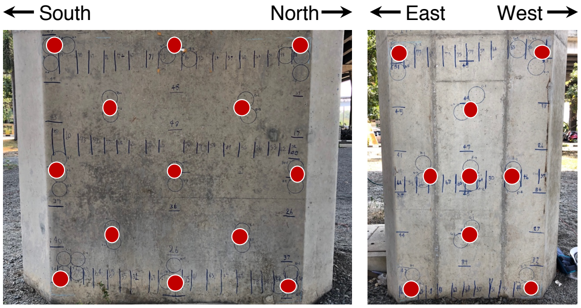


Fig. 4 Surface air permeability kT vs. compressive strength f'$_c$ by structure



East face (C1-E)

North face (C1-N)

Fig. 5 Spatial distribution of measurement points (indicated by red circles) for Column 1

on the east face, and in the centers of both the right and left halves of the north face. For both faces, the strength values decrease when moving outwards - particularly towards the upper corners of both surfaces.

Some consistency can be seen between the surface moisture content and surface air permeability distributions. The regions with higher air permeability tend to correspond to the regions with lower surface moisture - particularly towards the upper left corners of both faces - and vice versa. The compressive strength distributions of both faces, however, are distinctly shaped when compared to the moisture content and air permeability distributions. As strength measurement is less sensitive to fluctuations in the environment, its results may be more stable and provide a clearer picture of the spatial variability of the concrete quality across the structure surface. Conversely, the air permeability distribution may be more dependent on changes in the surface moisture content, which is subject to various environmental factors, such as sunlight, wind, and rain exposure, temperature cycles, and so forth.

4. CONCLUSION

(1) This paper examined the variability of surface air permeability measurements taken in-situ from four concrete road structures in Thailand. Two analyses were carried out: one exploring the relationships between the moisture content, air permeability, and compressive strength, and one

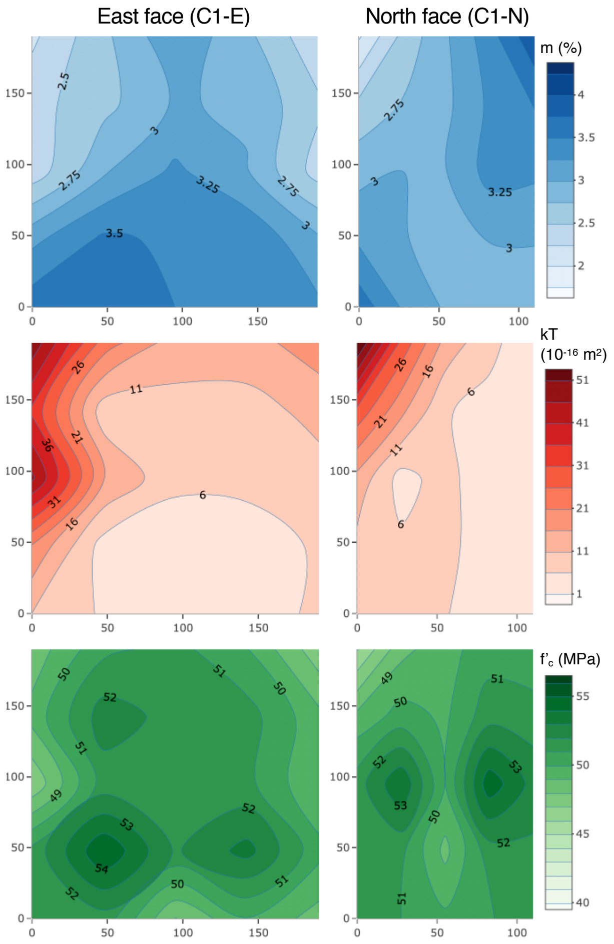


Fig. 6 Contour plots of the surface moisture content m (top), surface air permeability kT (middle), and compressive strength f'$_c$ (bottom) for Column 1

comparing the spatial variability of the surface air permeability with the other NDT results.

(2) The descriptive statistics and distributions of the surface air permeability results suggested that the four structures may possess similar mass transfer resistance characteristics. Statistical analysis by ANOVA confirmed that the air permeability distributions did not differ significantly.

