Committee Report : JCI- TC105A

Technical Committee on Shrinkage Effect Evaluation based on Durability Mechanics

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Abstract

In recent years, shrinkage of concrete has been actively discussed from the perspective of shrinkage of the aggregate itself or over-shrinkage of concrete. However, the effects that over-shrinkage has on concrete structures or their performance have scarcely been examined. The Committee therefore analyzed domestic and international research papers and design methods as a dual problem of material and structure, and put together the effects that shrinkage of concrete has on structural and durability performance, based on the systematization technique of durability mechanics recently proposed by the Durability Mechanics Working Group of JCI-TC-061A. The objectives of this Committee include the above, as well as contributing to setting the course of future research, and restructuring design methods.

Keywords: shrinkage, durability mechanics, dual problem, structural performance, durability, physicochemical model

1. Introduction

1.1 Objectives of the Committee, and its composition

Since it has been revealed that there are many cracks in PRC elevated bridges and they have deformation problems[1], shrinkage of concrete has been actively discussed in Japan in recent years from the perspective of shrinkage of the aggregate itself or over-shrinkage of concrete. Recently, cracking in PC structures has also been reported, which is assumed to be caused by excessive drying shrinkage[2]. At the same time, how to tackle concrete shrinkage in design was stipulated in the concrete standard specifications of the Japan Society of Civil Engineers and in JASS5 of the Architectural Institute of Japan, and research has actively been carried out. Also in JCI, a special presidential committee, the Exploratory Committee on Shrinkage of Concrete, was set up to study the results of research on the present situation of drying shrinkage of concrete, and examine methods of evaluating shrinkage test results[3].

Subsequently, the Technical Committee on Evaluation of Concrete Shrinkage and its Effect (JCI-TC-102A) was established around the same time as this Committee, and has continued to examine mechanisms of concrete shrinkage and methods to evaluate each constituent material. However, there has been almost no research on how excessive shrinkage acts on concrete structures or affects their performance, and it was considered that systematic examination of these matters would be required in the future.

Consequently, this Committee was established to carry out an examination based on the systematization technique according to durability mechanics recently proposed by the Durability Mechanics Working Group of the Technical Committee on Time-dependent Behavior of Cement-based Materials (JCI-TC-061A)[4),5)]. The objectives are as follows: to analyze domestic and international research papers and design methods as a dual problem of material and structure; to put together the effects that concrete shrinkage has on structural and durability performance; and to contribute to setting the course of future research and restructuring design methods.

The composition of this Committee is shown in **Table 1**. Regarding the effects that excessive concrete shrinkage has on the performance of concrete structures, two working groups were formed: the Structure WG to address effects on the mechanical performance of structures, and the Material WG to address the effects on durability. The objective of the Structure WG (headed by Shimomura) was to examine effects that volume change has on structural performance from the perspectives of understanding the phenomena, modeling and design formula. In particular, the WG conducted investigation and research on crack width, deformation, and their effects on shear proof stress. The objective of the Material WG (headed by Ujike) was to examine effects that concrete cracking, including shrinkage cracking, has on durability from the perspectives of understanding the phenomena and modeling. In particular, the WG conducted investigation and research focused on mass transfer and reinforcement corrosion.

The research subject addressed by this Committee, the dual problem of volume change and structural performance of concrete material, deals with complicated phenomena, and has a relatively short history. Therefore, we conducted an investigation and research activities aiming to create a new academic and technological field in concrete technology ten years later. We also held an intermediate workshop in August 2011 and, with two keynote lectures, one invited paper presentation, twelve general paper presentations, and a panel discussion inviting seven panelists, we defined the meaning and issues of the Committee, and reflected them in the preparation of the final report.

Table 1: Committee members

Chairman	Ryoichi SATO	Hiroshima University
Vice-chairman	Takumi SHIMOMURA	Nagaoka University of Technology
Secretary	Ippei MARUYAMA	Nagoya University
	Kenichiro NAKARAI	Gunma University
Structure WG		
Chief examiner	Takumi SHIMOMURA	Nagaoka University of Technology
Deputy chief examiner	Tsutomu KOMURO	Taisei Corporation
Group member	Kaoru KOBAYASHI	East Japan Railway Company
	Yasuhiko SATO	Hokkaido University
	Noriyuki TAKAHASHI	The University of Tokyo
	Hikaru NAKAMURA	Nagoya University
	Toshiaki HASEGAWA	Shimizu Corporation
	Yoshihiko TAIRA	Sumitomo Mitsui Construction Co., Ltd
	Takeshi FUKUHARA.	Takenaka Corporation
	Tomohiro MIKI	Kobe University
	Toshiaki MIZOBUCHI	Hosei University
	Makoto MARUTA	Shimane University
	Shingo MIYAZAWA	Ashikaga Institute of Technology
	Hikotsugu HYODO	Taiheiyo Cement Corporation
Material WG		
Chief examiner	Isao UJIKE	Ehime University
Deputy chief examiner	Tetsuya ISHIDA	The University of Tokyo
Group member	Kei-ichi IMAMOTO	Tokyo University of Science
	Manabu KANEMATSU	Tokyo University of Science
	Tatsuhiko SAEKI	Niigata University
	Toshinori OYAMOTO	Kajima Corporation
	Kazuhiko HAYASHI	Yokohama National University
	Tsuyoshi MARUYA	Taisei Corporation
	Toru YAMAJI	The Port and Airport Research Institute
Cooperate Member		
	Yusuke AOKI	Kisarazu National College of Technology
	Takehiro SUZUKI	East Japan Railway Company
	Masahiro SUZUKI	P.S. Mitsubishi Construction Co., Ltd.
	Makoto TANIMURA	Taiheiyo Cement Corporation
	Nobuhiro CHIJIWA	The University of Tokyo
	Kohji TERANISHI	Meijo University
	Akira HOSODA	Yokohama National University
	Zhuguo LI	Yamaguchi University

