Committee Report : JCI- TC083A

Technical Committee on Reduction of Shrinkage Cracks and Durability Enhancement from Viewpoints of Mineral Admixtures

Toyoharu NAWA, Kazuo YAMADA, Tetsushi KANDA, Makoto HISADA, Yoshitaka ISHIKAWA

Abstract

From the viewpoint of reducing environmental load and CO_2 emission, promoting the utilization of admixtures such as limestone fine powder, blast furnace slag fine powder and fly ash is essential. The Committee proposed a test method to quantitatively evaluate the resistance to cracking that is one of the problems that have interrupted the popularity of these admixtures, verified the validity of the method, and conducted a common test on the effect of the admixtures. The Committee also proposed a performance verification standard for blended cement using some kinds of admixtures together. The performance verification is based on the intrinsic performance of the cement, and does not depend on the standards of the individual components. In addition, the relationship between construction conditions and durability, and the present usage situation of blended cement, were summarized based on the literature.

Keywords: Admixture, cracking resistance, durability, performance verification quality standard, construction condition, usage situation

1. Introduction

From the viewpoint of reducing environmental load and CO_2 emission, it is absolutely necessary to accelerate the utilization rate of industrial byproducts such as limestone fine powder, blast-furnace slag fine powder and fly ash those are being in blended cement as admixtures, and to develop low CO_2 emission type new cements. However, does the use of blended cement always result in durable concrete? For some concretes using blended cements, new problems associated with increasing early cracking sensitivity are reported. Further, the interactions between mineral admixtures including expansion agents and between mineral admixtures and organic admixtures are not yet understood completely. In order to develop the new technologies to use widely the admixtures, the Committee examines the cracking resistances of concretes with blended cements and does a systematic review of all the literature about the properties of concrete from the viewpoints of protecting early age cracking and improving durability.

The Committee has established the following four Working Groups and moved the activities forward. The members of each WG are shown in **Table 1**.

The Work Group (WG) of Quality-Performance concerning cracking (WG1) proposed a testing method of cracking resistance, and evaluated the effect of various blended cements on cracking resistance of concrete. The WG Quality-Performance concerning durability (WG2) reviewed the performance required of blended cement and proposed a performance verification quality standard. The Standard-Construction WG (WG3) studied the relation between initial strength decrease due to using the mineral admixture and construction conditions (especially curing). The Utilization WG (WG4) studied the characteristics of mineral admixture focused on shrinkage cracking and neutralization, based on the literature. WG4 also researched construction experiences and development of guidelines, and summarized the present usage situation of the admixtures.

The committee report will consist of four WG reports. The activities of the WGs are as follows.

Table 1: Committee members

Chairman	Toyoharu NAWA	Hokkaido University
Secretary-general	Kazuo YAMADA	Taiheiyo Cement Corporation., WG2 leader
WG1 leader	Tetsushi KANDA	Kajima Corporation
WG3 leader	Makoto HISADA	Tohoku University Graduate School
WG4 leader	Yoshitaka ISHIKAWA	Electric Power Development Co., Ltd
Managers	Yasuhiro DAN	Nippon Steel Corporation
	Nobunori TAKEDA	Obayashi Corporation
Members (WG1)	Masami ISHIKAWA	Tohoku Gakuin University
	Keiichi IMAMOTO	Tokyo University of Science
	Mitsuru TANIMURA	Taiheiyo Cement Corporation
	Shingo ASAMOTO	Saitama University
	Kazumasa INOUE	Takenaka Corporation
	Toshihiro OTANI	Oita University
Members (WG2)	Ippei MARUYAMA	Nagoya University Graduate School
	Kenichiro NAKAI	Gunma University
	Tatsuhiko SAEKI	Niigata University
	Manabu KANEMATSU	Tokyo University of Science
	Yuichiro KAWABATA	Port and Airport Research Institute
	Natsuki YOSHIDA	General Building Research Corporation of Japan
	Shigeru TAKAHASHI	Japan Cement Association
Members (WG3)	Isao KURASHIGE	Central Research Institute of Electric Power Industry

	Hiroshi NONOME	Toda Construction Co., Ltd.
	Hiroshi JINNAI	Taisei Corporation
Members (WG4)	Tatsuya SHIRAI	Taisei Corporation
	Kazuto FUKUDOME	Hazama Corporation
	Akio HIROSHIMA	DC Co. Ltd, replacement
	Nobukazu NITO	DC Co. Ltd, new
	Yuichi OTABE	Sumitomo Osaka Cement Co., Ltd.
	Hideaki NAKAYAMA	Institute of Ube-Mitsubishi Cement Corporation
Communication members	Haruki MOMOSE	Kajima Corporation
	Kenji FUNAMOTO	Kyushu Electric Power Co., Inc.

2. Evaluation of shrinkage cracking of concrete using various admixtures (WG1)

2.1 Test method for evaluation of shrinkage cracking

(1) State of the arts and problems in test method for shrinkage cracking evaluation

Many test methods for evaluating resistance to shrinkage cracking in concrete have been proposed. Among them, JIS A 1151 using outer restraint by steel has been used as the standard test method and contributed to the generalization of shrinkage cracking resistance evaluation. However, a problem is that JIS A 1151 requires special steel form and restraint jigs, and the initial cost and labor for the test are large. As interest in shrinkage cracking control continues to increase, the requirement for a method to evaluate shrinkage cracking resistance quantitatively and relatively easily has been increasing on practical and industrial levels. WG1 studied a test method to meet this requirement.

(2) Improved test method

A test method for autogenous shrinkage stress of concrete[1)] (hereinafter called “autogenous shrinkage stress test method”) was applied to the improved test method. **Figure 1** shows a diagram of a restraint test specimen. Since, in the restraint test specimen, a rebar with large diameter placed in the center of the cross section restrains the contraction of concrete, the history of autogenous shrinkage stress development due to the restraint rebar leading to cracking of the concrete can be measured. By testing a free shrinkage specimen to obtain free shrinkage strain paired with the restraint test specimen, the creep characteristics and the occurrence of cracking can be analyzed.

(3) Validation of improved test method

The validation of the improved test method focused on the following two questions based on the strain behavior measured on the restraint test specimen.

One question is that the autogenous stress test method can be utilized to measure restraint drying shrinkage stress. This arises due to the internal stress distribution in concrete section.

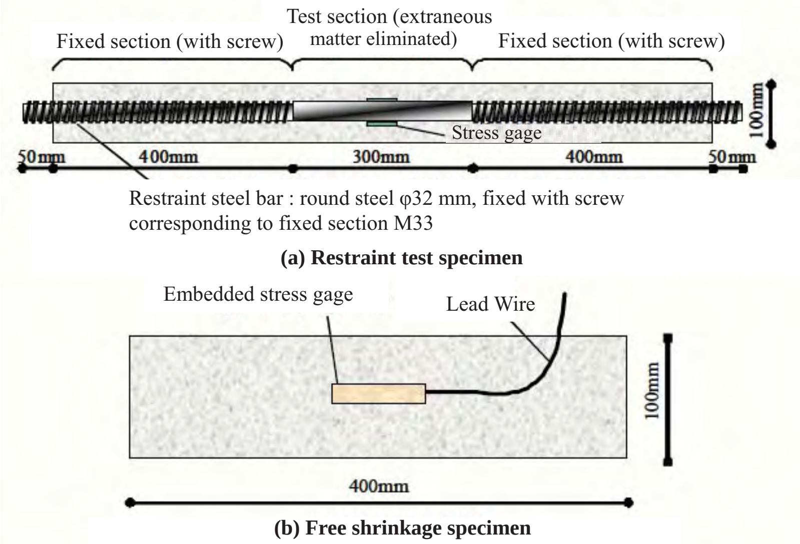

Figure 1: Diagram of shrinkage cracking test specimen
(Cross section of every specimen is 100 × 100 mm)

