Durability mechanics of concrete and concrete structures - re-definition and a new approach -

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ABSTRACT: This paper gives a summary of the activities of the Working Group on Durability Mechanics (WG3) within the Japan Concrete Institute (JCI) Technical Committee on Time Dependent Behavior of Cement-Based Materials (JCI-TC061A). A re-definition of and new approach to durability mechanics is proposed for establishing systematic prediction and evaluation of the time-dependent behavior of concrete materials and structures. The chemo-mechanical deterioration of cementitious materials over time due to chemical reaction, environmental action, and external load, are described by physicochemical models of reaction, transport, fracture and their coupling. Furthermore, the performance of concrete structures over time is also discussed. In addition, the outlines of several representative research projects on durability mechanics will be introduced.

1 INTRODUCTION

Concrete is a well-known resource used in public works and buildings that support the lives of people. The performance of concrete structures can be sustained for a long time if such structures are appropriately designed and constructed.

However, in the U.S. a nation with a long established infrastructure, poor maintenance and repair caused bridge failures and slab caving, resulting in a large loss to society and leading to the publication of “America in Ruins” in the 80s (Choate & Walter 1981). More recently in North America, reinforcing steel corrosion and the combined actions of freezing and thawing caused a couple of bridge collapses.

Japan, on the other hand, experienced a construction boom in the period of high economic growth from the latter half of the 60s to the 80s, when a very large number of concrete structures including mass concrete structures were built, approximately 30 years after the USA. The concrete pump was first introduced in this period, leading to the requirement of high unit water content for concrete, and hydration heat induced cracking problems were exposed. Before 1980, chloride attack and the alkali-aggregate reaction were not taken as seriously as today and standards and guidelines failed to clearly described them. This invited the major problem of early-stage degradation, the occurrence and degradation mechanisms of which are being studied to this day.

Early-stage degradation develop in conjunction with several factors: ingress of harmful substances into the pore structure formed during hydration reactions, reactions between the harmful substances and hydration products or reinforcing steels, damage accumulation including cracks associated with hydration-induced temperature rises, autogenous shrinkage, drying shrinkage depending on the outer environment, and loading. The complexity of these factors is also compounded by various chemical and physical interactions. Lifetime design of concrete structures must solve physicochemical interactions and their couplings.

Durability Mechanics was first formulated in the 6th CONCREEP in 2001 by Prof. Ulm as a new discipline of Engineering Mechanics concerned with early-stage degradation and a number of critical problems related to safe and economic hazardous waste storage (Coussy & Ulm 2001). Durability Mechanics includes three sub-fields: 1) degradation kinetics, 2) chemo-mechanical couplings at the materials level and 3) prevention, diagnosis/prognosis on the structural level.

Inspired by Ulm’s approach and based on a huge amount of related studies in our country, our working group defined an independent Durability Mechanics as a discipline where performance evaluation of concrete structures is dealt with by micro-macroscopic chemo-physical models taking account of complex couplings of materials and structures in space-time continua.

2 PROPOSED RE-DEFINITION OF "DURABILITY MECHANICS"

The Working Group on Durability Mechanics within the Japan Concrete Institute (JCI) Technical Committee on Time Dependent Behavior of Cement-Based Materials has proposed the following re-definition of *durability mechanics* based on the proposal of Coussy & Ulm (2001) in order to systematize each deterioration factor so as to lead finally to the prediction and evaluation of the structural performance of concrete structures:

"Durability Mechanics for concrete structures is one of the academic disciplines of Engineering Mechanics for the systematic prediction and evaluation of time-dependent behavior of concrete materials and structures, in which the chemo-mechanical deterioration of cementitious materials over time due to chemical reaction, environmental action, and external load, can be described by physicochemical models of reaction, transport, fracture and their coupling, and the performance of concrete structures over time can be also predicted by constitutive models of deteriorating materials."

