Committee Report : JCI- TC102A

Technical Committee on Evaluation of Concrete Shrinkage and its Effect

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Abstract

The Committee investigated some of the issues raised by the FY2009 Presidential Special Committee, the "Committee Studying Concrete Shrinkage". WG1, to study identification and measuring methods for the shrinkage mechanism, conducted common tests relating to the effect of concrete-structuring materials on shrinkage characteristics, and as the outcome of the study, it proposed three draft plans on an evaluation method for shrinkage of concrete and concrete-structuring materials. WG2, to survey the effect of shrinkage on cracks, mainly focused on the relation between the magnitude of the drying shrinkage strain of concrete and cracks generated in actual structures, and the outcome was summarized in (1) shrinkage of concrete specimens and cracks in actual structures, (2) present accuracy of the method of evaluating cracks caused by drying shrinkage, and (3) verification result of the effect of measures to reduce shrinkage.

Keywords: concrete shrinkage, crack, test method, measures to reduce shrinkage

1. Introduction

Concrete shrinkage is a long-discussed issue. In recent years, however, there arose significant movements in both the architectural and civil engineering fields, and they have had considerable impact on the concrete business. That is, although the architectural field has enforced a standard to specify the shrinkage of ready-mixed concrete, ready-mixed concrete firms are struggling to meet the specification of the standard. In the civil engineering field, large bridges generated cracks presumably caused by concrete shrinkage which has caused social problems. Nevertheless, the Guidelines for Concrete cannot give definitive solutions. In response to this situation, JCI organized a Presidential Special Committee, the "Committee Studying Concrete Shrinkage" [1)], in FY2009, to study how to make a detailed proposal for the standardization of shrinkage.

Table 1: Committee Members

Chairman	Hirotaka KAWANO	Kyoto Univ.
Observer	Shigeyuki SOGO	Hiroshima Institute of Technology
Manager	Takafumi NOGUCHI	Tokyo Univ.
	Toshiki AYANO	Okayama Univ.
	Kei-ichi IMAMOTO	Tokyo Univ. of Science
	Atsushi UENO	Tokyo Metropolitan Univ.
	Tetsushi KANDA	Kajima Corp.
	Hideaki TANIGUCHI	Sumitomo Mitsui Construction CoLtd
	Koji MANO	Japan Testing Center for Const. Materials
Member	Yasuaki ISHIKAWA	Meijo Univ.
	Hidefumi IZUO	Japan Cement Association
	Takumi SUGAMATA	BASF Pozzolith Ltd.
	Hiroshi KATAHIRA	Public Works Research Institute
	Takahiro GOTO	Mitsubishi Material Corp.
	Takumi SHIMOMURA	Nagaoka Univ. of Technology
	Shoji SHIROKUNI, Junji ASAUMI	ZENNAMA
	Makoto TANIMURA	Taiheiyo Cement Corp.
	Yasuhiro DAN	Nippon Steel Blast-Furnace Slag Cement CoLtd
	Masanori TSUZUKI	Obayashi Corp.
	Kenro MITSUI, Kazumasa INOUE	Takenaka Corp.
	Shingo MIYAZAWA	Ashikaga Institute of Technology
	Minoru MORIOKA	Denki Kagaku Kogyou
	Tetsuo TSUKADA	Tsukada Tokan
	Yusuke FUJIKURA	Fujita Corp.

The Committee grasped the present state of shrinkage, reviewed the treatment of shrinkage by the Architectural Institute of Japan and by the Guidelines for Concrete prepared by the Japan Society of Civil Engineers, gave consideration to current test methods and evaluation methods, and thus gave an overview of the measures to reduce shrinkage and the effect of the measures. However, the Committee failed to make a distinctive action proposal. The Committee Report [1)] identified many issues to be investigated, as listed below.

(1) Quantification of individual shrinkage factors of concrete shrinkage affecting cracks.

(2) Necessity of evaluation method for each material to determine the shrinkage percentage of concrete.

(3) Identification of shrinkage mechanism.

(4) Method to apply the concrete shrinkage percentage to design.

(5) Awareness of need for standardization of concrete shrinkage.

(6) Other issues

Among the above issues to be investigated, the Research Committee focused mainly on the technical issues (1) to (3), and conducted activities over a period of two years during the course of further investigation.

The Committee decided an operation policy by the Board of Governors whose core members comprised the Chairman and Governors (Chief Investigators), the actual activities of the Committee mainly being handled by WGs. WG1, to study identification and measuring methods for the shrinkage mechanism, conducted common tests relating to the effect of concrete structural materials on shrinkage characteristics, and studied a method for evaluating the shrinkage of the materials. WG2, to survey the effect of shrinkage on cracks, mainly focused on the relation between the magnitude of the drying shrinkage strain of concrete and the cracks generated in actual structures, and the outcome was summarized in (1) shrinkage of concrete specimens and cracks in actual structures, (2) present accuracy of method for evaluating cracks due to drying shrinkage, and (3) verification of the effect of measures to reduce shrinkage. The details of each WG are described below, and this paper gives an overview of the activities of WGs.