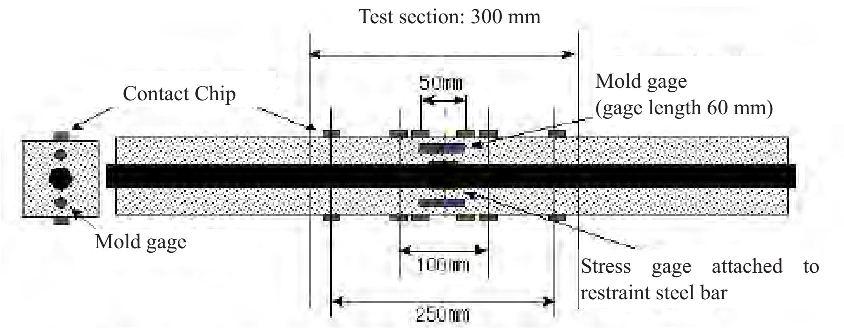

Figure 2: Verification experiment set-up

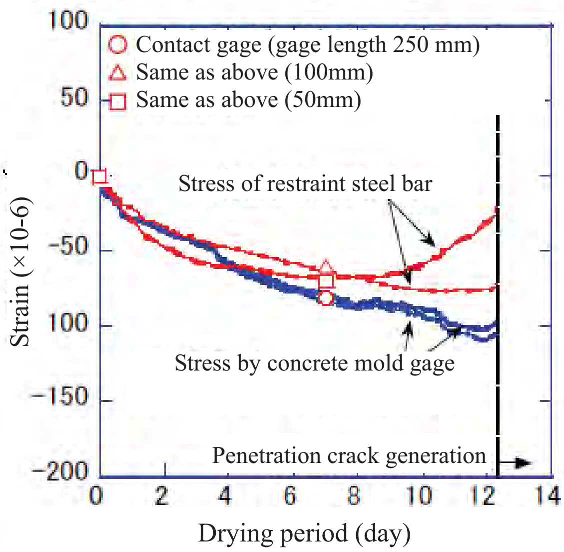

Figure 3: An Example of the result of strain correspondence test

In restraint autogenous shrinkage case, restraint stress appears uniform in concrete section. However, in the case of dry shrinkage, the shrinkage stress must be distributed in the cross section. Due to this stress distribution, the compatibility of average strains between rebar and concrete might not be ensured. Another question is that interfacial stress transfer length in specimen is sufficient or not, because the length of the test specimen was shortened to 1100 mm so as to test easily, 400 mm shorter than the test specimen length specified in the autogenous shrinkage stress test method.

To validate the correspondence of the strain of a restraint steel bar and the stress of concrete mentioned as the first question, an experiment to measure the strain of a mold gage embedded in the concrete and the strain of a contact gage on the surface of the concrete, and compare both strains with the strain of the steel bar, was conducted. A diagram of the test specimen is shown in **Figure 2**. The length of the fixed section and test section of the specimen are the same as shown in **Figure 1**. In the test, the test specimen was sealed by formwork and cured for 7 days of material aging. Then, it was totally exposed to the air under the environmental conditions of 20°C and 60%RH. An example of the test result is shown in **Figure 3**. The figure shows the change with time of the strains in the drying period after 7 days of material aging. The figure indicates that the difference in the strain of the restraint steel bar and that of the concrete mold gage is relatively small except near the 12th day in the drying period when penetration cracking was caused. It is possible that the concrete strain is localized by surface cracking and that of the steel bar is alleviated with decrease of concrete rigidity near the material age when penetration cracking is caused. In **Figure 3**, the strain measured by the contact gage roughly corresponds with the strain of the steel bar and that measured by the concrete mold gage at the 7th day in the drying period. Based on this result, we evaluate that the strain of the restraint steel bar and that of the concrete correspond in the test section.

The same test was conducted to measure the influence of the interfacial stress transfer section length of the test specimen. In this test, the test specimen shown in **Figure 2** and test specimens with the same test section, and 600 and 200 mm of the interfacial stress transfer sections, were used. The interfacial stress transfer section of 600 mm is the same as that of the autogenous shrinkage stress test method. The test showed that the influence of the interfacial stress transfer section in this range on the material age when penetration cracking on the shrinkage restraint stress was not significant. Based on this result, the interfacial stress transfer section of test specimen was conservatively set at 400 mm.

2.2 Common test to evaluate shrinkage cracking resistance

(1) Outline of common test

The round-robin test to evaluate the influence of admixtures on the shrinkage cracking resistance was conducted according to the improved test method by participating 13 institutes to which the committee members belong. The test parameters and levels are shown in **Table 2**. In the round-robin test, 50% of water-blender ratio, 47% of fine aggregate percentage and 175 kg/m^3 of unit water content were determined by the pre-kneading test as standard mix proportion. These conditions were commonly adopted among the 13 research institutes.

Table 2: Outline of round-robin test

Parameters	Level or range
Sort of admixture	Fly ash, blast-furnace slag, silica fume, and a mixture of these admixtures
Blending ratio of admixture (weight percent in blender)	0 to 62%
Curing period until drying	3, 7 and 14 days
Environmental temperature	10, 20, 30 °C

(2) Result of common test

Figure 4 shows the change with time of the shrinkage restraint stress development in the improved test method. The shrinkage restraint stress was calculated based on the equilibrium between section forces in the rebar and concrete. The figure shows restraint stress profile and cracking age in fly ash A concrete are similar to those in ordinary concrete. However, those in BFS concrete showed slightly faster restraint stress development and shorter cracking age. This result corresponds to the findings obtained from real constructions. From this result, it may be possible to easily determine the shrinkage cracking resistance in case of using various admixtures, and control shrinkage cracking on a practical level.

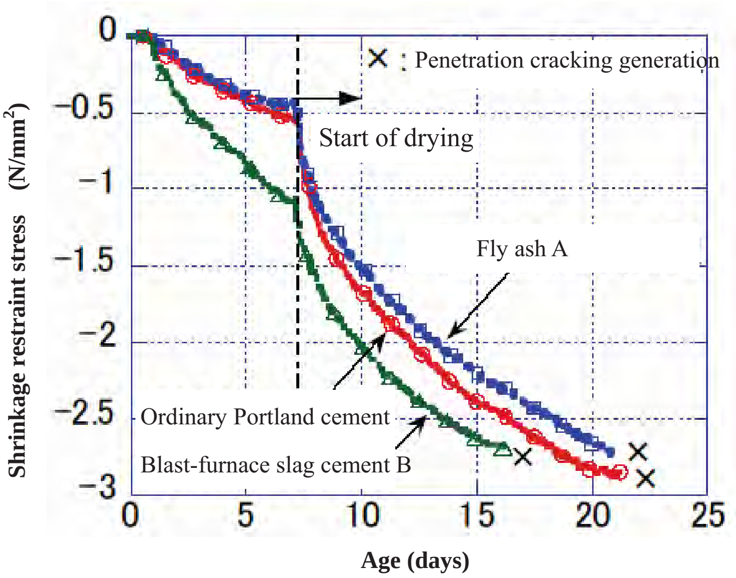

Figure 4: An Example of the test results in improved test method

(3) Expected conclusions from common test

The following conclusions are expected regarding the shrinkage cracking behavior of concrete using various admixtures by the analysis of the round-robin test data under planning.

