Committee Report: JCI-TC141A

Technical Committee on Functions and Techniques for Controlling of Air Voids in Concrete

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Abstract:

Air voids in concrete are generally known to affect the workability, the mechanical properties of hardened concrete, and the freeze-thaw resistance. However, recent studies have pointed out the use of materials like moderate-heat fly ash cement joins and/or breaks air voids, resulting in decrease in the freeze-thaw resistance, and the use of shrinkage reducing agents makes it difficult to maintain an appropriate air content. They thus have renewed our appreciation of the need for technology to control/manage the behavior of the air voids. This committee comprehensively reviewed the roles and effects of the air voids and the technology to control/manage the amount and quality of the air voids through literature search and experiment-based studies.

Keywords: Air void structure, air content, workability, freezing resistance, air entraining agent, shrinkage reducing agent, transportation, and vibration compaction

1. Introduction

Air voids in concrete are generally known to affect workability at stage of execution of work, the mechanical properties of hardened concrete, and the freeze-thaw resistance. In particular, in order to control damage to concrete due to freezing and thawing, it is crucial to create a mechanism to reduce the pressure caused by the movement of unfrozen water that accompanies a generation of crystals by entraining minute air voids in concrete. However, recent studies have pointed out that in concrete made of moderate-heat fly ash cement, which is widely used as dam concrete, the air voids entrained in the concrete join together, break, and then decrease the freeze-thaw resistance.1),2) Moreover the use of shrinkage reducing agents makes it difficult to maintain an appropriate air content.3),4) They thus have renewed our appreciation of the need for the technology to control/manage the behavior of air voids. Therefore, JCI-TC-141A "Technical Committee on Roles and Control of Air Voids in Concrete (hereafter referred to as Air Void Committee) was set up with the aim to comprehensively review the roles and effects of the air voids and the technology to control/manage the amount

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and quality of the air voids through literature search and experiment-based studies.

The structure of Air Void Committee is shown in Table-1. The committee has three working groups: a working group for survey and research of the roles of air voids in concrete (hereafter referred to as Role WG), a working group for tests and evaluation of air void structures in concrete (hereafter referred to as Evaluation WG), and a working group for the technology to control air voids in concrete (hereafter referred to as Control WG). They took the following approaches:

Role WG reviewed the roles and effects of the air voids in concrete, and determined the air void structures required for different roles by examining the literature on the past studies and the actual structures. Evaluation WG organized the methods of testing and evaluating air void structures in fresh concrete and hardened concrete, and investigated impacts of the transportation and vibration compaction on changing the air content of fresh concrete and the air void structures of hardened concrete based on experiments. Control WG examined the literature on the existing studies concerning the technology to inject air voids into concrete and control them.

Chapters of the report were originally arranged in the following order: the roles of air voids in concrete; the methods of testing and evaluating air void structures in concrete; and the technology to inject/control air voids in concrete, in accordance with the purposes of the activities of WGs. However, since there is a particularly close link between the roles of air voids and the control of them, it is inappropriate to describe them in separate chapters. It is also necessary to provide individual chapters for the examinations of the actual structures by Role WG and the experiment-based studies by Evaluation WG for its more appropriate structure. In this regard, the committee decided to re-arrange the chapters as follows:

Chapter 1 "Overview"

Chapter 2 "Mechanism of Air Void Entrainment"

Chapter 3 "Methods of Evaluating Air Voids"

Chapter 4 "Effects of Materials Used and Concrete Types on Air Void Structures"

Chapter 5 "Effects of Stages of Manufacturing and Execution of Work on Air Void Structures"

Chapter 6 "Effects of Air Void Structures on Properties of Concrete"

Chapter 7 "Verification Experiments concerning Air Void Structures and Examinations of Actual Structures"

Chapter 8 "Other Technologies for Injection and Control of Air Voids"

Chapter 9 "Conclusion"

Table-1: Committee Structure

Chairman	：	Yukio HAMA（Muroran Institute of Technology）
Vice-Chairman	：	Hidehiko OGATA（Tottori University）
Secretary-General	：	Daisuke HAYASHI（Kajima Corporation）
Secretary	：	Minoru ABA（Hachinohe Institute of Technology） Noboru YUASA（Nihon University） Daiki ATARASHI（Shimane University）
[Role WG]	：	◎Minoru ABA（Hachinohe Institute of Technology） Tetsuya OYAMADA（Iwate University） Shin-Ichiro HASHIMOTO（Fukuoka University） Akio ISHIGAMI（Civil Engineering Research Institute for Cold Region） Hiroshi KATAHIRA（Public Works Research Institut Ryosuke SAITO（Shimizu Corporation） Yoshiyuki SUZUKI（Hazama Ando Corporation） Kazuhide HOSHI（Yamaso Chemical Co.,Ltd.） Yuki SAKOI（Hachinohe Institute of Technology） Yoshinori GONDAI（National Institute of Technology, Sendai College）
[Evaluation WG]	：	◎Noboru YUASA（Nihon University） Madoka TANIGUCHI（Northern Regional Building Research Institute） Ryosuke SAITO（Shimizu Corporation） Taku SANDA（Misawa Homes Institute of Research and Development Co.,Ltd.） Manabu HASHIMOTO（Kajima Corporation） Kazuhide SAITO（Takemoto Oil & Fat Co., Ltd.） Jiro SAKUEI（BASF Japan） Hironobu NISHI（FLOWRIC Co.,Ltd.）
[Control WG]	：	◎Daiki ATARASHI（Shimane University） Masafumi KITATSUJI（Miyagi University） Ryosuke SAITO（Shimizu Corporation） Noriyuki HOSHIDA（Milcon Co.,Ltd.） Kazuhide SAITO（Takemoto Oil & Fat Co., Ltd.） Jiro SAKUEI（BASF Japan） Kazuhide HOSHI（Yamaso Chemical Co.,Ltd.） Hironobu NISHI（FLOWRIC Co.,Ltd.）
Collaborative Committee Member	：	Hironobu YAMAMIYA（BASF Japan）
Former Collaborative Committee Member	：	Noboru SAKATA（Kajima Corporation）

◎: Head of WG

Chapter 2 of the report takes up "air voids", the primary keyword in this committee, and explains the mechanism of entraining air voids in concrete. The major topic dealt with in the subsequent Chapters 3 through 6 and 8 is literature search. Chapter 7 describes the examinations of the actual structures and experiment-based studies. Note that "Verification

Experiments of Methods of Evaluating Air Content" and "Verification Experiments of Methods of Evaluating Quality of Air Voids" in Chapter 3 are experiments performed as a part of the experiment-based studies described in Chapter 7.