2. Identification of shrinkage mechanism and investigation of measurement method

The common tests of the three Series listed in **Table 2.1** were conducted to grasp the magnitude of the effect of the kind and quality of materials used in concrete on drying shrinkage of hardened concrete, to investigate the mechanism of shrinkage, and further to obtain basic data (common data) to standardize the test method for evaluating the magnitude of the effect on drying shrinkage. In this paper, the mortar prepared by or based on JIS R5201 (Physical Testing Method for Cement) is referred to as “JIS Mortar” for convenience.

Table 2.1: Experiments (Common experiments)

Series No., Name	Description
Series 1 Investigation using fine aggregates prepared by crushing respective coarse aggregates	Test samples were fine aggregates prepared by crushing nine kinds of coarse aggregates with known drying shrinkage percentage of concrete. For mortar specimens prepared using the respective fine aggregates, drying shrinkage percentage, compression strength and Young's modulus of the mortar specimens were determined. A comparison was also made of the relation between the micropore volume of aggregate particles and drying shrinkage property for mortar and concrete.
Series 2 Common experiments on drying shrinkage of JIS Mortar for various kinds of concrete materials	Mortar specimens were prepared in accordance with JIS R 5201 targeting four kinds of cement, 15 kinds of fine aggregate, and six kinds of admixture, and drying shrinkage percentage, compression strength, and Young's modulus were determined for each specimen. Based on standardization of the test method, an investigation was made of the scatter in test results and measurement method for determining length changes.
Series 3 Common experiments on drying shrinkage of concrete using various kinds of concrete materials	Based on the experimental result of Series 2, typical materials were selected to prepare concretes having 12 kinds of composition. Drying shrinkage percentage, compression strength, and elastic modulus were determined. A comparison was also made of the drying shrinkage test results between mortar and concrete.

2.1 Investigation of Series 1

Generally, aggregates have a function to reduce paste shrinkage. Based on the results of our investigation, the drying shrinkage percentage of concrete is about 60% of that of mortar, as illustrated in **Fig. 2.1**. The reduction of shrinkage percentage in the concrete is presumably due to both the effect of aggregate size and the effect of aggregate volume. Since the aggregate volume rate is 0.58 for mortar and about 0.67 for concrete, volume difference alone cannot cause the difference in drying shrinkage percentage. That is, coarse particles have a stronger restriction effect on the shrinkage of media. Although the tendency is significant in the effect of fine aggregate on the drying shrinkage percentage of mortar, the effect of fine aggregate is small in the drying shrinkage percentage of concrete, which agrees with previous studies reporting the significance of the effect of coarse aggregates.

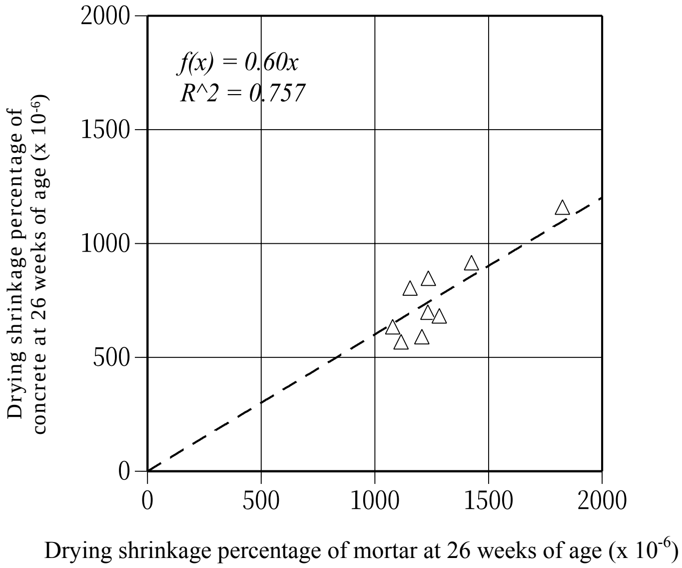


Fig. 2.1: Effect of aggregate particle size on shrinkage percentage

2.2 Investigations of Series 2 and 3

Figs. 2.2 and **2.3** illustrate the drying shrinkage test result for JIS Mortar using test samples of cements, fine aggregates, and admixtures. As seen in these figures, the drying shrinkage percentage of JIS Mortar differs considerably depending on the test sample. Therefore, the magnitude of the effect of the performance of materials comprising the concrete on drying shrinkage percentage, can be evaluated by the drying shrinkage percentage of JIS Mortar.