- Understanding of the factors affecting shrinkage cracking behavior, and the degree of the effect
- Finding out the tensile creep behavior and the conditions under which cracking is generated
- Predicting analysis of cracking behavior occurred in structural member in buildings

3. Performance standard for hydraulic cements covering multi-component blended cement (WG2)

3.1 Need for performance standard for hydraulic cement

For conventional two-component cements in which a mineral admixture is blended with ordinary Portland cement, such as blast-furnace slag cement or fly ash cement, existing standards can be applied. However, there is no domestic standard for multi-component cement using limestone fine powder and other mineral admixtures. Also, it is not realistic to establish a standard for every component because there are too many kinds of admixture.

Additionally, new cements with different components from conventional cements may be developed in the future. Therefore, it is significant to propose a performance standard for hydraulic cement in order to encourage the diversification of cement by reconsidering the essential performance required of cement.

WG2 reported overseas performance standards for hydraulic cement, and the background of the establishment and current usage situation in North America. Further, WG2 proposed an original performance standard for hydraulic cement. The essential performance required of cement is classified into items common to every cement and items required for individual uses, and an evaluation method and classification of these terms are proposed. These proposals cover only items we can think of currently. There may be items we must study more in the future. It is essential to explain the technical background of a proposed standard in detail as much as possible for future study. Therefore, the technical background is described after the proposal of the standard. Lastly, the future view of this subject is summarized.

3.2 Overseas performance standards for hydraulic cement

Regarding overseas performance standards for hydraulic cement, there are similar standards in Australia and New Zealand in addition to ASTMC1157. ASTM C1157 sorts out cements based on performance into general use (GU), high early strength (HE), medium sulfate resistance (MS), high sulfate resistance (HM), moderate-heat (MH) and low-heat (LH), and provides test methods and criterion values to evaluate each performance. For alkali-aggregate reaction resistance cement, R is suggested as an option. Fineness, strength (a different age can be specified depending on use), setting time and stability are common items.

An interview for the Portland Cement Association (PCA) was held to study the background of the standard establishment and its current usage.

The existing blended cement standards only regulate limited kinds of cements and composition ranges, and do not allow optimization or innovation for sustainable development. By moving to the performance standard, users can get the best performance they want without regard to components, and manufacturers can blend any materials to bring out the performance of the cement without unnecessary regulations. In other words, it is possible to use the optimum material available to manufacture the optimum cement.

The U.S. cement industry has proposed ASTM C1157 asking for diversification of cement, but the usage of these new cements is limited to less than 1% of all cements consumption at present. Their use in the architectural field is permitted in many states. However, only limited number of states permits their use in the civil engineering field. Users appear not to want any risks of the new cements.

Table 3: Contents of performance standard for hydraulic cement (proposal)

1. Scope
2. Classification and usage
3. Description of each class
3.1 Common performance
3.1.1 Terminology and definitions
3.1.2 Test methods
3.1.3 Description of common performance
3.2 Performance classification
3.2.1 General-purpose
3.2.2 High early strength
3.2.3 Sulfate resistance
3.2.4 Acid resistance
3.2.5 Shrinkage cracking resistance
3.2.6 Thermal cracking resistance
3.2.7 Chloride ion resistance
3.2.8 Permeability resistance
3.3 Additional performance
3.3.1 Neutralization resistance
3.3.2 Alkali-aggregate reaction resistance
4. Method of cement designation
4.1 Classification of cement
4.2 Cement strength
4.3 Designation of additional performance
5. Chemical composition*)
6. Physical characteristics**)
7. Test methods***)
Appendix: Performance evaluation method
(1) Accelerating neutralization test
(2) Alkali-aggregate reaction resistance test
(3) Sulfate resistance test
(4) Acid resistance test
(5) Adiabatic temperature rise test by mortar
(6) Chloride ion penetration resistance test

*) This item is not established in this standard.
**) Fineness, stability, false setting, setting time, classified performance, additional performance, and performance level are presented in a table.
***) The existing standards are cited and the new standards are contained in the Appendix.

3.3 Proposal of Japanese performance standard for hydraulic cement

WG2 proposed a draft version of a performance standard to encourage discussion in the future. **Table 3** shows the details of the performance standard for hydraulic cement (proposal). The Committee reported the draft standard as follows.

1. Scope: shows what the standard aims to do.

2. Classification and usage: defines sorting out the common performances of cements, the performances required for each particular usage, and the optional performances for each cement type.

3. Description of each class: describes the common, specific, and optional performances.

3.1 Common performance: is the performance each cement has to have such as strength, setting time and so on. Test method and sampling are also explained.

3.2 Performance classification: is the main part of this performance standard. Cement is classified into seven categories.

General-purpose: Minimum necessary items are established for general-purpose products. Other categories are high early strength, sulfate resistance, acid resistance, drying cracking resistance, thermal cracking resistance, chloride ion transport resistance, and permeability resistance. Sulfate resistance is assuming physical sulfate deterioration by re-crystallization of hydrous alkali sulfate minerals and the resistance against chemical erosion by forming ettringite by external sulfate. Sulfuric acid resistance may be confused with sulfate resistance. In this category, application to sewage facilities is considered. Cracking resistance (thermal, shrinkage) is the major concern of the Committee. Since cracking by heat and shrinkage is affected by the sort of cement, it is discussed to propose to evaluate the drying/atotogeneous shrinkage cracking resistance and heat evolution of cement. However, because cracking resistance is considered to be affected by many factors other than cement, no standard was proposed in this version. For the evaluation of heat evolution, instead of traditional hydration heat measurement, which has been criticized not representing temperature rise in real structures, adiabatic temperature rise test using mortar is adopted. The chloride ion resistance of concrete is significantly affected by the concrete composition and also the type of cement. Therefore, a method of evaluating the basic chloride ion resistance of cement is proposed. Permeability is not an object of this study, but the item is merely proposed as an important indicator of performance. Many of relevant standard test methods to evaluate each category have not established. The performance standard is one set with the test method standard. The proposal of some cement performance standards are accompanied by some corresponding proposals of the test method standards.

3.3 Additional performance: specifies additional performances that are required for each category depending on the environments and materials used. Neutralization resistance and alkali-aggregate reaction resistance are specified.

Neutralization resistance: Since the new cements will be used mainly for reinforced concrete, a performance evaluation method under the most severe environmental conditions is proposed.

Alkali-aggregate reaction resistance (ASR): ASR expansion must be avoided from all concretes. It is difficult to obtain a completely innocuous aggregate. However, a substantial degree of ASR depression effect can be obtained by specific kind of cement. Test method using Pyrex glass and criteria are proposed.

4. Method of cement designation: explains that when cement user purchase cement, how to designate cement.

5. Chemical composition: is not the fundamental requirement in performance standard. This standard opens to use variety of materials. Simultaneously, however, in order to get reliability of users, it is preferable to disclose the chemical composition and its basic constituents.

6. Physical properties: specify generally required properties for cement such as fineness, stability, false setting, setting time, classified performance, additional performance, and performance level.
7. Test methods: specify required test methods newly introduced in this proposal in order to evaluate various performances of cement such as neutralization, ASR resistance, sulfate resistance, acid resistance, adiabatic temperature rise of mortar, and chloride ion penetration resistance.

3.4 Technical background of performance standard (proposal)

If the background of the performance standard is not well understood, it is very difficult to evaluate its validity. Therefore, the technical backgrounds of this proposal are described in details. To bring out the basic performance of cement in concrete, a mixture proportion designing of concrete is essential. The requirements for such a design are also described.

(1) Neutralization

The difference of neutralization by the accelerated carbonation test between blended cement and ordinary Portland cement is said to be much larger than that experienced in real structures. An accelerated carbonation mortar test is proposed as a cement evaluation test because extreme usage conditions should be supposed to evaluate the potential performance of cement. Class was determined based on the performance of cements corresponding to Portland cement, blast furnace blended cement type B (30-60% replacement) and type C (60-70%). If the difference of environments is considered, it should not be considered in basic performance tests of materials but should be considered as an environmental force for deterioration.