This committee report outlines the report. Please refer to the report for details. The following sections outline the content of the report in the order of the table of contents.

2. Mechanism of Air Void Entrainment

The quality control of the air voids entrained in concrete today uses surfactants (air entraining agents) and anti-foaming agents, and is at a highly advanced technical level.

Entraining air voids (entrained air) in concrete requires surfactant (air entraining agent) molecules. A surfactant molecule has: a "hydrophilic group", which is hydrophilic and oleophobic; and a "hydrophobic group", which is oleophilic and hydrophobic, in its molecular structure. This allows the surfactant molecule to have an effect of adsorbing gas-liquid interface, the boundary surface between the air and the water (to orient the hydrophobic group in the direction of the air), and to change the surface properties. At the instant when the air enters a surfactant solution, surfactants adsorb to the air-water interface, orient, and form an adsorption layer. This phenomenon is applied in the formation of bubbles. The bubbles are liquids or solids enclosing gas, and divided into two large groups: foam, a mass of bubbles; and bubbles, closed cells.

Usually, when using air-entraining cement dispersing agents, the entrained air is entrained with air entraining agents after deleting coarse air voids (unstable foam) by adding a fixed amount of anti-foaming agents. Anti-foaming agents are divided into: foam breakers (temporary anti-foaming agents), which break formed bubbles; and foam inhibitors (lasting anti-foaming agents), which suppress foaming. In the field of concrete, the adjustment of air content in concrete uses either or both of them. The air content adjustment immediately after the mixing primarily uses foam breakers, and the subsequent air content adjustment mainly uses foam inhibitors. Anti-foaming requires the following three conditions: the surface tension of the anti-foaming agent is less than that of the foam film; the surface tension of the anti-foaming agent and foam film is low, allowing the anti-foaming agent to enter the foam film; and the anti-foaming agent is insoluble in the foam film.

Although it is possible to control the quality of the air voids entrained in concrete at a highly advanced technical level using the air entraining agents and the anti-foaming agents, the entraining air voids always accompanies the distribution of diameters. For example, when we try to entrain only minute entrained airs of no larger than 50 μm, which are necessary for the freeze-thaw resistance, a certain amount of the air voids of 100 μm or larger are also entrained. This distribution of the air content entrained using commercial air entraining agents is one of the challenges to be overcome with regard to the control of air voids, even though the chemical compounds designed to exclude unnecessary air voids are selected. Besides, one of the related issues is the effects of shrinkage reducing agents. The development of air entraining agents, which are resistant to shrinkage reducing agents is also a task to be achieved.

3. Methods of Evaluating Air Voids

The air content in concrete impacts not only the workability but also the strength and the freeze-thaw resistance. Regarding the air content in fresh concrete, under a fixed slump and cement content per unit, the ball bearing effect of minute closed cells entrained in concrete reduces the water content per unit by 2 to 4% per 1% of the air content. As for hardened concrete, while it contributes to the freeze-thaw resistance, the compressive strength reduces by 5 to 7% per 1% increase in the air content when all other conditions are fixed. This means that it is important to evaluate whether the air content is within a specified range.

3.1 Methods of Evaluating Air Voids in Fresh Concrete

3.1.1 Evaluation of Air Content

Methods of measuring the air content in fresh concrete include the pressure method, volumetric method, mass method and water column pressure method which are prescribed in JIS, as well as measurement by mini air meters.

The pressure method is divided into flooding and non-flooding methods. The non-flooding method may generates an error unless the concrete surface matches the upper surface of the container. The volumetric method measures with high accuracy, and causes less breakdown. This method is appropriate to measure concrete with porous aggregates, as the aggregate correction factors that are generally smaller than those used in the pressure method are used to correct the effect of the water absorption by the aggregates during the test. However, this method requires time for measurement. In the measurement with the mass method, with the same mix proportion, the air content of concrete can be lower compared to the pressure method and the volumetric method. The mini air meters measure the air content that is almost the same as the content measured by the conventional volumetric method. They are light in weight, require less sample quantity, can be used both for normal concrete and lightweight concrete, and are believed to deliver reliable results promptly.

3.1.2 Evaluation of Quality of Air Voids

The air voids entrained in concrete are divided into two large groups: the entrained air voids with diameters of approximately 25 to 250 μm; and the coarse, irregular shaped entrapped air voids which account for 1 to 2% of air content. It is acknowledged that the entrained air is important for the freeze-thaw resistance of concrete. The entrained air is evaluated by the spacing factor, which indicates the size of the air voids and the space between them. The spacing factors are measured with the method, ASTM C457 "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete" generally intended for hardened concrete, while the air void distribution of fresh concrete can be measured with the method using optical fiber sensors or with the buoyancy method.

The method using optical fiber sensors detects the size of the air voids directly with optical fiber sensors, allowing portable devices to measure the air content quickly on the site. For the buoyancy method, as the larger the diameter of an air void rising to the water surface, the higher the speed at which the air void rises, the method uses this feature and measures the buoyancy changes caused by an air void that has risen over time. Thus it enables the analysis of parameters such as the air void diameter distribution, air content, specific surface area, and spacing factor by applying Stokes' rule.

3.1.3 Verification Experiments of Methods of Evaluating Air Content

The air content of fresh concrete is often measured with the pressure method as prescribed in JIS. However, the variation in the measurements by different persons has not been evaluated sufficiently. Therefore, Evaluation WG verified the variation in the air content of fresh concrete obtained by different persons with the pressure method (non-flooding method) using ready-mixed concrete as a target.

Table-2 shows the mix proportions of concrete, and Table-3 lists the materials used. The mix proportions of concrete were determined with reference to the JIS-compliant proportions which are available at the fresh concrete plant. Two types of mixes were prepared: proportion for construction (hereafter referred to as SL18) and proportion for civil engineering (hereafter referred to as SL8). The slump was set at 18 ± 2.5 cm for the mix proportion for construction, and 8 ± 2.5 cm for the mix proportion for civil engineering, with the air content of no less than 4.5% at the point of arriving at the site for both mix proportions.