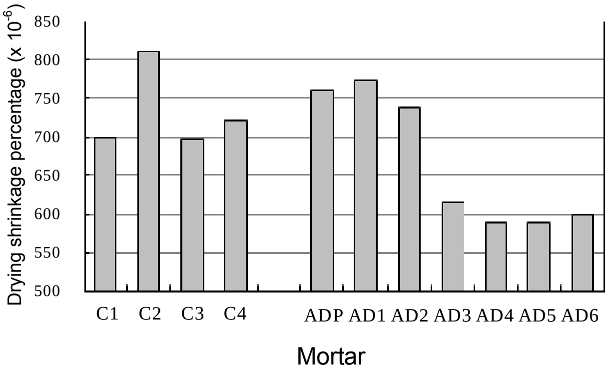


Fig. 2.2: Shrinkage percentage of JIS Mortar (cement, admixture)

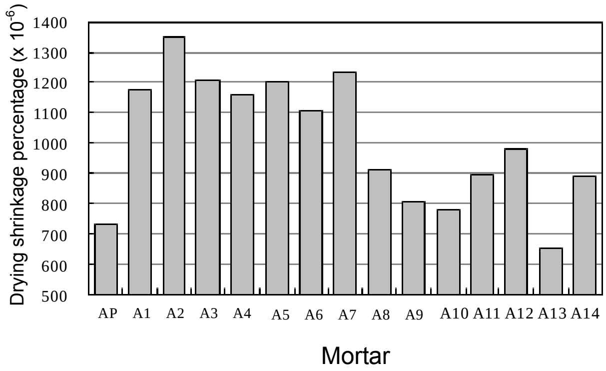


Fig. 2.3: Shrinkage percentage of JIS Mortar (kind of fine aggregate)

Fig. 2.4 illustrates the drying shrinkage percentage of mortars and concretes prepared from cements supplied by different cement manufacturers up to 13 weeks of drying. As shown in the figure, the range of drying shrinkage percentage for three manufacturers was 118 x 10^{-6} for JIS Mortar, and 52 x 10^{-6} for concrete. Also the tests of previous studies, shown by the gray hatched zone in **Fig. 2.4**, indicated 185 x 10^{-6} for JIS Mortar prepared by 12 manufacturers, and 58 x 10^{-6} for concrete. For both tests, inclusion of coarse aggregate decreased the effect of different cement manufacturers. As illustrated in **Fig. 2.5**, the drying shrinkage percentage of concrete with different kinds of Con2-4 cements, Con5-7 aggregates, and Con8-12 admixtures tended to become smaller than that of the test result for JIS Mortar. **Fig. 2.1** shows that the "effect of suppressing shrinkage is more significant for coarse aggregate than for fine aggregate". According to **Fig. 2.5**, however, the test result for JIS Mortar differs with concrete type, thus the test method should be selected considering this point.