3 SUMMARY OF ACTIVITY OF WG

3.1 *Approach to durability mechanics*

Figure 1 shows the approach to materialization of *durability mechanics* of WG3. The cause, mechanism and coupling effect in the process of time-dependent deterioration of concrete and concrete structures are systemized, including the effects of environmental action and external load.

As a preliminary step to the materialization of the concept of durability mechanics, a flow diagram describing the process of deterioration has been prepared by reordering related information. Next, a framework of the time-dependent processes of 1) production, change and consumption of substances, 2) transport of substances, 3) material and structural properties, and 4) their interaction, named "Mandala for durability mechanics," has been made. Then, the element models describing phenomena resulting in deterioration and the prediction methods for each deterioration processes are summarized. Finally, examples of the interaction between materials property and structural performance as well as modeling and simulation of structural performance are introduced.

3.2 *Mandala for Durability Mechanics*

Figure 2 shows the Mandala, which is a figure describing the whole system of durability mechanics. This figure includes the process before casting, because the quality of construction strongly affects the quality of hardened concrete. However, this paper focuses on the phenomena after casting because of the limited number of theoretical approaches evaluating the influence of the construction process on the material properties.

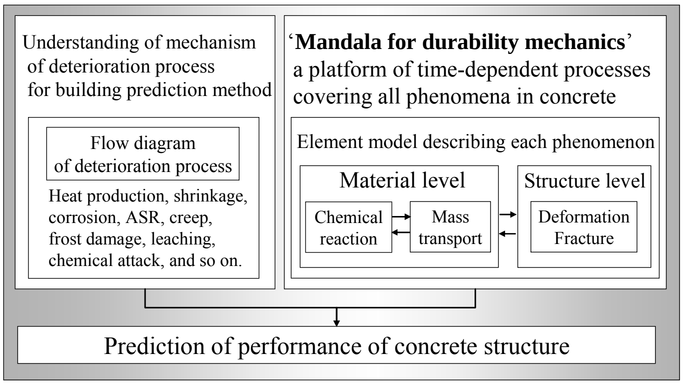

Figure 1. Approach to *durability mechanics.*

3.3 *Contents of Japanese report*

The WG released a Japanese report on December 21, 2007. This report was for Japanese researchers and engineers. The contents of that report are given below.

1. INTRODUCTION
1.1. Background
1.2. Durability mechanics as proposed by Ulm
1.3. Definition of Durability Mechanics
1.4. Mandala for Durability Mechanics
1.5. Contents of report
2. MECHANISM OF DEGRADATION
2.1. Introduction
2.2. Outline of degradation
3. MODEL ELEMENTS FOR DURABILITY MECHANICS
3.1. Models regarding generation, transition and consumption
3.1.1. Rate of chemical reaction
3.1.2. Equilibrium
3.1.3. Heat generation
3.1.4. Micro pore structure
3.1.5. Moisture equilibrium
3.1.6. Rate of chemical reaction
3.2. Models regarding mass transport
3.2.1. Outline of modeling
3.3. Examples of models regarding mass transport
3.3.1. Moisture transport
3.3.2. Heat transport
3.3.3. Interaction of heat and moisture transport
3.3.4. Gas transport
3.3.5. Ion transport
3.4. Models regarding volume change, deformation, stress and cracking
3.4.1. Volume change and deformation
3.4.2. Change of strength and stiffness
3.4.3. Cracks
4. PREDICTION OF DEGRADATION IN DURABILITY MECHANICS
4.1. Introduction
4.2. Outline of prediction