(2) ASR resistance cement

Since it is difficult to prepare aggregate with the same reactivity, Pyrex glass is selected as the standard aggregate. The index is the expansion rate at the 14th day of material age in the mortar bar test using cement with 1.0% of equivalent alkaline quantity and specimens are kept at 40°C and saturated wet condition similar to the condition of JIS A1146 “ Mortar bar method.” Cement with 0.10% or less of expansion rate is classified as option R (ASR resistance), and 0.05% or less is classified as option HR (high ASR resistance). R can be applied for usage of conventional blended cement like blast-furnace slag cement type B. HR can be used to suppress severe pessimum effects with highly reactive minerals and supply of condensed alkaline solution like antifreezing agent, for which R cannot be used.

(3) High early strength

Strength development is an importance character of cement. However, there are strong requirement for high early strength in some works. Therefore, high early strength is defined as one performance in this standard. Including traditional high early strength portland cement, more rapid hardening type cements are intended to include.

(4) Sulfate resistance and acid resistance

At first, the difference between sulfate resistance and acid resistance should be recognized.

The main mechanisms of deterioration by sulfate ions are chemical deterioration and physical deterioration. A dipping test using sulfate solution is applied to evaluate the former deterioration, and a partial dipping test is applied to the latter deterioration. In chemical deterioration, Na_2SO_4 and $MgSO_4$ give different mechanisms. Thaumasite deterioration occurs only at low temperature, and ordinary sulfate deterioration is also accelerated at low temperature. Therefore, in the dipping test, the kind of dipping solution and temperature suited to each purpose should be selected. Corresponding to the deterioration mechanism, as the evaluation criterion, length change (case of expansion by ettringite formation) or external observation (case of transformation from C-S-H) should be selected. The indices in the partial dipping test are external observation and mass change.

Information about the correlation between the result of the above test and the real deterioration situation is lacking, and it is difficult to show the absolute value to evaluate the performance at present. Thus, only an indication is proposed.

As to the acid resistance test, it is possible to present only questions because there are difficult problems regarding the type of solution and its circulation.

(5) Thermal cracking resistance

Cracking is caused by the combination of temperature stress and restraint stress by the change of cement paste length. The effect of temperature stress is evaluated based on the measured data of a mortar using an adiabatic calorimeter in the three temperature ranges of low, ordinary and high. The effects of temperature and restraint stress are tried to evaluate based on the restraint test result of a mortar under pseudo adiabatic conditions, and the evaluation results are classified into three stages depending on generated stress and whether cracking is caused. However, this kind of cracks are significantly affected by concrete mixture proportion and the range of the effect of cement is not clear. Therefore, instead of cracking test, only adiabatic temperature rise test using mortar is adopted. Traditional hydration heat cannot be representative for slag blended cement and this new approach is proposed in WG2.

(6) Chloride ion transport resistance

Chloride ion transport resistance is evaluated based on the apparent diffusion coefficient obtained from the immersion test of a mortar. The evaluation results are classified into three classes corresponding normal portland cement, blended cement types B and C.

4. Existing findings and future issues on influence of construction and curing on performance of concrete using admixtures (WG3)

4.1 Outline

It has been pointed out that a concrete structure is not maintenance-free and conversely, early deterioration can be caused. Therefore, to acquire sufficient durability during its design lifetime has become very essential as the required performance of a concrete structure. While emphasizing the importance of durability, a discussion of "curing", which is the most basic actions in the process of concrete structures, is very important. WG3 summarized the existing findings and future issues on the important points in considering how curing should be done in a construction using cement containing admixture.

4.2 Performance of concrete using admixture

(1) Pore structure

Figure 5 shows the effects of curing conditions on the pore structure of hardened concrete using three kinds of binders, ordinary Portland cement (OPC), fly ash (FA) and blast furnace slag (S1) [2]. In the experiment, the pore distributions were measured at 180 days. The combination of atmospheric curing (20°C, 60%RH, symbol A in figure) and water curing (20°C, symbol W in figure) during a total curing period of 180 days was used as a parameter. According to **Figure 5**, in any concrete, the volume of pores with larger diameter increases with a shorter underwater curing period during the initial stage of material age. If some ordinary Portland cement is replaced by fly ash or blast furnace slag, the effect of initial curing on increase of pore volume becomes significant. These results indicate that the importance of initial curing is higher for concrete using admixture.

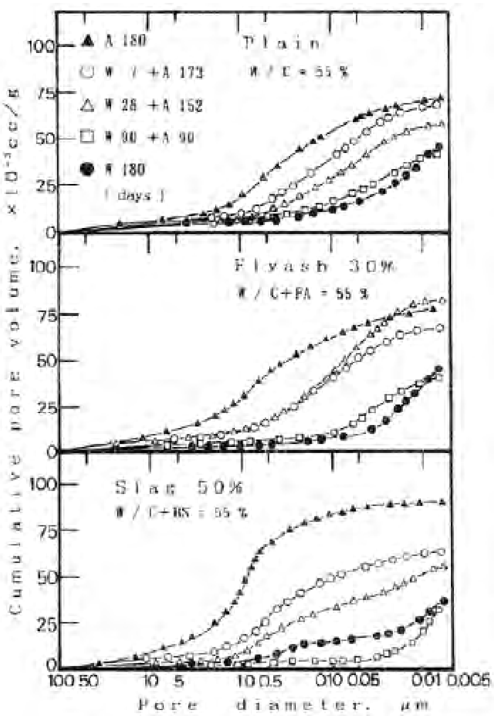

Figure 5: Effect of underwater curing period on pore structure of concrete [2]

(2) Compressive strength

Koh and Kasami, et al [3)] examined the effect of the demolding time of a test specimen cast with cement at 55% of water-cement ratio, using four kinds of binder, ordinary Portland cement, low-heat Portland cement, fly ash cement B and blast furnace slag cement type B. The demolding time was changed from the 2nd day to the 28th day of material age. The demolded test specimen is described as being stored in a constant temperature and moist room, but the humidity condition is not described. **Figure 6** [3)] shows the relation between the demolding time and the ratio of the strength to the compressive strength of the specimen at the 28th day of material age, cured in water at 20°C. The strengths of test specimens demolded from the 2nd to 28th day of material age were divided between the strengths of specimens demolded on the next day and stored in a constant temperature and humidity room, and those of specimens cured in water at 20°C for the entire period. The distribution range of the strength ratio of concrete using fly ash cement type B or blast furnace slag cement type B is wider than that using ordinary Portland