Table-2: Mix Proportions of Concrete

Mix Proportion Name	Water-Cement Ratio (%)	Fine Aggregate Ratio (%)	Target Slump (cm)	Target Air Content (%)	Quantity of Material per Unit Volume of Concrete (kg/m^3)							
					W	C	S1	S2	S3	G2	Ad1 C×%	Ad2* (A)
Mix Proportion for Construction (SL18) 27-18-20N	55.0	49.3	18±2.5	No less than 4.5	185	337	258	301	301	894	1.10	2A
Mix Proportion for Civil Engineering (SL8) 27-8-20N	55.0	48.4	8±2.5	No less than 4.5	167	304	264	308	309	950	1.10	2A

* 1A=C×0.001%

Table-3: List of Materials Used

Material Name	Symbol	Remarks
Water	W	Supernatant Water, Density: 1.0 g/cm^3
Cement	C	Normal Portland Cement, Density: 3.16 g/cm^3
Fine Aggregate	S1	Crushed Sand from Okutama-machi, Nishitama-gun Tokyo; Density in Saturated Surface-dry Condition: 2.65 g/cm^3 (no more than 2.5 mm); Fineness Modulus: 3.00
	S2	Pit Sand from Mandano, Ichihara-shi, Chiba; Density in Saturated Surface-dry Condition: 2.58g/cm^3 (no more than 2.5 mm); Fineness Modulus: 2.00
	S3	Crushed Sand from Yokoze-machi, Chichibu-gun, Saitama; Density in Saturated Surface-dry Condition: 2.65 g/cm^3 (No more than 2.5 mm); Fineness Modulus: 3.00
Coarse Aggregate	G	Crushed Stone from Okutama-machi, Nishitama-gun Tokyo; 20 to 5 mm; Density in Saturated Surface-dry Condition: 2.65 g/cm^3; Solid Content: 60.0
Chemical Admixture	Ad1	Air-entraining and Water-reducing Admixture (Normal Type), (Main Ingredients: Lignin Sulfonate and Oxycarboxylic Acid Salt)
	Ad2	Air Entraining Agent (Main Ingredients: Denatured Rosin Acid Compound Negative Ion Surfactant)

The following steps were taken to measure the air content of fresh concrete: 1) check the target performance of the concrete immediately after mixing; 2) load 4 m^3 of concrete into an agitator car; 3) transport the concrete for about 30 minutes; and 4) measure the air content at the point of arriving at the site using five air meters operated by five persons. The air meters were calibrated on the day of the test. The air content of the concrete immediately after mixing was measured using one of the five air meters.

Table-4 shows the measurement results and the basic statistics. The average air content of the concrete at the point of arriving at the site was 6.3% with the mix proportion for construction, and 6.7% with the mix proportion for civil engineering, showing a tendency to increase from that immediately after mixing. For both mix proportions, the air content tended to increase at the point of arriving at the site compared to that at the point of leaving the fresh concrete plant. For the variation in the air content at the point of arriving at the site, the difference between the maximum and minimum values was 0.7% with the mix proportion for construction, and 0.4% with the mix proportion for civil engineering. The standard deviation calculated from these values was 0.24% with the mix proportion for construction, and 0.16% with the mix proportion for civil engineering. The coefficients of variation were 0.04 and 0.02 for the mix proportion for construction and the mix proportion for civil engineering, respectively, indicating that there was no large discrepancy among measuring persons.

Table-4: Air Content Measurement Results and Basic Statistics

Mix Proportion Name	Basic Statistic		Fresh Concrete		Mix Proportion Name	Basic Statistic		Fresh Concrete	
			Air Content					Air Content	
			Immediately after mixing	About 30 min. later				Immediately after Mixing	About 30 min. later
Mix Proportion for Construction (SL18)	Overall Data	*n*	1	5	Mix Proportion for Civil Engineering (SL8)	Overall Data	*n*	1	5
		Average	5.9	6.3			Average	6.2	6.7
		Standard Deviation	—	0.24			Standard Deviation	—	0.16
		Minimum Value	—	6.0			Minimum Value	—	6.5
		Maximum Value	—	6.7			Maximum Value	—	6.9
		Median	—	6.3			Median	—	6.7
		Coefficient of Variation	—	0.04			Coefficient of Variation	—	0.02

3.2 Methods of Evaluating Air Voids in Hardened Concrete (Verification Experiments of Methods of Evaluating Quality of Air Voids)

ASTM C457 prescribes the standards for the methods of measuring air void structures of hardened concrete, and the measurements in accordance with these standards are common. However, these standards do not necessarily specify all of the measurement procedures in detail. For example, there are many cases where detailed procedures including methods for polishing, measurement of line pitches, and scaling factors for the observation rely on performance in individual cases. In addition, since the measurement performed by humans, issues such as the effect of different recognition of air voids among individuals (skill levels) are often pointed out. In recent years, the attempts to reduce time spent on measurements have promoted semi-automatic measuring devices, and there have been an increasing number of cases where semi-automatic measuring devices were used. In countries outside of Japan, the results of the round-robin tests using manual measurements and automatic measuring devices have been reported.5) However, there are almost no reports on studies on variations/differences in the results of the measurements using devices that are currently available in Japan. For this reason, in order to examine variations in the results obtained by measurements in different conditions, Evaluation WG decided to perform round-robin tests in facilities in Japan using the same sample to verify the linear traverse method, one of the methods for testing air void structures of hardened concrete. The test specimens were those prepared for the later-described "Effect of the Stage of Execution of Work on Air Void Structures".

The specimens were two 100 φ × 200 mm cylinders, each of which was made of either of the two types of ready-mixed concrete (Table-2 and Table-3) at the point of arrival at the site. Underwater curing of the specimens was performed for 14 days at 20 ºC. For the measurement of air voids, a splice with a thickness of about 20 mm was taken from the middle height of the specimens.

Five facilities (A and G were the same, and C and D were the same) participated in the experiment, and eight measurements were performed. Table-5 shows the measurement data and skill levels of measuring persons for each measurement. The skill levels were graded by number of specimens the person has measured; the skill level is 1 for 10 pieces or fewer, 2 for 10 to 100, 3 for 100 to 1,000, and 4 for over 1,000. The devices were classified into two categories: manual devices and semi-automatic ones. The manual measuring device refers to a device in which a conventional optical micro scope is combined with a stage and the measurement is performed while the measuring person looks at the stage of the device with his eye. The semi-automatic device consists of a CCD camera, which are available in the market in recent years and an automatic stage. The measurement are performed by taking enlarged images and automatically recognizing air voids with image analysis software. As the recognition performance of the automatic devices is not always sufficient, the air voids were manually (visually) recognized after the automatic recognition by the automatic device in the facilities where the automatic devices were used. This is the reason for the name of "semi-automatic device". The facilities to which A & G and C & D belong had both manual and semi-automatic devices, the facilities to which B and D belong had the semi-automatic device only, and the facility to which F belongs had the manual device only. All of the semi-automatic devices of the facilities participating in this experiment were manufactured by the same manufacturer.