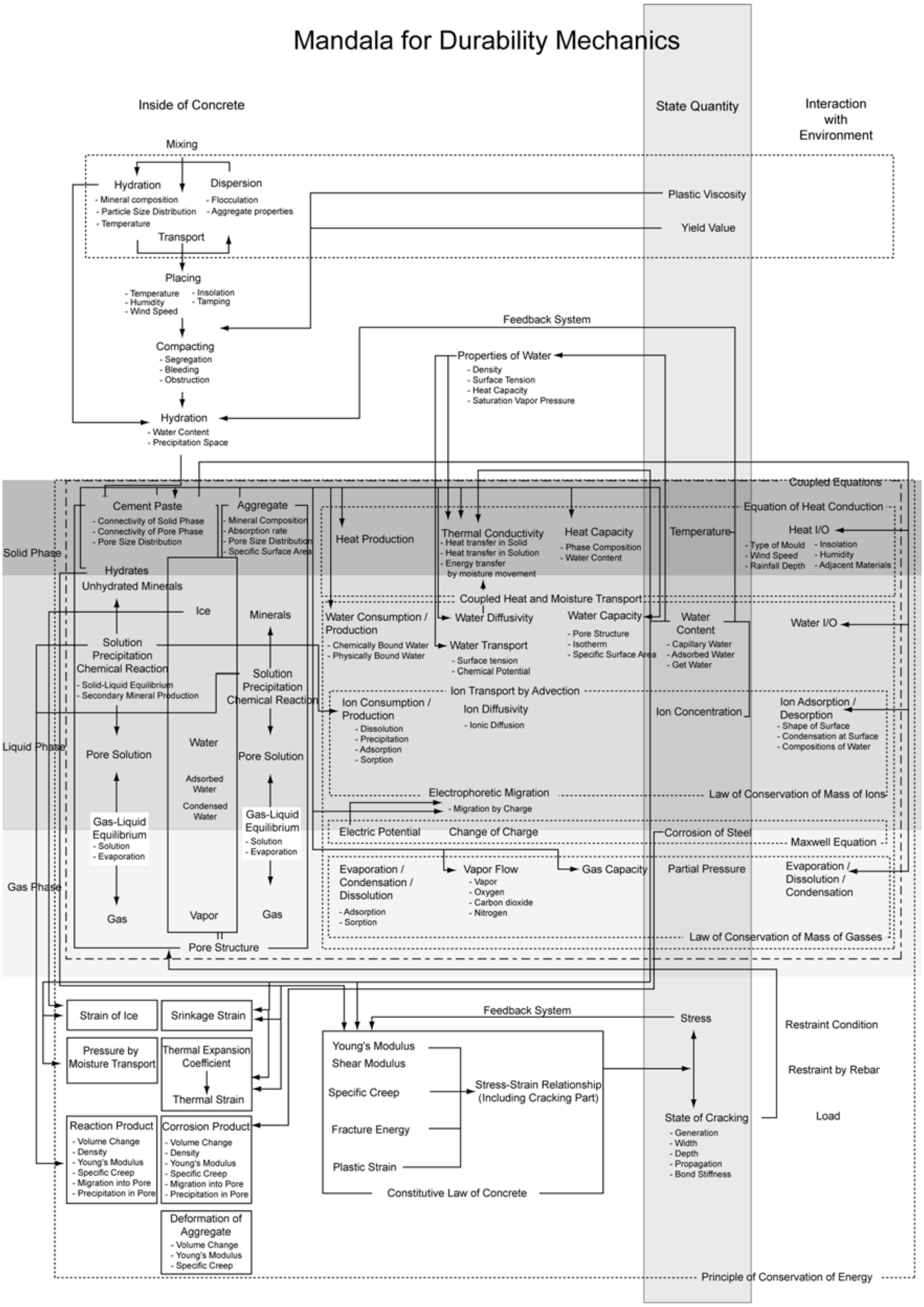

Figure 2. Mandala for *durability mechanics.*

5. APPROACH OF DURABLILITY MECHANICS TO STRUCTRAL PERFORMANCE EVALUATION
5.1. Introduction
5.2. Analysis of interactions between materials and structures based on experiments
5.3. Modeling and numerical simulation for structural performance evaluation
6. CONCLUSIONS

4 OUTLINE OF DURABILITY MECHANICS OF DEGRADATION

This chapter introduces approaches to each degradation phenomenon from the point of view of *durability mechanics*. As the performance of reinforced concrete structures, as well as structures with cement based materials, should be evaluated through structural performance, not only the degradation process itself, but also the relevant alteration of structural performances, are discussed.