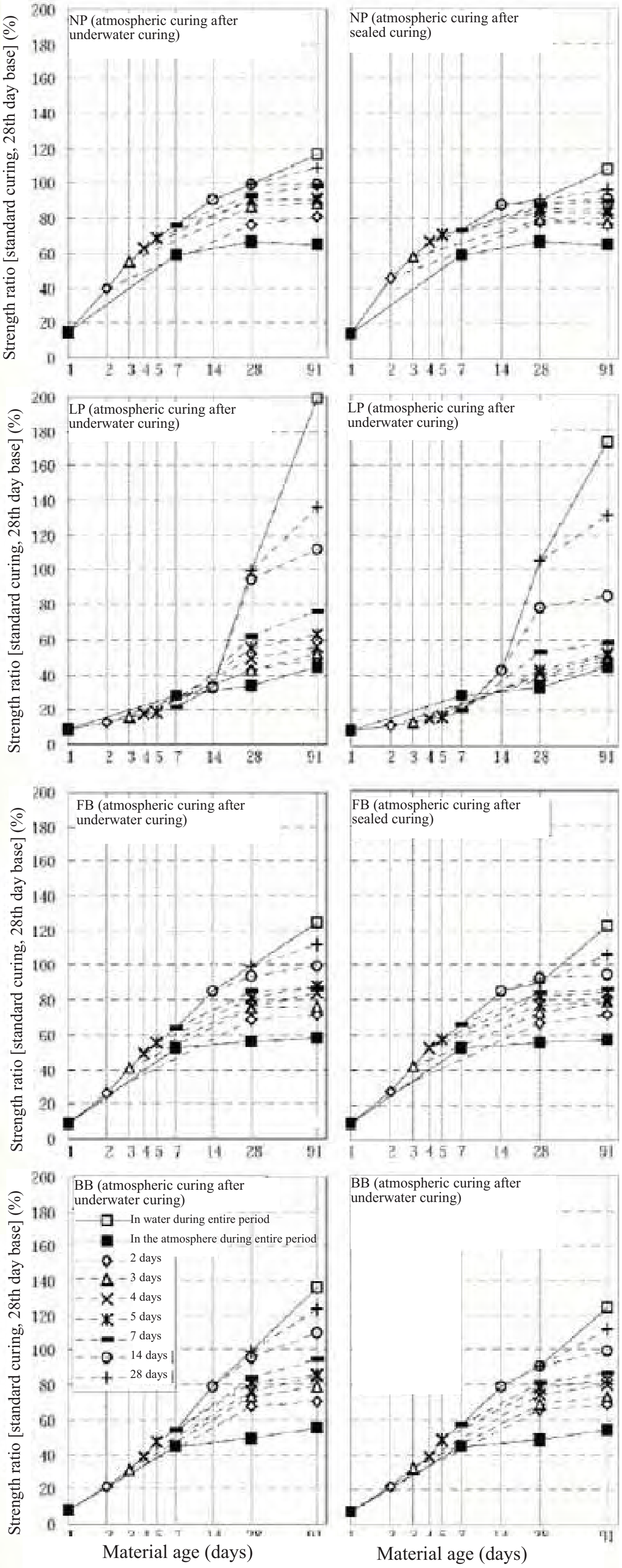

Figure 6: Effect of demolding time of test specimen on compressive strength [3)]

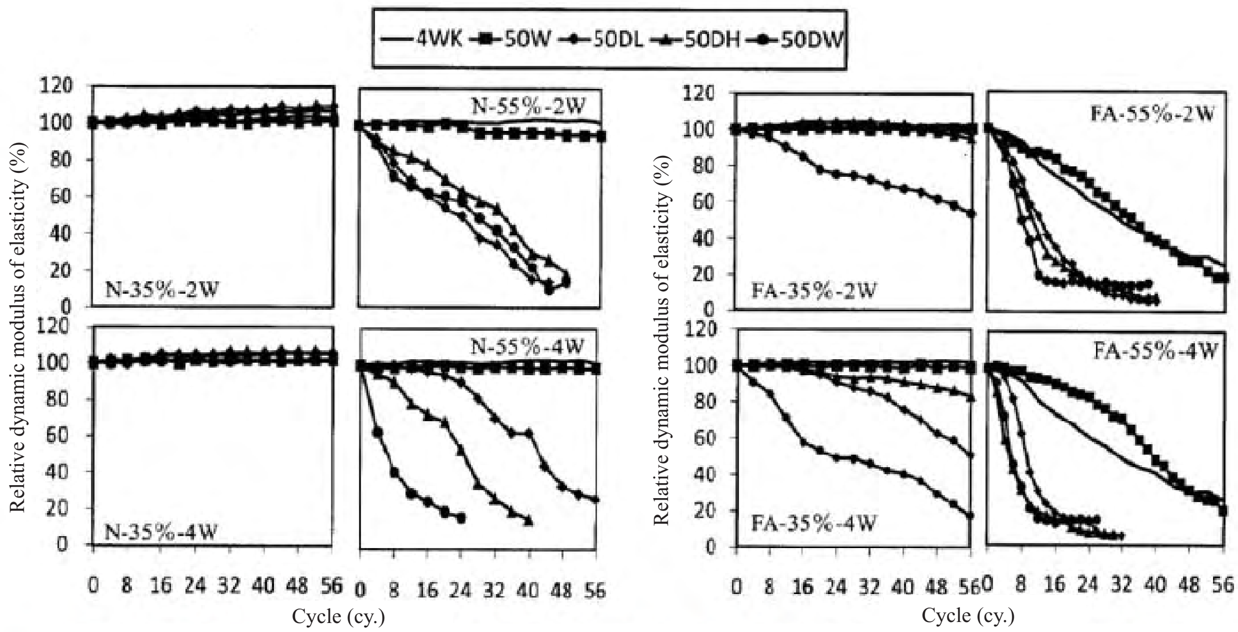

Figure 7: Relation of curing condition after 28 days of underwater curing and freezing, and thawing resistance (left: OPC, right: OPC/FA=85/15) [4)]

cement, and narrower than that using low temperature cement. Therefore, it is thought that initial wet curing is more significant for concrete using fly ash cement type B and blast furnace slag cement type B than that using ordinary Portland cement.

(3) Freezing and thawing resistance

Using 2 kinds of binders, 100% ordinary Portland cement and a blended cement of ordinary Portland cement: fly ash cement = 85: 15, Ueda and Hama, et al [4) 5)] made many mortar test specimens (40 x 40 x 160 mm) with a 35% and 55% water-binder ratio, cured them in water at 20°C for 28 days of material age, and examined the effect of curing conditions after 28 days of underwater curing on the freezing and thawing resistance. **Figure 7** shows the relation of curing conditions after 28 days of underwater curing to the freezing and thawing resistance shown in the reference paper 4. There were four curing conditions after 28 days of underwater curing, i.e., in water at 50°C (symbol 50W in figure), a temperature of 50°C and humidity of 60% (50DH in figure), and a temperature of 50°C and alternating dry and wet (3 days in an atmosphere at a temperature of 50°C and a humidity of 60%, with 0.5 days in water at a temperature of 50°C, 50DW in figure). The test material ages were 2 weeks and 4 weeks after the start of curing following 28 days of pre-curing.

Figure 7 shows that with a 35% water-binder ratio, the freezing and thawing resistance of the mortal using 100% ordinary Portland cement is not affected by underwater curing for 28 days. However, the freezing and thawing resistance of the mortal with a 35% water-binder ratio using fly ash cement is decreased by drying after 28 days of underwater curing, and in the case of a 55% water-binder ratio, the trend becomes more significant.

Table 4: Blending conditions[6)]

	Blending symbol	W/C (%)	W/B (%)	S/a (%)	Bulk volume of coarse aggregate (m³/m³)	Unit quantity, kg/m³				
						W	C	Fa	S	G
Series I	P65	65	65	47.7	0.59	170	263	0	868	973
	F55-65		55	46.2			263	46	816	973
	F45-65		45	43.6			261	117	736	973
	P55	55	55	46.6			309	0	829	973
	F45-55		45	44.1			310	68	751	973
	P45	45	45	44.8			378	0	772	973
Series II	P40	40	40	43.6	0.59		425	0	736	973
	F30-40		30	40.9	0.52		425	142	624	922
	P30	30	30	42.6	0.52		567	0	668	922

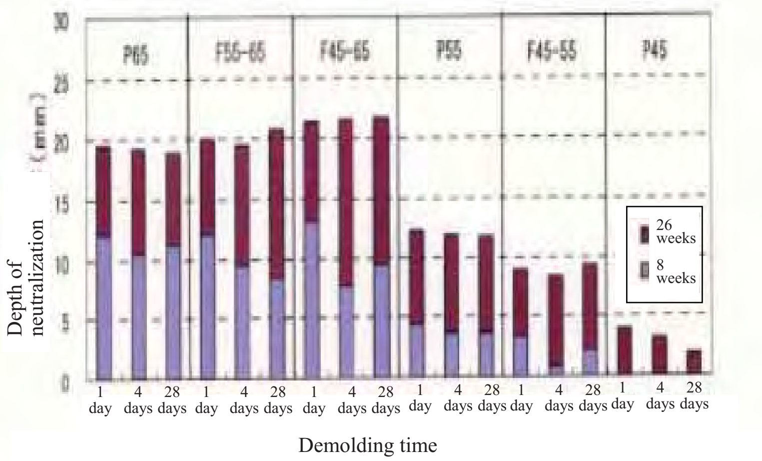

Figure 8: Relation of demolding time and depth of neutralization [6)]

(4) Neutralization resistance, water content, air permeability

Ishikawa et al [6)] made 600 x 600 x 250 mm concrete wall test specimens, and measured properties at 1, 4 and 8 days of demolded time. **Table 4** shows the blending conditions of these test specimens.