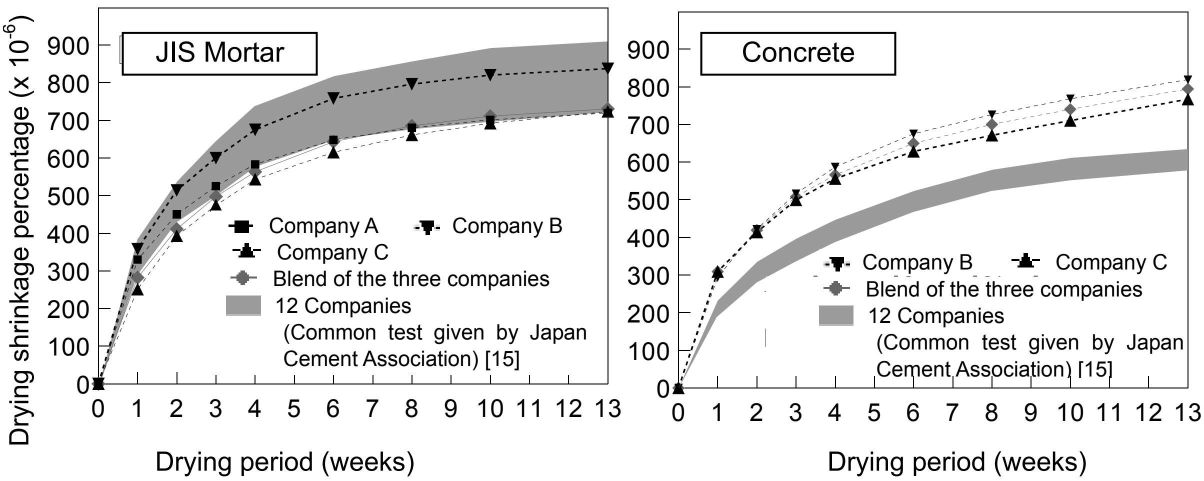


Fig. 2.4: Effect of shrinkage of cement paste on concrete

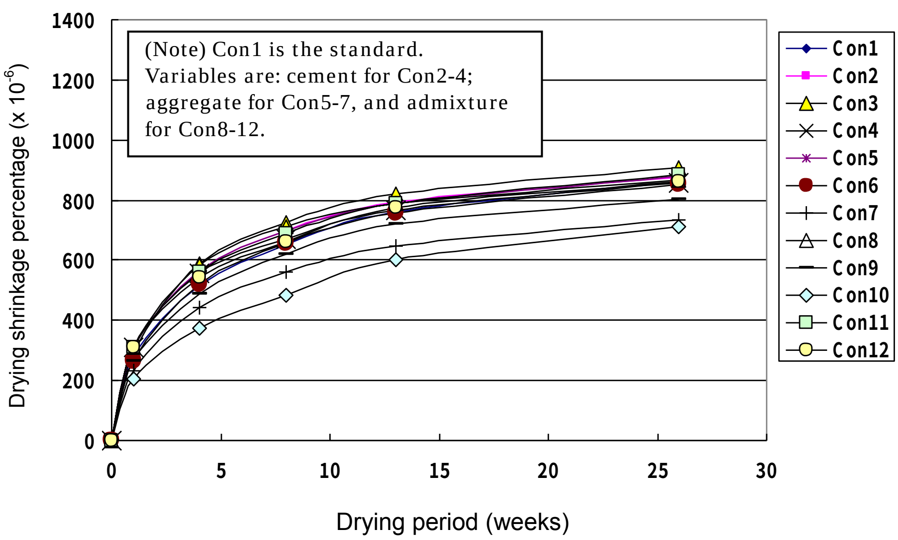


Fig. 2.5: Drying shrinkage percentage of concrete

2.3 Investigation of mechanism

Fig. 2.6 shows the correlation factor for the individual ranges of micropore radius. Both mortar and concrete showed a relatively strong correlation at 150 mm or smaller micropore radius. Also for the specific surface area inside the aggregate which was determined by focusing on the water-vapor adsorption characteristic, there was a strong correlation with drying shrinkage percentage. These phenomena suggest that fine voids in aggregate significantly affect the drying shrinkage percentage of mortar, which presumably follows a similar mechanism to increase in capillary tension (hydrostatic tension), reduction in separation pressure, or a composite of both tensions in the drying shrinkage percentage of mortar and concrete.

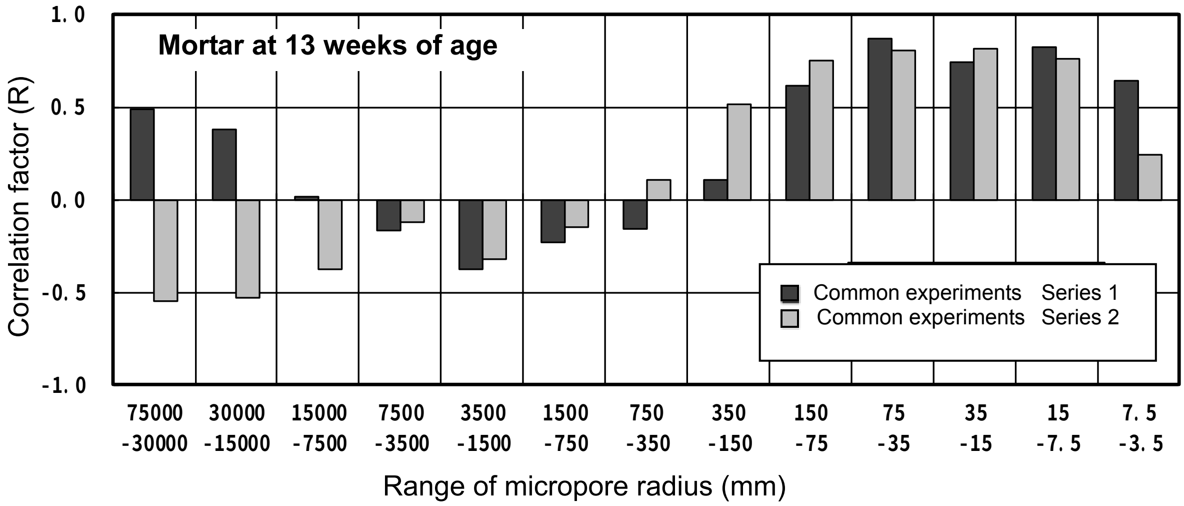


Fig. 2.6: Correlation factor in the respective ranges of micropore radius (Mortar)

3. Survey of effect of shrinkage on cracks

3.1 Relation between shrinkage of specimens and shrinkage of actual structures

Drying shrinkage as a major element of concrete shrinkage is caused by dissipation of water from concrete, and its change with time is affected by the temperature surrounding the structure, environmental conditions such as humidity, kind of binder, aggregate and other applied materials, concrete composition, and shape and dimensions of a cross section of the member. To estimate the concrete shrinkage in a structure taking reasonable account of these elements, it is desirable to determine the concrete shrinkage of individual members based on an analysis of water migration in concrete. However, if the concrete member is assumed to be a rod-shaped member and the deformation caused by drying shrinkage of concrete is assumed to follow the flat-support hypothesis, to derive a simplified solution, the drying shrinkage strain of, for example, a square pillar specimen of 100 x 100 x 400 mm cured for 7 days, measured at an age t of the material, is often determined by a hyperbolic curve given by Equation (3.1).

$$\varepsilon'_{sh}(t,7)=\frac{\varepsilon'_{sh,\inf}\times(t-7)}{\alpha+(t-7)} \tag{3-1}$$