1.2 Approach to shrinkage problem with durability mechanics

The durability mechanics of concrete structures defined by the Durability Mechanics WG of JCI-TC-061A[4),5)] was developed from the concept proposed by Professor Ulm, and is an academic system to systematically predict and evaluate the time-dependent behavior of concrete material and structures. In other words, it is an academic system to make it possible to predict the time-dependent behavior of concrete structures by describing the temporal change of physicochemical deterioration phenomena of cement- based materials due to chemical reactions, environmental effects and external loads by way of physicochemical models of reactions, mass transfer, fractures and their composite phenomena, and thus create rules regarding preparation of concrete materials.

An overview of the issues addressed by this Committee in investigation and research of effects that excessive shrinkage of concrete has on structures, along with the corresponding sections in this report, is shown in **Fig. 1**. When the volume change of concrete caused by drying shrinkage, heat of hydration, etc., is restrained, a stress is generated, and when its value exceeds the fracture criteria, damage occurs to the concrete. Depending on the width and density of the cracks that occur and the accumulated stress, the structural performance and durability of structures vary. Here, the action of external conditions, such as the temperature, humidity and load, also has an effect.

In the activities of this Committee, we intended to take considerations and discussions one step further than conventional examinations by trying to extract the physicochemical parameters that are considered to dominate macro phenomena in concrete structures, and perform an attribution analysis in experiments to provide back data for engineering design formulae. However, our effort is still only halfway complete, partly because sufficient information required for detailed examination has not been acquired, and we are still continuing this study. We hope you understand that we are at the starting point for continuous development in the future.

2. Stress accumulation and damage due to shrinkage of concrete

2.1 Initial cracking in structures due to shrinkage

One of the important effects that concrete shrinkage has on structures is that it causes cracking. Cracking in concrete structures due to drying shrinkage is predicted by analyzing the moisture transfer in concrete, the shrinkage stress in structures associated with the escape of moisture, and the occurrence and development of cracking. However, a generalized, specific method does not exist, compared to prediction of temperature cracking of mass concrete structures that has similarities as a mathematical problem. This Committee carried out an examination from the following perspectives.