Figure 8 shows the result of an acceleration neutralization test (at a temperature of 20°C, humidity of 60% and a CO_2 concentration of 5%) on ϕ150 mm x 250 mm core specimens obtained from wall specimens at 91 days and coated on the side surfaces[6)]. The specimens were measured at 8 and 26 weeks of the accelerating period, and the depth of neutralization was measured on a split-core specimen for each material age. **Figure 8** shows that the neutralization depth at 8 weeks, which means that specimens have a tendency to increase with brevity of demolding time, but that specimen at 26 weeks does not change with demolding time.

Figure 9 [6)] shows the water content with depth after drying at 105°C on ϕ150 mm x 250 mm of core specimens, it is obtained that wall specimens at 91 days. **Figure 10** [6)] shows the air permeability. Despite the variation of data, these figures show that, with brevity of demolding time, the water content until 91 days has a tendency to decrease and the air permeability has a tendency to increase. From these results, early demolding seems not to have a good effect on neutralization resistance.

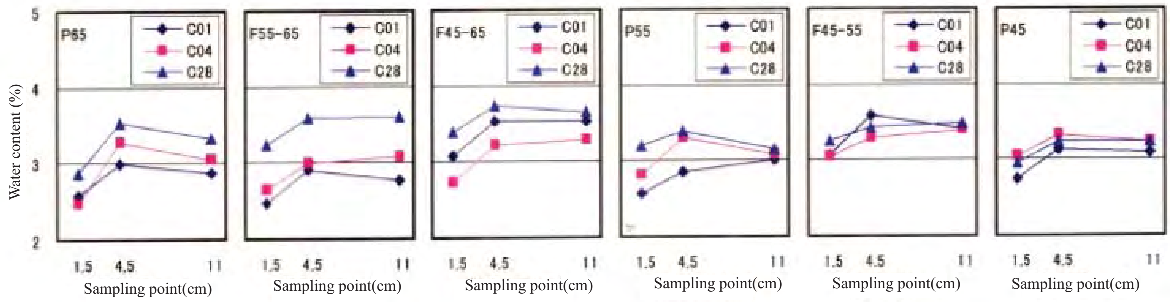

Figure 9: Relation of demolding time and water content [6)]

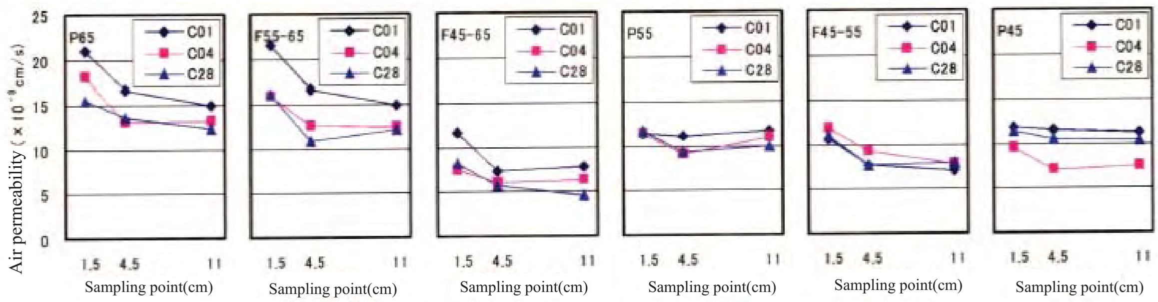

Figure 10: Relation of demolding time and air permeability[6)]

4.3 Questions on construction of concrete using admixture

(1) Relation of concrete performance and construction-curing

WG3 has studied the evaluation of performance of concrete using admixture focusing mainly on curing in concrete structure construction work. WG's debates resulted in the following discussions.

It is obvious that if curing is appropriate, the concrete using admixture delivers higher performance than the concrete using ordinary Portland cement. However, if the necessary curing is not done appropriately, the concrete using admixture cannot deliver its performance successfully, and in some cases, brings out lower performance than concrete using ordinary Portland cement.

Considering progress with the time of hydration reaction of cement, it is thought to be valid that the performance of complex materials, i.e., so-called hardened cement paste, changes with time. Therefore, it is expected that although curing is insufficient in the initial stage of construction, the performance not obtained in the early stage is complemented by the progress of the hydration reaction in the service period.

However, according to existing cases of study reports, these complements cannot be expected to extend to pore structure, compressive strength and properties regarding durability. Particularly, it is obvious that the lack of early curing dominantly affects durability like an after-effect.

From the above discussion, it is concluded that concrete using admixture requires more careful curing conditions and more precise construction methods than concrete using only ordinary Portland cement.

(2) Evaluation method

According to many existing study reports about properties of cement using admixture, concepts that have been recognized generally as implicit knowledge - i.e., if strength is acquired, durability is also necessarily acquired - is not applicable to cement using admixture. Therefore, as to the evaluation of concrete performance, it is essential to adopt not only conventional control and evaluation methods using strength such as demolding strength and design basis strength, but also evaluation methods using durability, for the construction work.

For example, the surface of concrete (covering) that is important to protect reinforcing steel from extraneous deterioration factors demands durability rather than strength. On the other hand, the reinforcing steel demands strength to ensure physical performance. As discussed previously, each part of a concrete structure requires different performance. Therefore, it is desired to build an evaluation system for each part of concrete.

Unfortunately, there is no evaluation system at present that can surely respond to such a proposal. However, in recent years, findings about evaluation methods for durability of concrete surface such as the Trent method and a method using the electrical properties of concrete have been proposed. An evaluation system centered on such methods is expected to be established.

5. Current situation of study on properties of concrete using mineral admixture, its construction experience, and its guidelines and specifications (WG4)

5.1 Outline of activity

WG4 selected blast furnace slag, fly ash, silica fume and their complex as mineral admixtures, and reviewed current studies on the performance, centered shrinkage property and carbonation property, of concrete using those mineral admixtures. WG4 also collected many experiences of construction using the mineral admixtures, and researched ways of handling them in guidelines and various specifications. Finally, a view toward future use of the mineral admixtures was proposed.

5.2 Research of performance of concrete using mineral admixtures

(1) Required performance of intended concrete and research coverage

There are many performance parameters required of concrete. The main problems of concrete using mineral admixture are drying shrinkage and carbonation. It has been pointed out that the amount of shrinkage of concrete using blast furnace slag has become larger because recently, the fineness of slag fine powder has increased. It is generally recognized that the carbonation rate of concrete using slag is higher than that of concrete using ordinary Portland cement. Meanwhile, it is said that the concrete using fly ash has the effect of inhibiting cracking because both its unit water content and drying shrinkage are reduced. However, the carbonation rate of concrete using fly ash is generally recognized to be higher than that of concrete using ordinary Portland cement. Silica fume is used in high strength concrete with low water-binder ratio to improve fluidity and strength in Japan. It has been pointed out that self-shrinkage increase in concrete using silica fume.