Table-5: Overview of Round-Robin Test

Facility #			A	B	C	D	E	F	F	G
Measuring Person	Skill Level		3	2	1	1	2	2	2	1
Measurement Data	Manual/Automatic		Manual	Semi-Automatic	Manual	Semi-Automatic	Semi-Automatic	Manual	Manual	Semi-Automatic
	Measurement Time		3 hours	3 to 4 hours	4 hours	30 min.	60 min.	4 hours	3 hours	60 min.
	Observation Face		Circle	Rectangle	Rectangle	Rectangle	Rectangle	Rectangle	Rectangle	Rectangle
	Number of Surfaces		1	2	2	2	2	1	1	2
	Measurement Method		Linear	Linear	Linear	Linear	Linear	Linear	Linear	Linear
	Measurement Line Interval		3	2	2.5	2.5	1.4	2	2	1.4
	Scaling Factor	Normal	150	120	400	120	120	40	40	120
		Enlarged	300	—	400	—	—	—	—	—
Remarks								SL18	SL8	

The same sample was used for measurement. After one facility finished the measurement, the sample used was sent to the next facility for the next measurement. The results of the measurements are shown in Fig.-1. The results of the round-robin test show that there was no significant difference among the measurement methods in the measured air content of hardened concrete. However, for the air void distribution of hardened concrete, there was a difference between the manual and the semi-automatic measurements in the recognition of minute air voids. Furthermore, the difference among facilities in the manual measurements was found, and that the coefficient of variation in spacing factors of hardened concrete was about 10%.

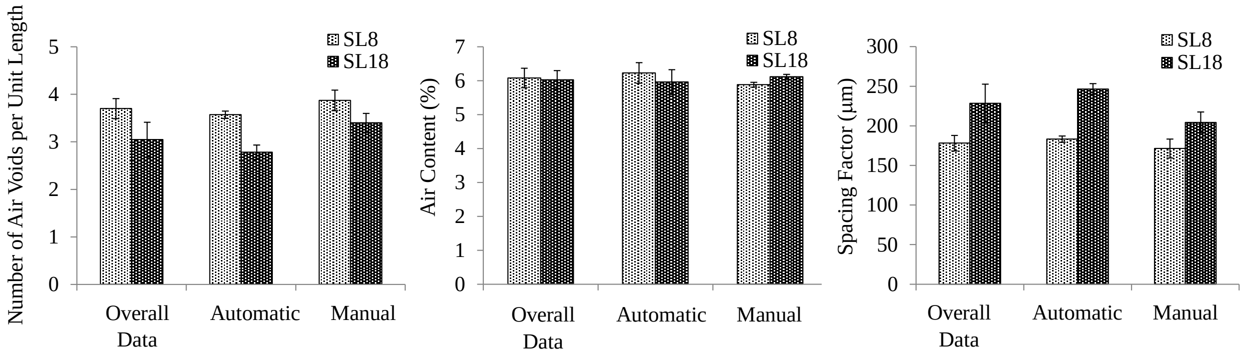

Fig.-1: Air Void Measurement Results

(Number of Air Voids per Unit Length, Air Content, and Spacing Factor)

4. Effects of Materials and Concrete Types on Air Void Structures

4.1 Effects of Materials

In addition to chemical admixtures, each of the materials used, for example, cement, mineral admixtures, and aggregate also affect air void structures in concrete. Based on the examination on past studies, the effects of the used materials on the air void structure were reviewed as follows:

(1) Chemical Admixtures

For chemical admixtures, it is widely accepted that air entraining agents are critical for entraining air voids in concrete. Generally, the air content in air-entrained concrete is high with a low concrete temperature, and decreases as the temperature rises. While shrinkage reducing agents are important chemical admixtures used to reduce the drying shrinkage of concrete, it has been pointed out that they reduce the freeze-thaw resistance of concrete with air entraining agents. There are reports indicating that the diameters of the air voids entrained by shrinkage reducing agents are larger compared to those of the entrained air voids and disadvantageous to concrete. Nevertheless, the other report finds that adding shrinkage reducing agents after mixing leads to a slight increase in the peak of the air void diameter range that is believed to be effective for the freeze-thaw resistance.3) There is also a study report indicating that while the use of shrinkage reducing agents reduces the total number of air voids, especially minute air voids with diameters of about 200 μm or smaller, and decreases the freeze-thaw resistance compared to the use of only the air entraining agent ; whereas, the use of an air entraining agent that entrains a large number of minute air voids secures the freeze-thaw resistance depending on the conditions.4) Furthermore, the shrinkage reducing agent is reported to ensures the freeze-thaw resistance by forming a hydrophobic compound6). The development of air entraining agents that are resistant to shrinkage reducing agents will be a key in the future.

(2) Cement

Regarding the air entrainment of cement and fresh concrete, it is known that the entrainment decreases as the fineness of cement and cement content per unit increase, when the same cement is used. This is more obvious in the conditions where ultra high-early-strength cement is used than in the conditions where normal cement is used. For cement types, in a condition using fly ash cement, unburned carbon contained in fly ash is known to adsorb air entraining agents, and reduces the entrained air content. As a result, the air entrained decreases as time passes and the spacing factor increases, resulting in the decrease in the freeze-thaw resistance.

Sakata et al.7) analyzed the data concerning the air void structures and freeze-thaw resistance of hardened concrete, and indicated that the air content of concrete decreases during the coagulation process. This tendency becomes more obvious when moderate-heat fly ash cement, which is widely used in dam concrete, is used rather than normal Portland cement. Nakamura et al.[8)] investigated the freeze-thaw resistance of low water-cement ratio high-strength concrete with low-heat Portland cement, with a particular focus on the ionic strength in the mixing water that affects the effect of the air entraining agents. Their study shows that when low-heat Portland cement is used, the liquid-phase ionic strength during the mixing is relatively low. The spacing factor in the low-air content area of about 3% may be larger than when normal Portland cement is used.

(3) Mineral Admixture

For mineral admixtures, findings on fly ash and blast-furnace slag have been reported as follows: while in concrete that contains fly ash as a mineral admixture, the spacing factor tends to be larger as the air content decreases, especially by the agitation, the use of special air entraining agents for fly ash enables the spacing factor to remain small even with the decrease in the air content. With regard to blast-furnace slag, in segregation inhibiting agent-added concrete, the increase in the amount of blast-furnace slag increases the ratio of air voids with small diameters, and reduces the ratio of those with large diameters.

(4) Aggregates

The particle size and particle shape of the aggregate affect the air in concrete. Especially, the air is affected easily by the fine aggregate, and the increase in the amount of the fine aggregate increases the air content. It is known that the fine aggregates with many portions having size of about 0.3 to 0.6 mm in size easily entrain air voids, and that those with many potions of 0.15 mm or less hardly entrain air voids. However, regarding the effects of the types of the aggregate on air void structures of hardened concrete, there have been limited data obtained through a comprehensive comparative study targeting various types of natural aggregates with an focus on the changes in air void structures of hardened concrete.