(3) Examination of the relationships between the surface air permeability and the surface moisture content for the four structures revealed that the variability of the air permeability for the wall structures may be due to variation in the concrete quality, rather than the moisture state. For the column, however, the relationship indicated that the mass transfer resistance may be more dependent on the moisture content distribution.

(4) A clear relationship between the surface air permeability and compressive strength could not be found. This may be caused by the differing moisture conditions between the structures.

(5) Good consistency was observed between the spatial distributions of the moisture content and air permeability. The strength results, however, exhibited a distinctly different spatial distribution, which may be due to its insensitivity to fluctuations in the moisture content.

(6) The results presented in this paper, while gathered from only a select few test locations, confirm that measurement of the surface air permeability alone, even in the dry state, does not provide sufficient information for the planning of maintenance activities. A combination of NDT methods is necessary to more fully capture the variability of mass transfer resistance and concrete quality, and to identify vulnerable locations which may require countermeasures to preserve the required structural performance.

ACKNOWLEDGEMENT

This investigation was supported by the Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP) for "Infrastructure Maintenance, Renewal, and Management Technology" (Funding agency: Japan Science and Technology Agency).

REFERENCES

[1] Torrent, R., Frenzer, G., “A method for the rapid determination of the coefficient of permeability of the ‘covercrete’,” Intl. Symp. on Non-destructive Testing in Civil Eng., 1995, pp. 985-992.

[2] Basheer, L., Kropp, J., Cleland, D.J. “Assessment of the durability of concrete from its permeation properties: a review,” Construction and Building Materials, Vol. 15, No. 2, 2012, pp. 93-103.

[3] Torrent, R.J., “A two-chamber vacuum cell for measuring the coefficient of permeability to air of the concrete cover on site,” Materials and Structures, Vol. 25, 1992, pp. 358-365.

[4] RILEM TC 189 NEC, “Non-destructive evaluation of the penetrability and thickness of the concrete cover”, Torrent, R. and Fernández Luco, L. (Eds.), RILEM Report 40, 2007.

[5] JSCE, “Quality of covercrete of structure and durability performance verification system,” Committee Report of JSCE 335 committee, Concrete Engineering Series Vol. 97, 2012. (in Japanese)

[6] Denariè, E., Jacobs, F., Leemann, A., Teruzzi, T., Torrent, R., “Specification and site control of the permeability of the cover concrete: the Swiss approach,” In: Leung, C. and Wan K.T. (Eds.), Intl. RILEM Conf. on Advances in Construction Materials Through Science and Engineering, 2011, pp. 478-485.

[7] Torrent, R., Imamoto, K., “Site testing of air-permeability as indicator for carbonation rate in old structures,” Proc. of the Intl. Conf. on the Regeneration and Conservation of Concrete Structures (Nagasaki, Japan), 2015.

[8] Kurashige, I., Yamada, K., Ogawa, S., “Feasibility study on quality verification of casted concrete using nondestructive air permeability test and electrical resistivity measurement toward radioactively contaminated waste disposal,” Cement Science and Concrete Technology, Vol. 69, 2015, pp. 287-294. (in Japanese)

[9] Nguyen, N.T., Sbartaï, Z.M., Lataste, J.F., Breysse, D., Bos, F., “Assessing the spatial variability of concrete structures using NDT techniques - laboratory tests and case study,” Construction and Building Materials, Vol. 49, 2013, pp. 240-250.

[10] Neves, R., Branco, F., de Brito, J., “About the statistical interpretation of air permeability assessment results,” Materials and Structures, Vol. 45, No. 4, 2012, pp. 529-539.

[11] JSCE, “Guideline for Experiment on Materials of Civil Works,” JSCE, Tokyo, 2005. (in Japanese)

[12] Henry, M., Horiuchi, K., Matsumoto, K., Sancharoen, P., “In-situ non-destructive investigation on the variability of concrete strength of road structures in Thailand,” 74th Japan Society of Civil Engineers Annual Conference, 2019, CS2-39.

[13] Breysse, D., “Nondestructive evaluation of concrete strength: An historical review and a new perspective by combining NDT methods,” Construction and Building Materials, Vol. 33, 2012, pp. 139-163.