The items to study regarding the performance required of concrete using mineral admixture focused on the shrinkage property and the carbonation property for concrete using blast furnace slag or fly ash, and the shrinkage property only for concrete using silica fume. For concrete using a complex mineral admixture, all the required performance parameters are considered as items for study.

In the literature survey, WG4 studied all the research papers which were published in Japan Society of Civil Engineers, Architectural Institute of Japan, and Japan Concrete Institute, during about 15 years from 1993 to 2008. As to the shrinkage of the concrete using blast furnace slag and fly ash, research paper containing 26 weeks of data for the drying shrinkage concrete test were basically reviewed to compare with the same material age data. WG4 tried to build a database comprising the drying shrinkage test results, mix proportion conditions and aggregate conditions in a unified manner.

(2) Summary of literature research

1) Shrinkage property

There were few studies that measured the shrinkage quantity of concrete using mineral admixture, and even fewer studies that measured the drying shrinkage and autogenous shrinkage simultaneously.

i) Blast furnace slag

The drying shrinkage amount of concrete using blast furnace slag is nearly equal that of concrete using ordinary Portland cement. However, the drying shrinkage amount is affected by curing period, and decreases after a long curing period. It is also reported that autogenous shrinkage increases as the water-binder ratio becomes lower and the fineness becomes higher.

ii) Fly ash

The method of deciding blending conditions for concrete using fly ash was studied in two cases, the constant unit water content case and the constant slump (flow) case. At unit water content case, as **Figure 11**[7] shows, many reports indicate that the drying shrinkage of the concrete using fly ash does not change with the blending rate of fly ash. However, according to a few reports, it decreases with blending rate of fly ash. Meanwhile, at constant slump (flow) case, the drying shrinkage tends to decrease with blending rate of fly ash because it is expected that the reduction of unit water content arose from the fly ash. However, data for drying shrinkage is lacking to quantitatively estimate the drying shrinkage rate with blending rate, and there are few measured data for autogenous shrinkage. Therefore, it is desired to collect data for shrinkage amount.

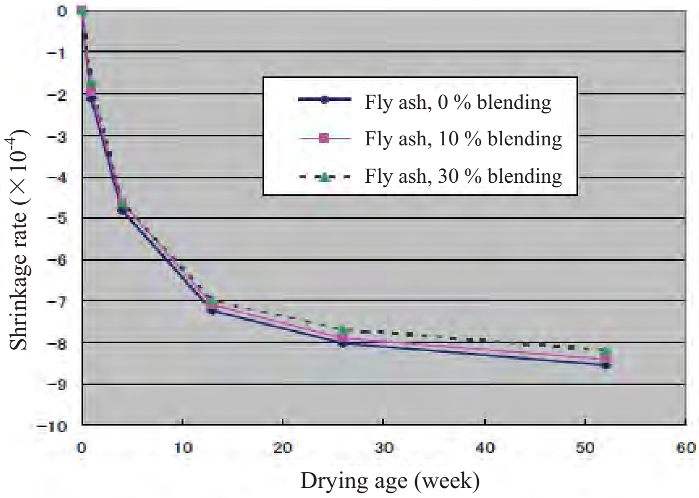

Figure 11: Drying shrinkage test result (at constant unit water content) [7]

iii) Silica fume

In concrete blending silica fume, water is used for the hydration reaction and pozzolanic reaction, but because the framework of hardened cement paste becomes dense, water movement does not occur easily. Since without water moving, autogenous drying arises in the hardened cement paste and autogenous shrinkage occurs easily, many studies report that autogenous shrinkage increases by blending of silica fume. It is also reported that the quality of silica fume affects autogenous shrinkage.

iv) Complex mineral admixture

A test result reported that by replacing 20 % of blast furnace slag cement B with fly ash, the drying shrinkage of concrete of 13 weeks material age is drastically reduced to about 50 % of that in the case of using 100 % blast furnace slag cement B. It has also been verified that replacing by fly ash improves the cracking resistance. However, since the unit water content and the water-binder ratio in the test are different between the concrete using blast furnace slag cement B and that using fly ash blended with blast furnace slag cement B, the above reduction of shrinkage and improvement of cracking resistance cannot be determined categorically to be the effect of fly ash.

In fact, a test result also reported that under conditions of the same unit water content and unit binder content, the shrinkage reduction by replacing blast furnace slag cement with fly ash is only about 10 %. At any rate, it is important to increase test data for complex mineral admixtures, validate the effect on shrinkage reduction, and seek the possibility of using complex mineral admixtures in the future.

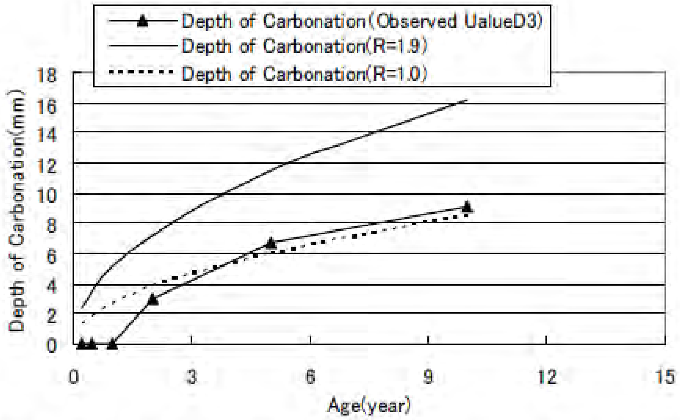

Figure 12: Neutralization of exposed test specimen (way of Kishitani 1: R=1.9 (FA), R=1.0 (OPC))[8)]

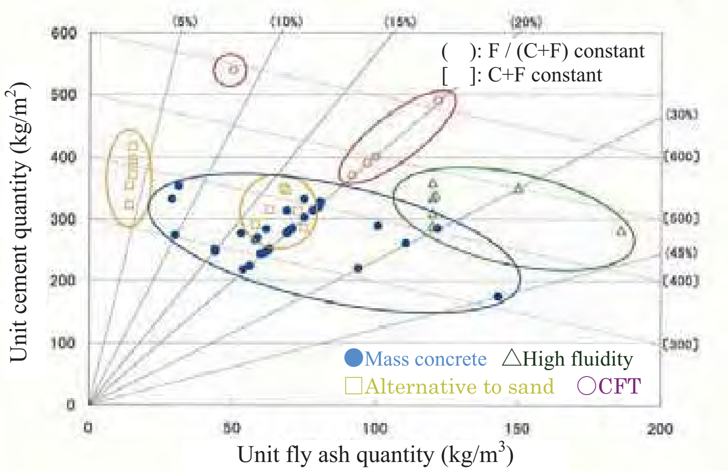

Figure 13: Relation between unit fly ash quantity and construction field

2) Carbonation property

It was intended to study the carbonation of specimens obtained from the outdoor exposure test body, and to study real structures. It was not intended to study carbonation by the accelerating test. The reason is that the carbonation rate by the accelerating test of concrete using mineral admixtures such as fly ash in particular is overrated more than that of real structures because the strength of concrete using mineral admixtures develops late, and the concrete is exposed under the severe condition of the accelerating test before the framework of concrete becomes dense.

Examples of measured carbonation data for specimens taken from outdoor exposure test bodies using mineral admixtures or real structures are scarce, although WG4 possibly collected data without defining the period subject to literature research. **Figure 12** [8)] shows an example of carbonation data for exposure test specimens using fly ash until 10 years of age.