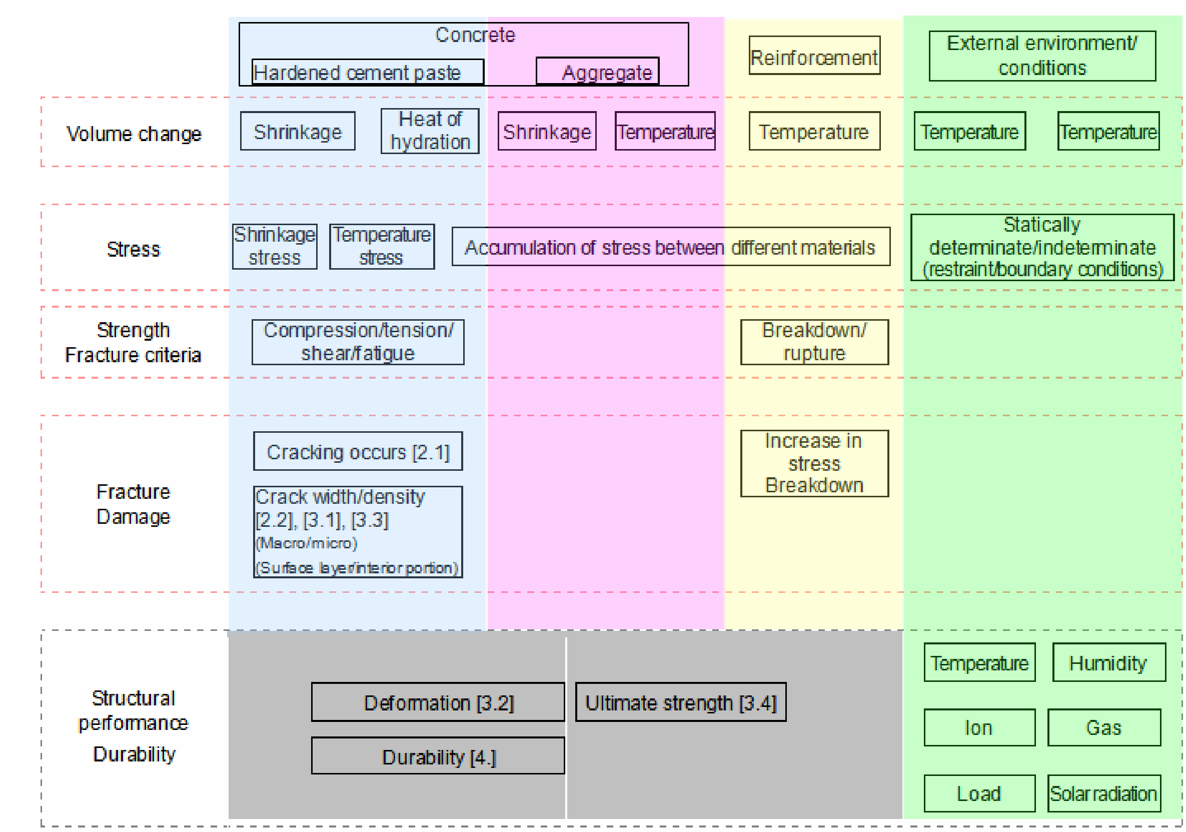

Fig. 1: Durability mechanical approach to the shrinkage problem
(Values in [ ] correspond to chapter and section numbers in this report)

(1) Prediction of shrinkage cracking in structures using numerical analysis

There are several technical issues when predicting shrinkage cracking in concrete structures using numerical analysis, and we performed an examination focusing on time-dependent stress analysis and crack development analysis considering creep.

Since drying shrinkage develops slowly except for the surface part immediately after the start of drying, it is necessary to consider creep to correctly evaluate the shrinkage stress. There are a number of methods to consider creep in stress analysis of concrete structures depending on the difference in creep models and mathematical solutions. In order to avoid complicated calculations, approximate solutions, such as using the effective elastic modulus as a function of time, are often used.

The Committee report outlines a creep analysis that integrates the stress history. Moreover, shrinkage cracking does not end when the first crack occurs. Instead, development of cracking or occurrence of multiple cracks may be found. We studied analysis methods considering these points.

(2) Taking account of autogenous shrinkage and drying shrinkage in prediction of temperature cracking

It is known that the stress caused when autogenous shrinkage is restrained is also compounded in the temperature stress of mass concrete. By considering autogenous shrinkage, it has been found that not only the accuracy of calculating stress is improved, but also there are cracks in mass concrete that can be explained, including the part where cracking occurs and the direction of cracking[6)].

Depending on the member thickness, both temperature stress resulting from the hydration of cement and drying shrinkage stress due to dryness occur, and they may combine to cause cracking.

(3) Prediction of cracking based on shrinkage stress evaluation of linear members and wall members

Since shrinkage cracking often occurs in thin members, and locations in structures that can be expressed as beams, walls, etc., there is a method to evaluate the risk of cracking by stress analysis with simplified dimensions of analysis and boundary conditions.

(4) Analysis of cracking in bridges

Cracking in bridges that occurs with shrinkage of concrete as one cause show no signs of significant decline. If the occurrence of cracking becomes accurately predictable by case analysis, measures can be taken at the design and construction stages to prevent cracking. However, the technology has not actually progressed to that extent.

To predict cracking in an actual structure, it must be possible to explain the shape, location, degree, etc., of cracking that actually occurred. In actual structures, there are numerous influencing factors. In the superstructure of a bridge, for example, not only the shrinkage characteristics of concrete, but also the member dimensions, thickness, bar arrangement, PC sheath arrangement, partial loss of concrete cross-section caused by the above, construction sequence, load during construction, prestress, drying condition of each location, etc., have effects. The Committee performed an examination of several cases, including an actual PC superstructure in which there was cracking damage that could not be expected in the usual design, and made a hypothesis about contributory factors. Its validation is an issue to be examined in the future.

2.2 Effects of creep and shrinkage on the width of cracking in RC and PRC structures

For some structures, cracking does not necessarily mean that the required performance is immediately compromised. In RC and PRC structures, it has been traditionally considered that no cracking is not a required performance, but that it is necessary to ensure the performance, that is, to limit the width of cracking that would occur in service within a range so that it would not hinder the performance. Accordingly, the method of calculating the crack width plays an important role in design calculation of structures. Since shrinkage and creep have effects on the change of crack width over time in structures in service, it is a research issue to appropriately consider these effects, and reflect them in the method to calculate the crack width.

(1) Existing research on effects of shrinkage on crack width

Many studies have been conducted on the crack width of reinforced concrete, in which the effects of shrinkage and creep have also been examined.

Ishibashi et al. proposed a method in which the concrete between cracks after cracking occurs due to the removal of frames and falsework, is considered as a free body to find the shrinkage warp, and use it in the expression to calculate the crack width (**Fig. 2**)[7]. Subsequently, Seki et al. clarified in laboratory experiments that concrete shrinkage between cracks was similar to free shrinkage, because shrinkage of the concrete near the cracks was larger[8].