4.2 Effects of Concrete Types

To ensure the freeze-thaw resistance, air void structures, which are evaluated by parameters such as the spacing factor, are more important rather than the absolute quantity of the air content. This applies not only to normal concrete but also to high-strength, high-fluidity concrete.

The measurement results of air content of fresh concrete, and the air void distribution and fine pore distribution of hardened concrete of three strength levels (low strength, medium strength, and high strength) suggest that: in general, the air content of hardened concrete is lower than that of concrete just after mixing, regardless of concrete types, the more the amount of the air entraining agent is used, the greater this decrease in the air content tends to be. Besides, even when the air content is the same, the higher the strength for which the mix proportion is intended, the larger the number of minute air voids is. In other words, the increase in the paste content per unit increases the number of minute air voids. It is expected that this is because the higher the strength of and the richer the mix proportion of concrete, the more easily air voids are distributed during the mixing, and because the ingredients of the chemical admixture are effective for the air void distribution. However, as ensuring the same air content in higher strength concrete requires more amount of the air entraining agent to be added, the results may possibly be related to the fact that the increase in the strength of concrete increases the total amount of the entrained air injected using the air entraining agent.

5. Effects of Stages of Manufacturing and Execution of Work on Air Void Structures

5.1. Effects of Manufacturing and Transportation Methods on Air Void Structures

For the effects of manufacturing methods on air void structures, there are some reports on the difference in the air content of concrete mixed by different mixers. For the effects of transportation methods on air void structures, studies have been conducted primarily on the changes in the air content before and after pumping. Many of the studies show that the air content after pumping is lower than that before pumping, depending on the distance and speed of the pumping. This applies to the concrete with air entraining agents and air-entraining and water-reducing admixtures. For the quality changes before and after the pumping in concrete with air-entraining and high-range water-reducing admixtures including high-strength, high-fluidity concrete, Nakata et al.9) summarized the literature published by the Architectural Institute of Japan and Japan Society of Civil Engineers for the past 17 years. The results of their literature search show that the air content tends to increase after the pumping at all strength levels (water-cement ratio) in general. This tendency can be unique to the concrete with air-entraining and high-range water-reducing admixtures, and is different from the results for the air-entrained concrete whose air content reduces after the pumping.

5.2 Effects of Placing and Compaction Methods, and Air Void Structures

For the relation between placing/compaction methods and air void structures, the air content decreases after the vibration compaction compared to that at immediately after mixing. It is believed that the more the air content of the concrete immediately after mixing is, the less the decrease in air content after vibration is, and the more the cement content per unit is, the less the decrease in air content after vibration compaction is.

5.3 Effects of Curing Methods on Changes in Air Content

The atmospheric pressure steam curing, which is most commonly used for manufacturing precast concrete products, was examined to conduct literature search on the effects of the temperature rise slope in the steam curing, the presteaming period, the highest temperature, and the secondary curing on air void structures of concrete. As the result, there was no effect of the temperature rise slope in the steam curing and the secondary curing on air void structures.

5.4 Factors Affecting Surface Air Voids

Factors that affect surface air voids of concrete include the type of the separating material and the material of the mold. The effects of the inclination angle of the mold have also been pointed out. The generation of surface air voids depends on the types of the separating materials. For oil-based separating materials, addition of surfactants reduces the surface air voids. The comparison between the oil-based and the water-based separating materials has shown that with the water-based ones, while less surface air voids are generated, a larger number of hidden air voids with openings covered by cement paste are generated internally.

6. Effects of Air Void Structures on Properties of Concrete

6.1 Workability

The Standard Specifications for Concrete Structures of Japan Society of Civil Engineers specify that the general air content at the point of the mixing is around 4 to 7% of the concrete volume. No study has been done on whether or not the difference in the air content (high/low content) in the above-mentioned range of the air content changes the workability of normal concrete. For high-strength concrete and high-fluidity concrete, there has been a study which examined the effects of the air content change on the fresh properties including the slump flow value, funnel efflux time, and box filling height.10) In this study, the air content was changed in the range of 2 to 8% by changing the amount of the air entraining agents added to the high-fluidity concrete of the same mix proportion. The results show that in this range of the air content, when the air content is high, the effect of the entrained air improves the freshness properties. In addition, an increase in the air content causes no segregation in this range of the air content.

6.2 Mechanical Properties

Active studies have been done on the air void structures and mechanical properties of concrete, as well as on the securing of the freezing resistance, and the correlativity between the air content and strength of air-entrained concrete has been shown. Studies have been done also on the air content and strength properties of high-fluidity concrete and high-strength concrete, and the examinations have been performed on the rate of the decrease in the compressive strength due to the increase in the air content of concrete in the fresh state, and on the effects of changes in the air content on the strength value, per 1% increase/decrease of the air content, based on the experiments using the types of binders, the strength for proportioning and the air content as parameters. With regard to the relation between the total amount of voids and the concrete strength, it is believed that the strength of the concrete with a large pore volume is low, and that under the same total pore volume, the higher the ratio of pores with large diameters is, the lower the strength of concrete is. There is a linear relation between the natural logarithm of the compressive strength and the effective total pore amount, and the effective total pore amount has been proved to work as an effective performance index also for concrete with different curing conditions and/or different aggregate types.

There are some studies which dealt with the strength and air content of the concrete with artificial lightweight aggregates with high percentage absorption and the fiber reinforced cementitious composites (FRCC). Studies on concrete with special materials are expected to increase in the future.

6.3 Freezing Resistance

(1) Internal Damage

To protect hardened cement paste from damage caused by freezing, proper air voids must be secured. According to the theoretical equations and models explaining the basic mechanism of freezing damage, even if the air content is the same, the smaller the sizes of the individual air voids are and the shorter the distances between air voids are, the more the pressure decreases and absorption of the unfrozen water works, leading to stronger freeze-thaw resistance. This means that the distance between air voids is more important than the air content in hardened paste. The spacing factor, which indicates the average distance between air voids, is often used as an index of this distance. To secure the freeze-thaw resistance of concrete, the concrete must be air-entrained one where microscopic closed air voids have been entrained.

It is widely accepted empirically that the air content of about 4 to 5% or more is required to secure the durability of no less than 60 at 300 freeze-thaw cycles in freezing and thawing tests (underwater freezing and underwater thawing) as prescribed in standards like JIS A 1148. Also, when performing freezing and thawing tests prescribed in standards like JIS A 1148, the spacing factor of no more than about 250 μm is normally required to secure the freeze-thaw resistance after the completion of 300 freeze-thaw cycles. In general, the spacing factor of the air-entrained concrete with about 5% air entrainment is around 200 μm, and Powers specifies that the spacing factor of concrete that is considered to be freeze-thaw resistant is around 250 µm.