4.1 *Durability Mechanics related to heat production and shrinkage*

4.1.1 *Mechanisms of cracking*

Cracking due to heat production and/or shrinkage is roughly explained by the following process; 1) volume change of concrete, 2) stress production by restraint of volume change, and 3) cracking of concrete.

Cracking due to heat production, which is frequently observed in mass concrete, is caused by volume change determined by difference of temperature and the thermal coefficient of concrete.

Shrinkage cracking is caused by shrinkage of concrete. The mechanism of shrinkage is usually explained by 3 well-known theories: capillary tension, disjoining pressure, and surface tension of colloidal cement hydrates (Powers 1965). In the case of water evaporation from the concrete surface, the term "drying shrinkage" is used, and in the case of self-desiccation due to cement hydration, the term "autogenous shrinkage" is used, although the mechanisms is usually considered to be the same. The process of cracking due to heat production and the process of cracking due to shrinkage are presented in Figure 3 and Figure 4, respectively.

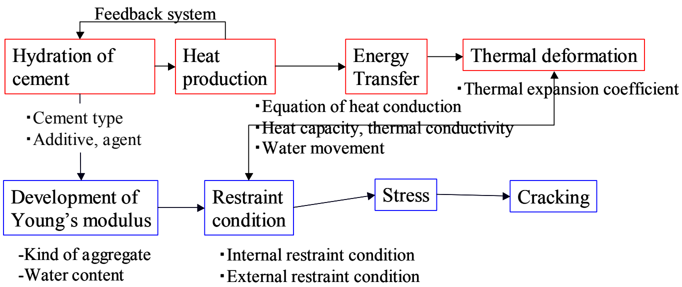

Figure 3. Process of cracking due to heat production.

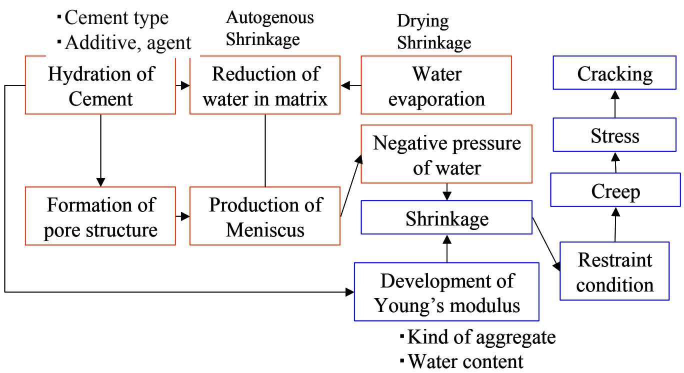

Figure 4. Process of cracking due to shrinkage.

4.1.2 *Approach of Durability Mechanics*

The components of interaction and flows for the evaluation of the risk of cracking and the prediction of cracking are summarized in Figure 5, and important items are discussed below.

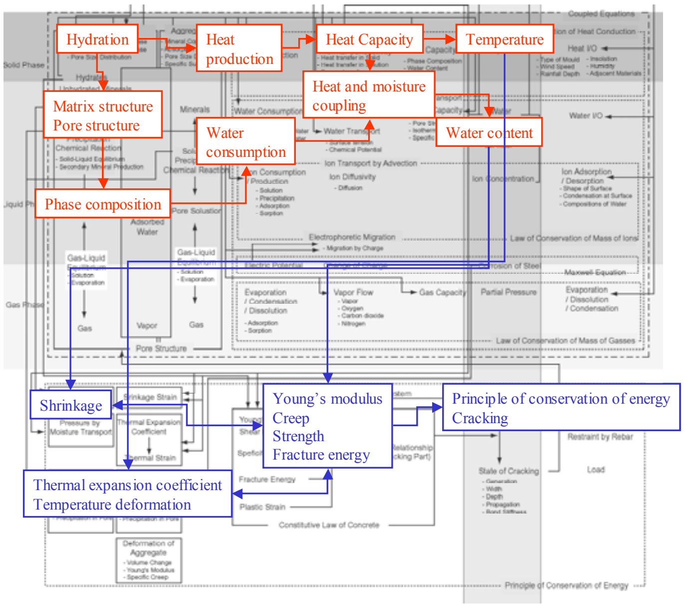

Figure 5. *Durability mechanics* regarding heat production and shrinkage.