Although the effects of shrinkage and creep on crack width are often discussed at the same time, what the effects of creep mean is not so clear as the effects of shrinkage. Creep on the side of compression of a bending member, tension creep of the concrete between cracks, and time-dependent deterioration of the bond between reinforcement and concrete (bond creep) are possible, and it should be noted that each has a different mechanism by which it has effects on crack width.

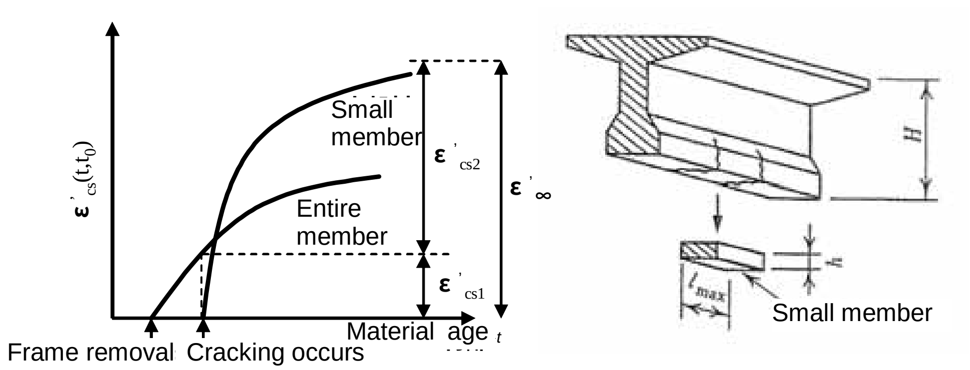

Fig. 2: Evaluation method for concrete shrinkage between cracks[7]

(2) Experiments and analyses in recent years

Both as an indicator in design and as a precondition for prediction of the subsequent deterioration process, it is essential to correctly predict the crack width in structures. A number of studies are being continued today. The Committee report presents experimental research[9)] and analytical research[10)] conducted by the members.

3. Effects of concrete shrinkage on structural performance

3.1 Effects of creep and shrinkage on deformation and stress of road and railway structures

In the civil engineering field, the effects of concrete shrinkage and creep have been considered in designing road and railway structures, such as bridges, in many different cases and in many ways. Among the methods and numerical values in design criteria today, there are those for which it is not clear how they were stipulated.

For example, several design criteria in the civil engineering field, such as the concrete standard specifications of the Japan Society of Civil Engineers, stipulate that the value of shrinkage should be set to 150 μ when finding the statically indeterminate force due to shrinkage in a rigid-framed structure, etc., using elastic analysis. Actually, the first standard specifications of the Japan Society of Civil Engineers in 1931 stipulated that "If it is necessary to consider the effects of shrinkage, it should be set to a value that has an effect equivalent to 15°C decrease in temperature", and this has been passed down to today. Because the value of 150 μ is an input value to calculate the stress allowing for stress relaxation due to creep with a simplified elastic analysis without performing creep analysis, it is an imaginary value, and it does not mean that the shrinkage warp of a free shrinkage specimen actually has this value. Also, although shrinkage of the cross-section of a member intrinsically varies depending on the composition of concrete, cross-section dimensions, environmental conditions, arrangement of bar, and material age when starting drying, it is considered that the value may be used if the conditions are within a standard range.

Setting the value of shrinkage to 150 μ is not at all inconvenient, but rather this value has actual results of being used for a long time. However, since this value may determine important specifications of structures, the reason for it and its applicability must be clarified. Effects of shrinkage and creep in the stress and crack width of statically indeterminate structures have been actually measured systematically, especially railway structures, and examined [11), 12)].

3.2 Recent issues regarding long-term deformation of PC bridges

Among the structural issues related to shrinkage and creep, one that has drawn attention of researchers all around the world is the long-term deflection of PC bridges. It has been revealed that long-term deflection over a period of several years to several decades calculated using shrinkage and creep prediction expressions for design to calculate the average distortion of the cross-section, varies depending on the prediction expression used, and that any prediction expression cannot reproduce actual long-term measured values accurately. The reason is considered to be as follows.

In the case of a PC bridge where sequential construction was performed using the cantilever erection method, not only the ultimate value of creep but also the progress curve has an effect on deflection because the loading time varies depending on the segment. The progress curve significantly varies depending on the creep prediction expression used. Also, because the cross-section of these PC bridges is a box section, and the temperature and humidity conditions of the inner and outer surfaces of the top deck board, bottom deck board and web are different, a shrinkage prediction expression or a creep prediction expression for design to calculate the average distortion in the axis direction of linear material cannot give an accurate prediction. This is also a fatalistic problem of shrinkage or creep prediction expressions that are mainly used for calculating the prestress loss or short-term behavior over a period of one or two years.

In order to overcome these problems and perform accurate prediction of long-term deflection, application of a method of analyzing multiscale structures, considering moisture transfer and heat transfer in structures according to actual conditions and incorporating accurate shrinkage and creep models, has been attempted[13)].