Internal damage caused by the freeze-thaw effects differs depending not only on the air void properties inside the hardened paste but also on the external environmental factors such as the freezing velocity and lowest temperature, and the effects of these various kinds of factors are very complicated. The moisture state in concrete is also one of the major factors of causing freezing damage. One of the methods of performing evaluation based on the moisture state (degree of water saturation) is the critical degree of saturation method. This method calculates the critical degree of saturation (Scr), which is defined as the minimum degree of water saturation where the internal damage caused by the freeze-thaw effects can be narrowly detected; then, obtains another degree of saturation (Scap) by performing a water absorption test separately; and finally, compares these two degrees of saturation to evaluate the freeze-thaw resistance. The difference between them not greater than 0 indicates that the concrete will suffer freezing damage. The generally accepted critical degree of saturation is around 80% to 90%, and the degree of saturation higher than this range is believed to cause a significant reduction in freeze-thaw resistance. Such a high degree of saturation is considered to fill 50% or more of air voids with water. Based on the concept of the spacing factor, it is important to inject not only air voids that are small in size but also those that are not filled with water.

High-strength concrete, which rapidly spread from the 1970s, is basically has a strong freezing resistance with its consolidated cement paste structures, even though the spacing factor can be larger due to the effects of the admixtures including high-range water-reducing admixtures and silica fumes. However, it had been pointed out that curing with high initial curing temperatures such as autoclave curing could reduce the freezing resistance. In the 1990s, an increasing number of verifications were performed on high-strength concrete as "high-strength, high-fluidity concrete," together with high-fluidity concrete developed in the late 1980s. The verifications were varied and aimed at evaluating the freezing resistance for the conditions including admixtures, curing methods, and exposure conditions. The findings of these verifications are as follows: in high-strength, high-fluidity concrete, it is important to ensure the air content of no less than 3% and the spacing factor of no more than 200 to 250 µm as the case in normal concrete, to secure the freezing resistance, considering the effects of admixtures and exposure conditions, and the long-term freeze-thaw resistance; and it is also important to grasp and evaluate the minute air void structures and pore structures of 100 µm or less, in addition to the air content and spacing factor, in order to evaluate and make judgments on the freezing resistance.

(2) Surface Damage

Most of the surface damage caused by freezing damage is recognized as scaling, which is characterized by its concentration on structures affected by sea water and/or anti-freezing agents, and recognized as different from internal damage that is evaluated quantitatively as the reduction in the relative dynamic modulus of elasticity. However, a lot of literature dealing with the air content and air void diameter distribution have no discrimination between internal damage and surface damage, or sort them as the same damage. The number of studies focusing on the surface damage is thus limited.

7. Verification Experiments concerning Air Void Structures and Examinations of Actual Structures

7.1. Effect of the Stage of Execution of Work on Air Void Structures

Evaluation WG carried out a real-scale experiment using mass blocks to grasp the effects of the mix proportion and placing/compaction of concrete on the air content of fresh concrete and the air void distribution of hardened concrete.

Two types of mass blocks, each of which was made of either of the two types of ready-mixed concrete (Table-2 and Table-3), were prepared with the dimension of 1 m × 1 m × 1 m. Bars were arranged in the mass block specimens as follows: all of the four faces had the main reinforcement (vertical reinforcement) of D22@150 and the distributing bar (horizontal reinforcement) of D19@150. Two types of vibrators were used for compaction: the high-frequency vibrator (φ 40 mm) for the center; and the convenient vibrator (φ 23 mm) for the cover. The placing was done in two layers (50 cm per layer).

14-day old cores of φ 100 mm were taken from the hardened mass block specimens to measure the air void distribution. As shown in Fig.-2, a core in the horizontal direction was taken at a distance of 250 mm from the base of the block; and the other in the vertical direction was taken at a distance of 250 mm from the side. From the core taken in the horizontal direction, samples were taken at three positions: the position located outside of the reinforcing bar, at a distance of 60 mm from the surface; the position located inside, at a distance of 125 mm from the surface; and the position located in the center of the mass block, at a distance of 500 mm from the surface. In the vertical direction, samples were taken at distances of 60 m, 500 m, and 940 m from the upper surface.

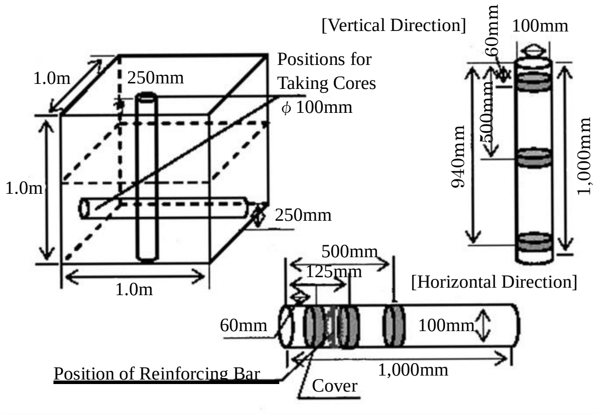

Fig.- 2: Positions for Taking Cores

The report of this experiment includes considerations of the differences in the air content and in the air void distribution, and the changes over time in the air void distribution for fresh concrete with the mix proportion for civil engineering and mix proportion for construction, but this committee report describes the differences in the air void distribution caused by the compacting. Fig.-3 shows the results of the comparison of the air content of hardened concrete of the core taken in the horizontal direction, and Fig.-4 shows the results of the comparison in the vertical direction. In these figures, the air content of hardened concrete is treated as the total air voids; the air voids with diameters of less than 0.30 mm, with the peak air content near the air void diameter of 0.15 mm as entrained air; and the air voids with diameters of 1 mm or more as entrapped air.