The figure shows that the carbonation rate coefficient of concrete using fly ash is nearly equal to that of the concrete using ordinary Portland cement. It is necessary to collect more examples of long-term measured data, and change the method of evaluating the carbonation property of concrete using mineral admixtures in the future.

5.3 Usage of concrete using mineral admixtures

(1) Acquisition of construction experience and analysis of usage

Domestic construction experiences using mineral admixtures were mainly collected, possibly with mix proportion data.

The trend of blast furnace slag usage could not be determined for certain because the blending rates of fine powder of blast furnace slag were nearly equal. Nevertheless, for fly ash, it was found that construction usage could be roughly sorted out based on the unit quantity of blended fly ash as shown in **Figure 13**. As to complex mineral admixtures, their use for the constructions of Akashi-Kaikyo Bridge, Yokohama Landmark Tower, etc., was studied.

As for overseas examples, focusing on China, data for blending conditions in the constructions of the Shanghai World Financial Center Building and a cement factory in Yandai were collected. It was found that the usage ratio of blended cements is higher overseas than in Japan, and blended cements are generally used.

(2) Establishment of guidelines and specifications for mineral admixtures

The use of mineral admixtures in guidelines and specifications of domestic academies and societies was studied. Many construction specifications in civil engineering specify the use of blast furnace slag, but only a few specifications specify that of fly ash. Few examples in specification of a building specify the positive use of mineral admixtures. The “Housing Quality Assurance Act” specifies fly ash and blast furnace slag. However, according to the notification, the water-binder ratio of concrete using blast furnace slag cement should be reduced by 7 to 8 %, and the unit cement quantity significantly increases. The Nippon Slag Association, considering the reduction of concrete quality and cost disadvantage, facilitated the use of blast furnace slag by gaining recognition of a special evaluation method from the Minister of Land, Infrastructure and Transportation. On the other hand, as to fly ash, the Act says “In using fly ash cement, fly ash as mineral admixture leaves out of consideration.”, and does not consider the effect of fly ash blending. Therefore we can say that effort of widespread utilization for fly ash wouldn't be enough as compared with that for blast furnace slag.

6. Conclusion and comments for the future

We can get the same quality cement anywhere in the world because its main raw material, limestone, is distributed relatively with uniformity and in great abundance around the world. Therefore cement has established itself as the main material in the construction industry. However, with aggravation of the global warming problem, emission of large amounts of CO_2 from the cement industry has been become as a problem. Therefore, use of hydraulic admixtures like blast furnace slag and fly ash is desired. The use of admixtures has been studied and put into practical use for many years overseas to protect the depletion of limestone resources, but has not became common in Japan. As reasons for this, problems such as fast neutralization rate and increasing shrinkage cracking sensitivity have been pointed out.

In the Committee, WG1 studied the cracking resistance of concrete and proposed the evaluation method using the uniaxial restrained shrinkage cracking test, because the cracking resistance of concrete is affected greatly not only by the drying shrinkage but also by the creep and the generation rate of restraint stress. The test method studied by WG4 is able to quantify the shrinkage cracking resistance, therefore it is useful for planning the proper structural design and construction to control shrinkage cracking on a practical level. It will be expected to contribute to the wider utilization of mineral admixtures. Further, the round-robin test results using the proposed test opens up great possibilities for revealing the effect of mineral admixtures on cracking resistance that had not been known systematically until now.

WG4 examined the previous studies about the basic properties of concrete using mineral admixtures, focused on shrinkage and carbonation. As a result, it was found that there is only a few basic data on the properties of shrinkage and neutralization of concrete using mineral admixtures, and particularly data for actual structures is lacking. WG4 obtained a finding, different from the existing indoor acceleration test result, that concrete using fly ash showed nearly the same neutralization rate coefficient as that using ordinary Portland cement from exposure test of specimens and actual structures. However, it is necessary to collect more field test data to urge and elucidate the effect of mineral admixtures.

The survey of WG4 about the utilization of mineral admixtures shows that the usage ratio of blended cements is higher overseas than in Japan, and blended cements are generally used. This is very different from Japan because in Japan the materials have been developed primarily to meet the need for rapid construction and thus the design of conventional facilities and systems of manufacture and construction system of concrete is based on the utilization of ordinary Portland cement.

The initial strength of concrete with mineral admixtures such as blast furnace slag and fly ash is lower than that with ordinary Portland cement because of their slow hydration reactions; therefore mineral admixtures require a longer curing period than ordinary Portland cement to sufficiently demonstrate its advantage such as high long-term strength and durability. This has been a great obstacle to the wider use of mineral admixtures. Although measure to increase the fineness has been taken against low early age strength development, this became a trigger of shrinkage cracking. Therefore, radical reviews of construction for concrete using mineral admixtures have been required. WG3 in the Committee studied the effect of construction, especially the effect of curing, on the properties of concrete using mineral admixture from the perspective of difference between “inherent performances” and “real performance”: In the conventional quality control of concrete, “inherent performances of concrete” is the properties of concrete cured sufficiently in water at 20°C in the room, and in general, it does not show the “real” performance of the concrete constructed after the processes of manufacturing in plant, transporting to the field, pumping, placing, compacting, finishing, remolding and curing.

If the performance of concrete using mineral admixtures is not enough in the constructing stage due to the lack of curing, we can be expected to be complemented by progress of the hydration reaction in the service starting period or service period because the hydration reaction rate of mineral admixture. However, past studies show that initial lack of curing deteriorates strongly the durability of concrete using admixtures. Therefore, it is essential that the concrete using mineral admixtures should be placed and cured more carefully than that concrete using ordinary Portland cement to bring out its inherent performance.

There can be questions: “How can we properly quantify the performance of actual concrete structures?” and “What are the key points of concrete using mineral admixtures?” Satisfactory answers to these questions have never been given. Thus, in order to possibly evaluate the performance of concrete using mineral admixtures, it is necessary to evaluate durability on a practical level in addition to conventional quality control and verification by strength.

Besides, establishment of institutions is important to actively use mineral admixtures. According to the result of research by WG4, one of the reasons why mineral admixtures are not used more widely is that outsourcers limit the use of admixtures in their specifications. Therefore, it is essential to accumulate enough data about the properties of concrete using mineral admixtures, propose a firm quality certification, and ease the limitations on institutions.

The mineral admixtures such as blast furnace slag, fly ash, limestone powder and silica fume can be applied to the multi-component cement except for binary cement. In this case, making standards for all multi-component cements is impractical because there are too many combinations. Thus, a quality standard to verify the inherent performance required of cement is needed. In the Committee, based on ASTM C1157, WG2 proposed that a draft of the standard performance specification for cement based on specific requirements. The draft has some shortcomings; the working mechanism for some requirements are not well understood; There is a lack of evaluating method for some requirements; The quality criterion becomes uncertain because of few information of relationship in behavior between evaluation test and actual concrete structure; The way how the performance of cement is efficient in concrete is ambiguous. WG2 tried to explain why such any shortcomings occur and proposed a draft based on the current technological level. This innovative proposal does not necessarily comply with the current construction activities but with the future construction activities in the future sustainable society.

In fact, the rate of utilization of ASTM C1157 has not increased as well as expected. In U.S. and Canada, there is a trend toward expanding the existing cement standards, for example easing the blending range of mineral admixtures like limestone fine powder, rather than innovating new standards. This trend is thought to show a direction for the wider utilization of mineral admixtures.

From the above conclusions, it is absolutely essential that the collaboration between industry, educational institutions and the administration is necessary to bring out the strategic shift from the construction industrial’s reliance on ordinary Portland cement to blended cement with consent of users and constructors. The collaborations include the fundamental studies about the “inherent” performance of mineral admixtures and the effect of construction system on the “real” performance of actual structures, and the relaxation of regulations and specifications.

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