3.3 Effects of concrete shrinkage on building construction

This section mainly describes the effects that creep and drying shrinkage of concrete have on the deformation and stress of building construction, shows how cracks and deformation are dealt with in architectural criteria, and shows whether shrinkage affects the stress or the earthquake response of building skeletons. It also describes the problem of shrinkage and creep in ultrahigh strength concrete used in super high-rise buildings in recent years, and the issue of shrinkage in composite constructions typified by CFT.

(1) How crack width and deformation under long-term load are dealt with in architectural criteria

The Building Standards Act does not clearly describe crack width regarding RC-based constructions. The Architectural Institute of Japan's "Prestressed Reinforced Concrete (Type III PC) Structural Design, Guide for Construction and Explanation (1986)" shows that the value of the maximum crack width is 0 to 0.2 mm depending on the environmental and acting stress conditions. Also, the Architectural Institute of Japan's "Reinforced Concrete Structure Calculation Criteria and Explanation (2010)" (hereafter referred to as "RC Criteria") stipulates the degree of long-term allowable reinforcement stress, and thus indirectly prevents the crack width from increasing. The limiting value of crack width is considered to be 0.2 to 0.25 mm for the building outer surface and 0.3 to 0.4 mm for the inner surface. It stipulates that shear shall not cause shear cracking in members in principle, but long-term allowable shear force expressions that have a reinforcement contribution term may be used for beams. The RC Criteria describes that the limiting value of the long-term deflection of bending members of beams or floor slabs should be determined. It stipulates that the limiting value of the deflection of floor slabs is lx/250, and specifies the expression to calculate the thickness of floor slabs. Based on studies to understand the actual conditions of long-term deflection with long-term load-carrying experiments on floor slabs, it describes that the long-term deflection amount δ_L is 12 to 16 times the elastic deflection δ_e when both ends are secured, and 6 to 12 times for a simple support. In addition, additional clause 7 of the RC Criteria gives a prediction expression for long-term deflection.

(2) Evaluation of statically indeterminate force, and its effects on earthquake response

For a method to calculate the self-balanced stress of rigid frames resulting from temperature stress, shrinkage, etc., Aoyama[14)] proposed a method to calculate the self-balanced stress of rigid frames from the balance of force at panel points. He pointed out that, in column and beam skeletons where self-strain occurs, self-strain does not have a large effect if overall collapse is guaranteed, but it may have a large effect on local collapse. Moreover, he pointed out that self-strain has a large effect on rigidity, proposed an expression to evaluate the decrease in rigidity, and validated the practicability of the method by comparing it with the result of static load experiments of simple beam and skeleton specimens.

In RC-based structures, the statically indeterminate moment due to drying shrinkage and creep may exceed the cracking moment. If the statically indeterminate moment due to drying shrinkage and creep causes cracking in members and decreases the rigidity of the members, it can be considered that it may have an effect on the earthquake response of the entire skeleton.

(3) Shrinkage and creep of ultrahigh strength concrete

As super high-rise condominium buildings have increased mainly in urban areas, ultrahigh strength concrete with Fc 100 or more has been applied to the lower tier columns that support the large axial force of buildings in the 40 to 50-story class[15)]. When using PC columns in which ultrahigh strength concrete is used for the lower tiers of a super high-rise building, the axial stress is often set high, and the axial strain tends to be large. Accordingly, it is very important to appropriately estimate the long-term compressibility, and reflect it in the design. For ultrahigh strength concrete, it is known that, due to self-shrinkage, cracking occurs due to the difference in strain between inner and outer concrete, and restriction by the reinforcement[16)]. It has been pointed out that these phenomena may have effects on structural members[17)].

(4) Issues in composite structures

Cases in which the CFT structure is used in high-rise buildings have increased. Recently in particular, there are also cases in which ultrahigh-strength steel and ultrahigh strength concrete are used in combination. Making the strength of material higher improves the performance, but it may have an adverse effect on the unity of steel pipes and concrete when considering autogenous shrinkage. For CFT, currently the load share situation in actual structures, taking into account the shrinkage problem of filled concrete, has not been clarified yet, and it is considered important at the moment to deal with the issue practically, such as verifying with structural experiments and modeling, and planning details assuming autogenous shrinkage.

3.4 Effects of concrete shrinkage on the ultimate strength of structures and their evaluation

It has been traditionally considered that concrete shrinkage has effects mostly on cracking, displacement, deformation and prestress loss, and that it does not have a large effect on the ultimate conditions of structures. In fact, regarding the bending of reinforced concrete, it has been confirmed that although shrinkage has effects on bending crack-generating load and initial stiffness, the effects of shrinkage disappear in the ultimate conditions, and it has only a small effect on the ultimate strength and ultimate deformation.

However, Sato et al. have revealed in recent years that, if the autogenous shrinkage of high strength concrete is restrained in reinforced concrete members, the shear crack-generating load (Vc) decreases (**Fig. 3**), and have pointed that concrete shrinkage may have a non-negligible effect on the ultimate load[18)].

Maekawa et al. have been successful in reproducing the decrease in shear capacity of RC members due to shrinkage of concrete seen in experiments by Sato et al. by way of numerical analysis[19].