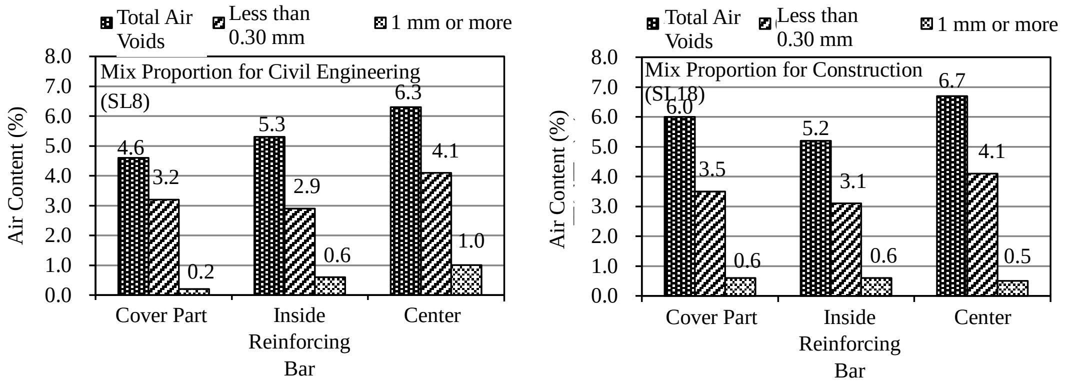

Fig.-3: Comparison of Air Content of Hardened Concrete in the Core Taken in the Horizontal Direction

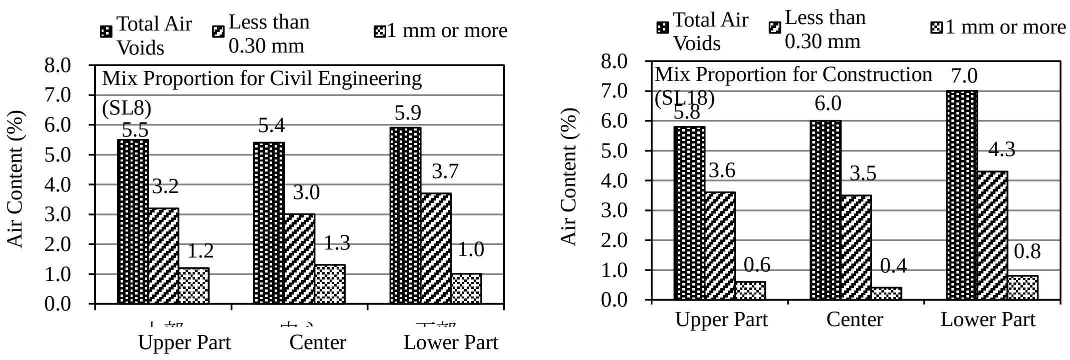

Fig.-4: Comparison of Air Content of Hardened Concrete in the Core Taken in the Vertical Direction

In the core taken in the horizontal direction, the comparison among the center, the inside the reinforcing bar, and the cover shows that the amount of the total air voids tended to be less in the part inside the reinforcing bars and in the cover part compared to the center. In the concrete with the mix proportion for civil engineering, the total air voids in the part inside the reinforcing bars accounted for 5.3%, which was 1.0% less than in the center, 6.3%; and those in the cover part accounted for 4.6%, 1.7% less than in the center. In the concrete with the mix proportion for construction, the total air voids in the part inside the reinforcing bars accounted for 5.2%, 1.5% less than in the center, 6.7%; and those in the cover part accounted for 6.0%, 0.7% less than in the center. This tendency applies also to the air voids with diameters of less than 0.30 mm: in the concrete with the mix proportion for civil engineering, the air voids accounted for 4.1% in the center, 2.9% in the part inside the reinforcing bars, and 3.2% in the cover part. In the concrete with the mix proportion for construction, they accounted for 4.1% in the center, 3.1% in the part inside the reinforcing bars, and 3.5% in the cover part. The results show the decrease of about 1.0% with both mix proportions. On the other hand, the air voids with diameters of 1 mm or more in the concrete with the proportion for civil engineering were 1.0% in the center, 0.6% in the part inside the reinforcing bar, and 0.2% in the cover part, showing significant decreases. However, no significant decrease was found in the concrete with the mix proportion for construction, and the amounts were almost the same at the three positions.

The decrease of air voids in the part inside the reinforcing bars and in the cover part may be due to the effect of the compaction. In the cover part, in addition to the φ 40 mm vibrator, the φ 23 mm vibrator was used for finishing; hence, performing compaction twice is considered to have effects on reducing the air voids. Furthermore, the compaction time with the proportion for civil engineering is eight seconds per position, which is longer than that in the mix proportion for construction, 6 seconds. Thus, the difference in the vibration energy is also considered to have affected the air void distribution. For the air voids with diameters of 1 mm or more, as the viscosity of the concrete with the proportion for civil engineering is higher than that of the concrete with the proportion for construction, the concrete with the proportion for civil engineering enfolds air voids more easily during the placing. Therefore, the compaction is considered to have reduced the enfolded air voids.

In the core taken in the vertical direction, the total air voids tended to decrease from the lower part toward the upper part. In the concrete with the mix proportion for civil engineering, the total air voids in the upper part accounted for 5.5%, which was 0.4% less than that in the lower part, 5.9%. In the concrete with the mix proportion for construction, the total air voids in the upper part accounted for 5.8%, which was 1.2% less than that in the lower part, 7.0%. In addition to the cause of decrease the compaction, breakage of air voids in concrete due to the rise of the bleeding water is considered to affect the air voids. It is considered that the air voids of hardened concrete broke and decreased at the higher position. In the concrete with the mix proportion for construction, the bleeding amount was 0.07 cm^3/cm^2, larger than that of the concrete with the mix proportion for civil engineering, 0.02 cm^3/cm^2. This is considered to have caused a larger difference of 1.2% decrease in the total air voids in the upper part against the lower part with the mix proportion for construction, compared with the difference of 0.4% in the mix proportion for civil engineering.

In conclusion, the air voids in the surface part decrease in the horizontal direction, especially, as a result of the finishing compaction on the cover part. In the vertical direction, the air voids in the upper part tend to decrease possibly due to compaction, as well as the effect of bleeding. The results indicate the need to consider the decrease of the air voids due to the factors including mix proportions and construction methods in the regions that have freezing damage, as air voids with diameters of less than 0.30 mm that are treated as entrained air voids are required to secure the freeze-thaw resistance.

7.2 Examinations of Air Void Structures of Concrete of Actual Structures with Boss Specimens

The air voids in concrete of actual structures are affected by the used materials, manufacturing methods at the ready-mixed concrete plants, transportation and placing in the construction sites, construction conditions such as the compaction, and others. However, there is a lack of necessary cases for the examinations of air void structures of hardened concrete in actual structures. For this reason, the committee installed boss specimens in bridge substructures (footings) to examine the air void structures and freezing resistance of the concrete in the actual structures. The boss specimens were installed in four positions (Construction A through Construction D). All of them are in the construction sites of the Reconstruction Road (Sanriku Coastal Road) located in Iwate Prefecture or Aomori Prefecture. The target of construction work was the footings of the bridge structures.

Table-6 shows the mix proportions of concrete for each construction. Three construction projects used Portland blast-furnace slag cement type B, the other used normal Portland cement. The water-cement ratio of the concrete used in the investigated construction was within the range of 50 to 55%.