If the drying shrinkage strain of concrete is a deformation accompanied by a diffusion phenomenon, theoretically, the ultimate value of the drying shrinkage strain of concrete, $\varepsilon'_{sh,inf}$, does not change independently of the size of member, and the time until reaching the ultimate value is increased proportionally to the square of the size of the member. That is, the drying shrinkage strain of a rod-shaped member with a member size of d mm which begins drying at an age t_0 of the material, is derived from Equation (3.2) using the ultimate value $\varepsilon'_{sh,inf}$ of drying shrinkage strain, which expresses the change of drying shrinkage strain with time determined from the square pillar specimen (100 x 100 x 400 mm) and the term α which expresses change with time.

$$\varepsilon'_{ds}(t,t_0)=\frac{\varepsilon'_{sh,\inf}\times(t-t_0)}{\left(\frac{d}{100}\right)^2\times\alpha+(t-t_0)} \tag{3-2}$$

Fig. 3.1 illustrates the change with time of the drying shrinkage strain of cylindrical specimens of diameter 50 mm and 75 mm, respectively, determined by Equation (3.2). The drying shrinkage strain determined on specimens with a size suitable for laboratory testing shows a deformation behavior accompanied by a diffusion phenomenon.

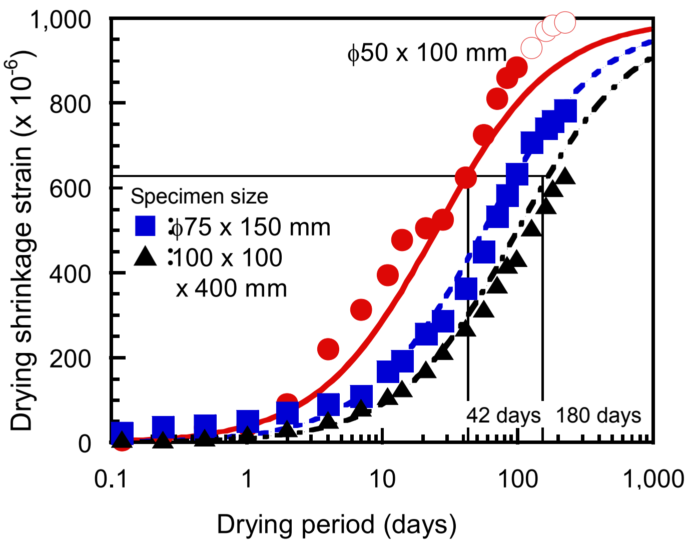


Fig. 3.1: Drying shrinkage strain of specimens having different member size

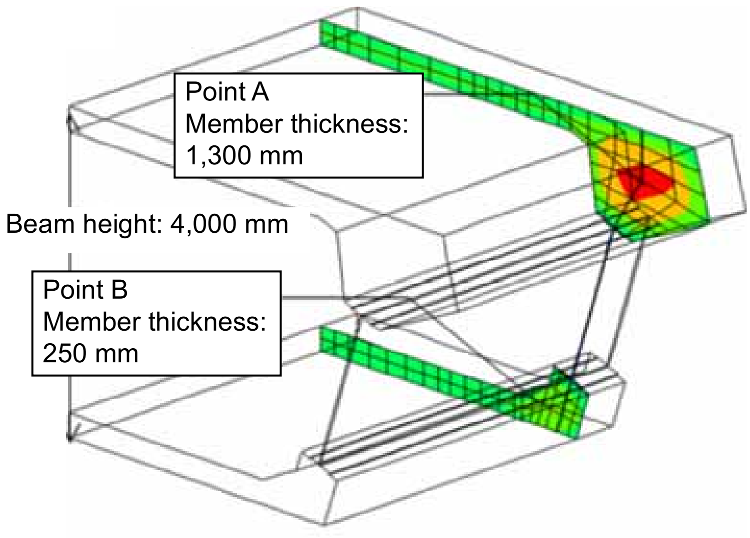


Fig. 3.2: Example of upper structure

For actual structures, however, such as the case of concreting the upper structure of a bridge in summer, the temperature of the concrete during curing may reach 80˚C or more depending on the member thickness, which is not necessarily the same curing condition as that of a laboratory. Even for an upper structure of the same material as shown in **Fig. 3.2**, there is a 20˚C or larger difference in the concrete temperature actually measured between an upper flange and a lower flange. To investigate the effect of temperature during the curing period on drying shrinkage strain, a temperature history shown in **Fig. 3.3** gives results for the drying shrinkage strain of concrete as shown in **Fig. 3.4**. A higher temperature history results in a smaller drying shrinkage strain of the concrete. Specifically, the drying shrinkage strain of concrete which had a temperature history at the point A shows a drying shrinkage strain smaller by about 60% than that of a concrete cured in a 20˚C thermostatic chamber.

As described above, the concrete in an actual structure is cured under different condition from that of laboratory specimens depending on the temperature history and other variables applied to the concrete. As a result, the concrete structure varies, and the drying shrinkage strain does not necessarily become the same to that obtained from a square pillar specimen (100 x 100 x 400 mm).