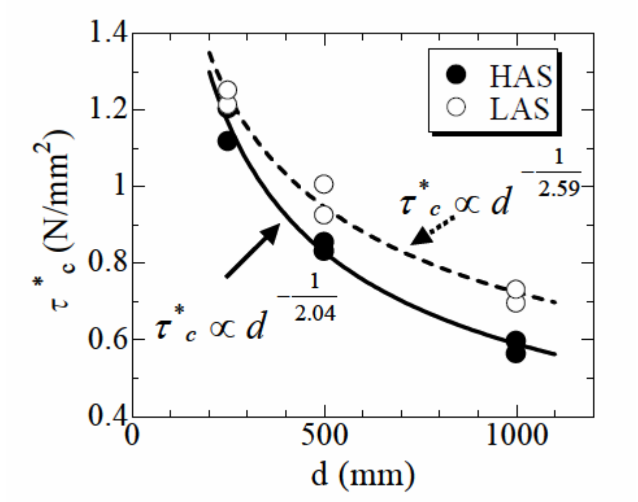

Fig. 3: Effects of shrinkage on shear capacity[18)]
(HAS: high shrinkage, LAS: low shrinkage)

4. Effects of concrete shrinkage on durability performance

The objective of Material WG was to evaluate the effects that concrete shrinkage itself has on the durability performance of concrete structures. However, since cases in which shrinkage directly relates to deterioration phenomena could not be found, the group took cracking, which is a damage caused by shrinkage or that increases due to shrinkage, and collected existing study cases regarding the effects that cracking has on mass transfer in concrete, reinforcement corrosion, and freezing damage.

4.1 Overseas research trends regarding effects of cracking on durability performance

There is a long history of research on cracking of concrete and durability, and here we report, as a relatively recent overseas approach, the activities of RILEM TC 214-CCD (Concrete cracking and its relation to durability: Integrating material properties with structural performance) in 2012. The head of the TC is Professor Jason Weiss of Purdue University of the United States, and the manager is Professor Mette Geiker of the Technical University of Denmark. The kickoff meeting was held in Quebec, Canada in 2006, and sessions have been held about once a year since then. In its state-of-the-art report, it is planned to present models of crack formation and models of mass transfer in cracking parts, and compare allowable crack width between countries, etc. Activities are now under way to realize the above (**Fig. 4**).

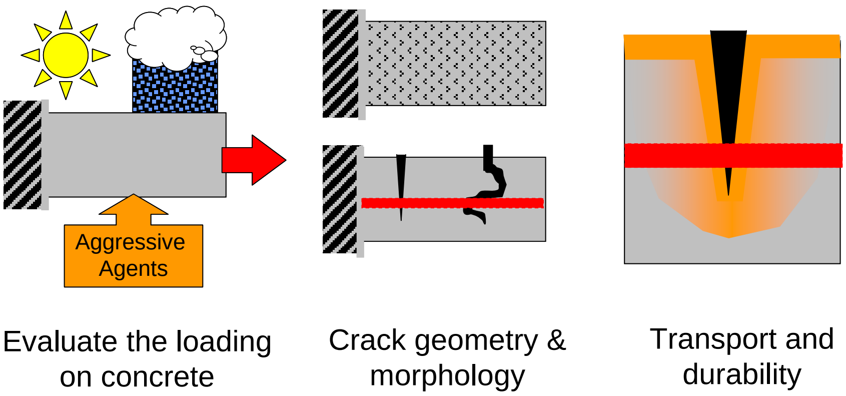

Fig. 4: Association chart between cracking and durability cited by the TC (excerpt from the minutes of 2008 TC meeting)

4.2 Effects of cracking in concrete on mass transfer, and their evaluation

(1) Effects of internal cracking on reinforcement corrosion

It is commonly known that internal cracking occurs around deformed bars in the tension part of reinforced concrete[20)]. Such internal cracking has effects on the bond characteristics between reinforcement and concrete, and also it decreases the density of cover concrete[21)]. Since the decreased density of cover concrete makes it easy for reinforcement corrosion factors, such as oxygen and moisture, to penetrate, it is considered that it facilitates reinforcement corrosion. Accordingly, we produced specimens with both sides pulled that have different amounts of chloride mixed in, provided them for corrosion facilitating tests, and examined the effects that internal cracking has on reinforcement corrosion. **Fig. 5** shows the reinforcement corrosion rate measured using the polarization resistance method[22)]. Although there is only one example, a result was obtained in which the reinforcement corrosion rate increased when a pull force was applied to generate internal cracking. The regression line in the diagram is drawn from a corrosion rate prediction expression in existing studies[23)].