Table-6: Mix Proportions of Concrete

Construction Name	Concrete Specification	Target Air Content (%)	Actual Measure-ment Air Content (%)	Quantity of Material per Unit Volume of Concrete (kg/m^3)							
				Water-Cement Ratio	Surfac-tant	C	W	Fine Aggregate		Coarse Aggregate	Chemical Admixture Air-entraining and Water-reducing Admixture
								Land Sand	Crushed Sand		
Construction A	24-12-25BB	4.5 ± 1.5	3.5	54.3	44.8	306	166	-	816	1,018	4.59
Construction B	24-8-20BB	4.5 ± 1.5	3.8	54.0	42.1	285	154	546	233	1,104	3.14
Construction C	24-8-25BB	6.0 ± 1.0	6.0	50.1	42.1	292	146	534	235	1,180	2.92
Construction D	24-8-25N	4.5 ± 1.5	5.0	53.2	44.9	296	157	828	-	1,020	2.96

Table-7 shows the results of the measurements of air void structures, and Fig.-5 illustrated the relation between the spacing factor and the air content of hardened concrete. In the structures with the target air content of 4.5%, there is a significant difference between the air content measured during the stock taking and the air content of hardened concrete. The results for the Construction A show that the air content of hardened concrete was 2% significantly lower than that measured during the stock taking. The figures also indicates that the spacing factor tended to decrease linearly with the decrease in the air content of hardened concrete, showing a good correspondence between them.

Based on these results, by considering the variation in air void structures at each manufacturing plant, the increase of the target air content of concrete in the actual structures can be considered as one of the effective measures to ensure the air content and quality with safety.

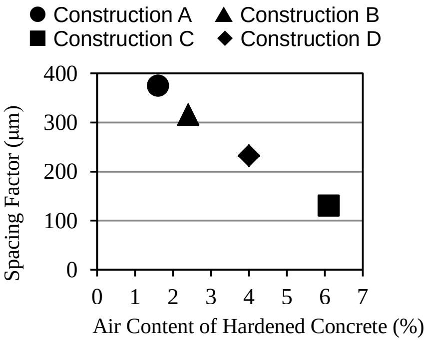

Fig.-5: Spacing Factor and Air Content of Hardened Concrete

Table-7: Results of Measurements of Air Void Structures

Construction Name	Construction A	Construction B	Construction C	Construction D
Number of Air Voids	198	288	1,164	419
Average Air Void Diameter (μm)	284	292	195	272
Actual Measured Air Content (%)	3.5	3.8	6.0	5.0
Air Content of Hardened Concrete (%)	1.6	2.4	6.1	4.0
Spacing Factor (μm)	375	316	131	232

8. Other Technologies for Injection and Control of Air Voids

Other technologies to inject/control air voids in concrete include methods that use preform air entraining agents, fly ash balloons, and hollow microspheres. For Autoclaved Lightweight Aerated Concrete (ALC), a method to generate air voids and inject them using foaming agents has been developed.

Preform air entraining agents are minute air voids generated through processing compressed air voids consisting the main ingredients, ether-type anionic surfactant and air-void film reinforcing agents, in the air-void generating device. The method using fly ash balloons adopts pore spaces of fly ash, which are hollow globules. In the method that uses hollow microspheres, the air voids are injected by hollow microspheres consisting of acrylonitrile-type ingredients. Each method is expected to contribute to the improvement of the freeze-thaw resistance by injecting minute air voids. Further development of researches is expected.

9. Conclusion

This committee report outlines the activities performed by the Air Void Committee for two years. The committee will hold sessions to report its activities at a location in Tokyo on June 29th, 2016, in Sendai on July 22th, and in Sapporo on August 5th. The committee considers that the activities have organized most of the current findings on the roles and effects of air voids in concrete and the technology to control/manage them. It is expected that this committee report will contribute to (i) the promotion of the use of industrial by-products including fly ash, the resistance of which against freezing/thawing caused by air voids needs to be improved, and the use of shrinkage reducing agents; and to (ii) the research/development of new types of concrete (high-strength concrete and secondary products, etc.), for which the air-void control technology is expected to be utilized.

References

1) N. Sakata, T. Sugamata, D. Hayashi and M. Hashimoto : Influence of Air Content on Frost Damage Resistance of Moderate –Heat Portland Cement Concrete with Fly Ash in Setting Process, Concrete Research and Technology, Vol. 22, No.3, pp.47-57, 2011 (in Japanese)
2) N. Sakat, T. Sugamata, D. Hayashi and M. Hashimoto : Investigation for Relationship between Frost Damage Resistance and Air-Void System in Concrete, Concrete Research and Technology, Vol. 23, No.1, pp.35-47, 2012 (in Japanese)
3) H. Kamimoto, K. Ishikawa and Y. Uchida : Freezing and Thawing Resistance of Concrete using a Shrinkage-reducing Admixture, Cement science and concrete technology,, Vol.54, pp.410-417, 2000 (in Japanese)
4) Y. Zhang, T. Fujiwara, T. Oyamada and Y. Zhang : Study of AE Agent to ensure Frost Resistance of Concrete using Shrinkage Reducing Agent , Proceedings of the Japan Concrete Institute, Vol.31, No.1, pp.1111-1116, 2009 (in Japanese)
5) U.H. Jakobsen, C. Pade, N. Thaulow, D. Brown, S. Sahu, O. Magnusson,S. De Buck, G. De Schutter : Automated air void analysis of hardened concrete −a Round Robin study, pp.1444‑1452, Cement and Concrete Research, 36, 2006
6) H. Nishi, S. Hashizume and T. Nawa : Development of Shrinkage Reducing Agent improved Frost Resistance, Proceedings of the Japan Concrete Institute, Vol.32, No.1, pp.143-148, 2010 (in Japanese)
7) N. Sakata, M. Hashimoto, T. Sugamata and H. Ogata：Research on the Frost Damage Resistance of Moderate-Heat Portland Cement Concrete with Fly Ash, Transactions of the Japan Concrete Institute, Vol.35, pp.895-900, 2013 (in Japanese)
8) S. Nakamura, Y. Uchida, Y. Edamatsu and R. Yasumoto : Frost Resistance of High Strength Concrete using Low-heat Portland Cement, Proceedings of the Japan Concrete Institute, Vol.24, No.1, pp.717-722, 2002 (in Japanese)
9) Y. Nakata, S. Otsuka and T. Kemi : Quality of Concrete using Superplasticizer before and after the pumping, Proceedings of the Japan Concrete Institute, Vol.29, No.2, pp.223-228, 2007 (in Japanese)
10) T. Oyamada, A. Wada, T. Fujiwara and J. Zhang : Influence of Entrained Air on Fluidity of High Fluidity Concrete, Cement science and concrete technology, No.54, pp.324-331, 2000 (in Japanese)