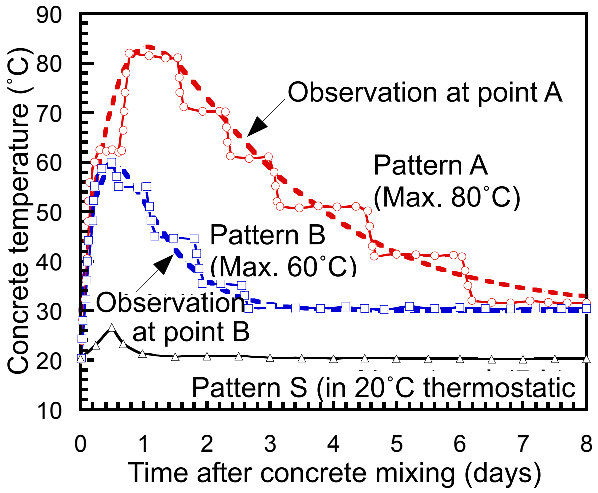


Fig. 3.3: Observed temperatures in upper structure of Fig. 3.2

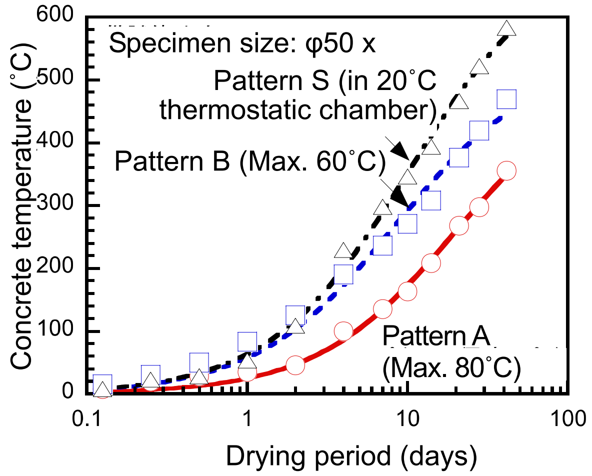


Fig. 3.4: Effect of temperature history on drying shrinkage strain

3.2 Evaluation method for cracks

To establish a correlation between the drying shrinkage percentage of the material of a concrete and the cracks occurring in structures, and to establish crack control of RC structures through a reasonable approach, it is required to quantitatively express crack occurrence in actual structures. A method of applying the above expression is to measure the width and length of cracks occurring in floor and wall members, to define the value of the area of cracks divided by the area of the member as the "crack density", and to utilize the crack density as an index of the degree of cracks.

As for the above index of crack occurrence, the crack coefficient ε_{cr} is adopted. We shall discuss its physical meaning and the suitability of the coefficient as a quantitative index. As shown in **Fig. 3.5**, the coefficient ε_{cr} is a value of the cumulative width of cracks occurring in floor and wall members divided by the member length.

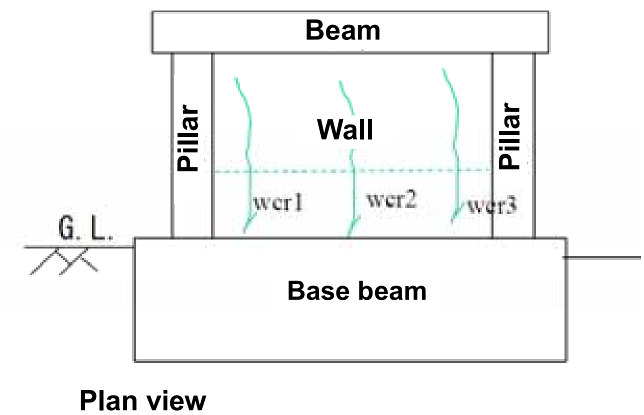


Fig. 3.5: Overview of crack coefficient

Fig. 3.6 shows schematic drawings of cracks due to the shrinkage of RC members. Due to the drying shrinkage of concrete, the member undergoes free shrinkage deformation. The free shrinkage deformation is then restricted, leading to restrained deformation which consists of elastic deformation and creep deformation. Cracks presumably occur due to the shrinkage restrained stress, generated proportionally to the elastic deformation and overriding the crack strength. Furthermore, once the cracks are formed, the shrinkage restrained stress is released to decrease the stress generated in the member, and the restrained deformation l_{rs} before the cracks occurred is presumably substituted by the displacement caused by the cracks except for the effect of creep l_{creep}. Consequently the strain ε_{cr} derived from the deformation due to the cumulative crack width divided by the member length is expressed by Equation (3.3).