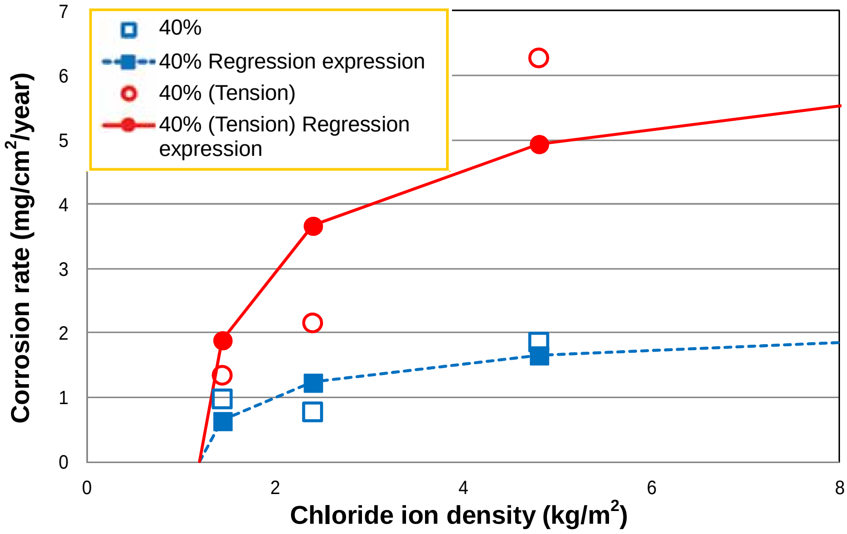

Fig. 5: Effects of internal cracking on the corrosion rate of reinforcement[22)] (W/C=40%, examination of whether or not tension is acting)

(2) Numerical analysis of the effects of cracking on mass transfer

Compared to the matrix part of hardened cement paste composed of microscopic voids, mass transfer is accelerated in the cracking part. Many existing studies that use numerical analysis models deal with the mass transfer phenomena of concrete containing cracks by modeling the transfer phenomenon in each of the matrix and cracking parts, and combining the models. One study evaluates the moisture flux in the cracking part with the average crack distortion[24)], and another expresses the increase of diffusion coefficients according to the crack width[25)]. For quantitative relations between the crack width, crack interval or average crack distortion and the mass transfer rate of moisture, gas and ion, a theory has not yet been established. This may be because the degree of acceleration varies compared to the matrix part, since the transfer mechanism in the cracking part varies depending on the conditions, such as whether vapor or gas transfer is a prominent issue in the cracking part, whether ion transfer always occurs in a permeated condition, or whether moisture transfer is the main factor under alternate wetting and drying conditions. Models that discretely deal with the shape of cracks[26),27)] and a method that deals with a wide range of void distributions from nano to milli[28)] have also been proposed in recent years, and highly accurate quantitative evaluation methods based on microscopic mechanisms are expected to be devised in the future.

4.3 Effects of cracking in concrete on reinforcement corrosion

(1) Examination of reinforcement corrosion in the cracking part including the effects of covering

It has been confirmed, through a number of experiments and studies, that the corrosion property of reinforcement in concrete containing cracks is affected by the crack width, and it is also well known that the corrosion content cannot be evaluated only by the crack width. Apart from crack width, there are many factors that affect corrosion, and one that is considered to have an especially large effect is "kaburi" (covering).

Kamiyama proposed, as an indicator to simultaneously evaluate the effects that crack width and kaburi have on reinforcement corrosion, [crack width/kaburi^2][29]. We applied this indicator to experimental and research results of other researchers[30)-34)], and examined its validity. As a result, although the corrosion content can be evaluated only by the crack width if the kaburi are the same, it was confirmed that [crack width/kaburi^2] is valid for evaluation when kaburi are largely different from each other. Based on this, [crack width/kaburi^2] is considered to be an indicator that can represent crack shape that has effects on the progress of corrosion. Naturally, however, if the material or composition is different or the cause of corrosion (salt damage, carbonation) or the corrosion environment (supply condition of chloride ion, temperature, humidity, etc.) is different, the corrosion content cannot be evaluated only by the crack width and kaburi.

(2) Effects of carbonation and cracking on reinforcement corrosion

In experiments to facilitate carbonation, whether there is cracking or not has a large effect on reinforcement corrosion, whereas the effect of crack width gives different results. However, according to some studies, a crack width of up to about 0.1 to 0.2 mm has a large effect on corrosion, whereas a crack with wider width than that results in a smaller effect. As a reason for this, it may be considered that, because the cracking has not reached the position of reinforcement or the crack width at the tip is extremely small, carbonation has not progressed sufficiently or the supply of moisture, etc., is restrained. A number of studies have pointed out that the kaburi thickness has a large effect on reinforcement corrosion. On the other hand, the results of long-term exposure and investigations of actual structures show some examples in which the crack width or kaburi thickness is not necessarily related to the corrosion content, and others in which the relation between cracking locations and corrosion is small. This may be partly because the effects of variation in construction quality or service environment on reinforcement corrosion are not sufficiently understood.

(3) Corrosion property of reinforcement in the cracking part in an environment where there is

a large supply of chloride ion

Based on the results of multiple exposure tests in the marine environment, we considered the corrosion behavior of the cracking part in the marine environment. It was observed that the macro-cell corrosion rate in the cracking part decreased over time, whereas the micro-cell corrosion rate tended to increase over time.