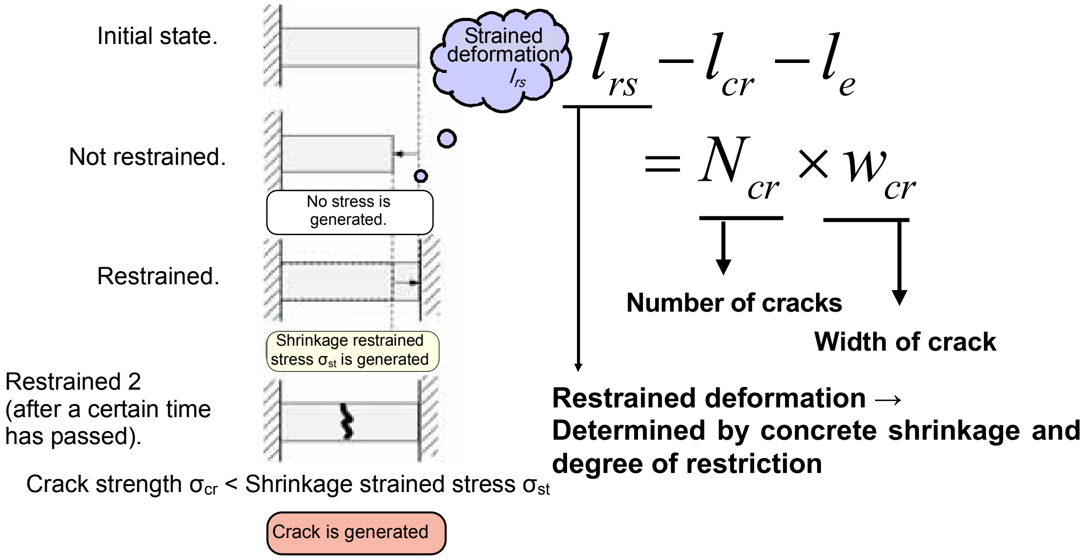


Fig. 3.6: Simplified model for calculating the shrinkage restrained stress

$$\varepsilon_{cr} \approx \frac{\left(l_{rs} - l_{creep}\right)}{L} \tag{3-3}$$

If the right side of Equation (3.3) is considered as a strain corresponding to the elastic deformation, the following Equation (3.4) can be derived.

$$\frac{\left(l_{rs} - l_{creep}\right)}{L} \approx \varepsilon_{sh} \times R/\phi \tag{3-4}$$

where ε_{sh} is the drying shrinkage strain of the member, R is the degree of restriction, and φ is the creep factor. Since the right side of Equation (3.4) is equal to the elastic strain which contributes to the generation of the shrinkage restrained stress σ_{st}, Equation (3.5) can be derived, where E_c is the elastic modulus of concrete.

$$\frac{\sigma_{st}}{E_c} \approx \varepsilon_{sh} \times R/\phi \tag{3-5}$$

These equations above suggest that ε_{cr} has a positive correlation with σ_{st} and clearly show the dynamic meaning of ε_{cr}. ε_{cr} is the crack coefficient used in a simplified crack evaluation.

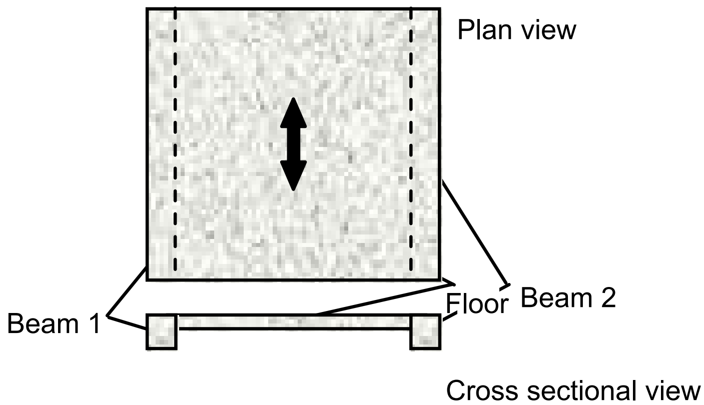
Table 3.1 is a summary of the drying shrinkage percentage of concrete and the result of change with time of the drying shrinkage strain of members derived from the volume to surface area ratio (hereinafter referred to as the "V/S") for actual floor members, in order to verify the suitability of the crack coefficient as a quantitative index of crack occurrence. For the floor members of **Table 3.1**, crack occurrence and the results of above the determination of shrinkage restrained stress are summarized in **Table 3.2**. **Table 3.2** is organized by the stress intensity ratio (shrinkage restrained stress σ_{st} divided by the crack strength). The shrinkage restrained stress σ_{st} is estimated by the following equation by simplifying the flat member receiving restriction as a uni-axial member shown in **Fig. 3.7**.

Table 3.1: List of members to be tested and their specifications

Symbol	Tested items				Concrete condition				Drying shrinkage strain of floor member at test ε_{sh} $(x\ 10^{-6})$
	Summary of items	Structure condition for analysis		Number of stairs	Nominal strength	W/C (%)	W (kg/m^3)	Drying shrinkage percentage ε_{sh0} $(x\ 10^{-6})$	
A-1	Item A	Multi-story car park	Flat deck slab Slab: 160 mm x 6,000 mm D13@150 mm (double) Steel beam: 700-300-13-24 (two beams)	2F	24	53.0	171	545	195
A-2				3F	24	53.0	171	545	195
A-3				4F	24	53.0	171	545	195
A-4				5F	24	53.0	171	545	195
B-1	Item B	Production facilities	Flat deck slab Slab: 150 mm x 13,250 mm D10@200 mm (double) Steel beam: 595-199-10-15 (three beams) 800-358-16-28 (two beams)	2F	27	53.8	177	807	-
B-2				3F	27	53.8	177	807	-
B-3				4F	27	53.8	177	807	188
B-4				5F	27	53.8	177	807	188
C-1	Item C	Commercial facilities	V-Deck slab Slab: 80 mm x 8,050 mm D13@150 mm, φ6@150 mm Steel beam: 588-300-12-20 (one beam) 600-300-12-22 (two beams)	3F1 Site	27	54.1	176	749	315
C-2				3F2 Site	27	54.1	176	749	277
C-3				4F1 Site	27	54.1	176	749	303
C-4				4F2 Site	27	54.1	176	749	285