When the types of cement are different, the corrosion situation varies even if the crack width is about the same. The corrosion in the cracking part was restrained in the case where the diffusion of chloride ion was slow, such as with Portland blast furnace slag cement. Moreover, a correlation was observed between the micro-cell corrosion rate at in cracking part and the chloride ion density at the reinforcement location. The start and progress of reinforcement corrosion in the cracking part is similar to that in a sound part without cracking, which suggests that "the chloride ion density around the cracking part" can be "an (engineering) indicator regarding corrosion around the cracking part". In other words, this suggests that the corrosion rate of reinforcement in the cracking part can be evaluated by considering the diffusion property of chloride ion in the cracking part.

(4) Cracking and macro-cell formation

Formation of a macro-cell corrosion circuit requires a non-uniform difference in spontaneous potential, and the space between cracks in concrete has an effect on the non-uniform difference. If the space between cracks is small, the degree of equalization of the spontaneous potential in the micro-cell corrosion circuit is large, and therefore, the relative difference of spontaneous potential between reinforcement elements is small and current density during formation of the macro-cell corrosion circuit is also small. On the other hand, if the space between cracks is large, the change in spontaneous potential in the micro-cell corrosion circuit is locally large, and therefore the current density during formation of the macro-cell corrosion circuit is also large. At this point, the cracking part becomes an anode, and therefore the corrosion content in the cracking part is also large. Note that the current density in the micro-cell corrosion circuit becomes larger as the number of cracks increases, and it is different from the current density during formation of the macro-cell corrosion circuit **(Fig. 6)**[35).

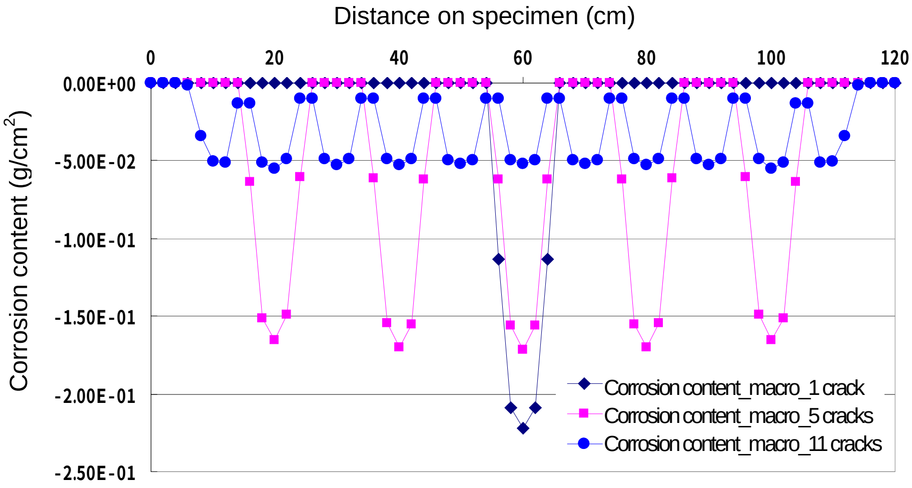

Fig. 6: Analysis results for the corrosion content of a shrinkage specimen[35)]

4.4 Effects of cracking in the concrete surface on freezing damage

Surface cracking due to drying shrinkage, etc., although depending on the width and crack density, causes many fine cracks to facilitate the penetration of moisture, and therefore has an adverse effect on freezing damage. This has been reported by the results of a fact-finding investigation of concrete structures in the Tohoku region[36)], an exposure experiment for 20 years introducing cracking[37)], experiments on steam-cured concrete[38), 39)], and others.

Otsuka et al.[38), 39)] revealed that fine surface cracks in steam-cured concrete have an adverse effect on durability. In particular, they indicate that, if the secondary curing in which products are stored on factory premises after the completion of steam curing is atmospheric curing, fine cracks that occurred due to steam curing develop due to drying shrinkage, and thus have an adverse effect on freezing and thawing resistance, neutralization resistance and salt permeability. Watanabe et al.[40)] indicate that, due to a similar mechanism, as characteristics of freeze deterioration of prestressed concrete telephone poles, fine cracks occur in the axial direction, and the cracks facilitate the penetration of chloride ion.

There is a report that says that through cracks with larger width do not have an effect of facilitating freezing damage[37)], whereas Naito et al.[41)] indicate that, in experiments introducing simulated cracks using slits, cracks open and develop due to the freezing expansion of water penetrating the cracking part because of the existence of initial cracks, even if AE concrete is used.

5. Conclusion

Effects of concrete shrinkage in the design of structures have been considered in various ways. On the other hand, as we indicated this time, issues regarding long-term deformation of PC bridges, decrease in shear capacity shown by recent experimental results, and new issues in ultrahigh strength concrete and composite structures, have also been revealed. Although there is a long history of research on the relation between cracking and durability, clarification of the mechanism or a quantitative evaluation has not yet been successful. To understand the essence of these effects that concrete shrinkage has on the performance of structures, evaluate them quantitatively, and take rational and effective measures, it is essential to address the subject as a dual problem of material and structure, and perform analyses based on the physicochemical mechanism. A method that is expected to fulfill that purpose is durability mechanics. With the activities of this Committee as a start, we would like to promote research activities in this field, and contribute to the improvement of techniques to design and build concrete structures that have the required performance.

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