Table 3.2: Crack survey and stress analysis results

Symbol	Crack survey		Analytical results		
	Age (days)	Crack coefficient ε_{cr} (x 10^{-6})	Shrinkage strained stressσ_{st} (N/mm ^{3})	Shrinkage crack generation intensityσ_{cr} (N/mm ^{3})	Stress intensification ratio σ_{st}/σ_{cr}
A-1	249	53	1.88	1.93	0.98
A-2	249	41	1.88	1.93	0.98
A-3	249	56	1.88	1.93	0.98
A-4	249	34	1.88	1.93	0.98
B-1	101	0	0.47	2.24	0.21
B-2	100	0	0.46	2.24	0.21
B-3	93	21	1.49	2.24	0.67
B-4	93	13	1.49	2.24	0.67
C-1	83	35	2.20	1.85	1.19
C-2	62	40	1.93	1.83	1.06
C-3	76	35	2.12	1.84	1.15
C-4	61	18	1.91	1.82	1.05



(The arrow shows the direction of stress generation.)

Fig. 3.7: Simplified model for calculating the shrinkage restrained stress

$$\sigma_{st}\left(t\right)=\int\frac{E(t')}{(1+\phi(t,t'))}\lambda(t')d\varepsilon_f(t') \tag{3-6}$$

where;

$$\lambda(t')=\frac{d\varepsilon_f(t')-d\varepsilon_{total}(t')}{d\varepsilon_f(t')} \tag{3-7}$$

where: $\sigma_{st}(t)$ is the estimated value of shrinkage restrained stress at an age of material (N/mm^2); t is the age of concrete (days); t' is the age of material generating free strain change (days); $E(t')$ is the Young's modulus at an age of material t' (N/mm^2); $\varphi(t,t')$ is the creep coefficient at an age of material t with loading condition at age t'; $\lambda(t')$ is the degree of restriction at an age of material ; $d\varepsilon_f(t')$ is the change rate of free strain (= strain due to temperature change + shrinkage strain) at an age of material t'; and $d\varepsilon_{total}(t')$ is the change rate of total strain (= free strain - elastic strain - creep strain) at an age of material t'.

Fig. 3.6 compares the shrinkage restrained stress σ_{st} of a structural concrete predominantly affecting the occurrence of shrinkage cracks, and the crack coefficient ε_{cr} which is used in simplified crack evaluation. There is a definite correlation between the stress intensity ratio determined from the analyzed shrinkage restrained stress and the crack coefficient derived from crack survey. That is, although the crack coefficient is a simplified tool, it is dynamically correlated with the crack occurrence mechanism, and is considered to be a suitable adaptable index expressing crack occurrence in a quantitative way.

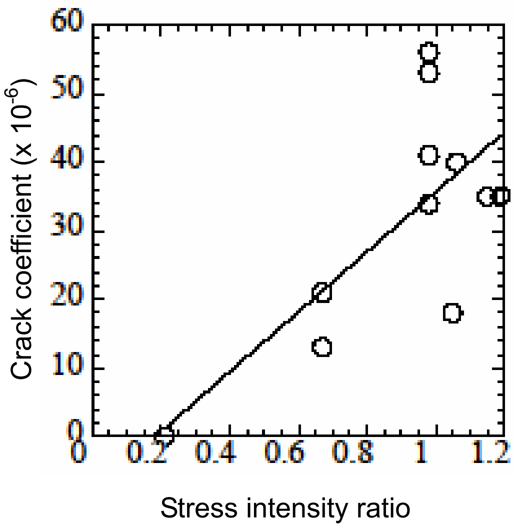


Fig. 3.5: Adaptability of crack coefficient

4. Conclusion

WG1, to study identification and measuring methods for the shrinkage mechanism, conducted common tests relating to the effect of concrete structural materials on the shrinkage characteristics, and as the outcome of the study, it will propose draft plans for an evaluation method for shrinkage of concrete and concrete structural materials. WG2, to survey the effect of shrinkage on cracks, mainly focused on the relation between the magnitude of the drying shrinkage strain of concrete and the cracks occurring in actual structures, and the outcome was summarized in (1) shrinkage of concrete specimens and cracks in actual structures, (2) present accuracy of the evaluation method for cracks due to drying shrinkage, and (3) verification of the effect of measures to reduce shrinkage, parts of which were introduced in this paper.

References

1) JCI committee report "Investigation on drying shrinkage of concrete", JCI, March 2010 (in Japanese).