4.1.2.1 *Hydration system*

The prediction of cement hydration is fundamental and essential for the evaluation of concrete performance, especially heat production, the water content of the system, and the microstructure of the cement paste matrix. This also contributes to the evaluation of the time-dependent behavior of concrete at early ages.

Prediction of the rate of cement hydration is one of the major concerns not only of the cement chemistry but also concrete engineering. The model by Kondo (1968) is famous as a model of classical research in the field of cement chemistry. Research of the application of the hydration model to the field of concrete engineering by Tomosawa (1974) stimulated the field of chemistry as well as the field of concrete engineering. In the last few decades, several hydration models, including HYMOSTRUC (van Breugel 1991), CEMHYD3D (Bentz 1997), DuCOM (Kishi & Maekawa 1994), Navi's model, (P. Navi, et al. 1996) and CCBM (Maruyama et al. 2007), have been put forth.

4.1.2.2 *Temperature prediction*

The temperature history and distribution in concrete members are commonly evaluated by unsteady thermal conductivity analysis, whose governing equation is:

$$\rho c\frac{\partial T}{\partial t}=-div\left(-gradT\right)+\dot{Q}(t) \tag{1}$$

where ρ: density of concrete, c: heat capacity of concrete, T: temperature, t: time, and $Q(t)$: rate of heat generation of concrete.

Regarding heat generation terms, the adiabatic temperature rise curve is widely used, and the following type of equation is adopted for guidelines (JSCE 2005b, AIJ 2008).

$$Q(t) = K(1 - e^{-\alpha t}) \tag{2}$$

where $Q(t)$: adiabatic temperature of concrete, K: ultimate temperature, α: coefficient for rate of temperature rise, and K and α are usually presented as a function of cement type and the temperature of fresh concrete.

Recently, prediction of this adiabatic temperature rise is being done with the aforesaid hydration models.

The constant values of thermal conductivity and heat capacity of concrete are generally used in unsteady thermal conductivity analysis, while heat transfer is seen in solid, liquid, and vapor phase in reality. For the purpose of high accuracy of prediction, the problem of heat and moisture coupling should be modeled with a hydration model (Maruyama et al. 2006).

4.1.2.3 *Volume change of concrete due to temperature change*

Evaluation of the volume change of concrete due to temperature change and the thermal expansion coefficient is necessary. The thermal expansion coefficient decreases until the setting time and increases after that gradually (Bjϕntegaard & Sellevold 2001, Yang & Sato 2002). The thermal expansion coefficient of concrete is affected by the water content (Mayer 1950) and type of aggregate (Neville 1995). The precise time-dependent behavior of the thermal expansion coefficient contributes to the evaluation of the risk of cracking at the surface of mass concrete as well as through cracking.

4.1.2.4 *Autogenous shrinkage*

Concrete with a low water to binder ratio exhibits considerable autogenous shrinkage. This type of concrete is usually used with a large amount of cement in unit volume, and thus it experiences a relatively high temperature rise at an early age. The evaluation of autogenous shrinkage in real size members, constituent separation of temperature deformation and autogenous shrinkage is important. From this aspect, various experiments on the thermal expansion coefficient have been done recently.

There are several models of autogenous shrinkage based on the hydration model. Bentz (1995) and Koenders (1997) use the surface tension theory, whose approach is similar to the Munich model proposed by Wittmann et al. (1982). The mathematical expression is as follows:

$$\frac{\partial \varepsilon_{sh}}{\partial \alpha} = \lambda \cdot \frac{\partial \gamma}{\partial \alpha} \tag{3}$$

$$\lambda = \frac{\Sigma \cdot \rho}{3E} \tag{4}$$

$$\gamma = RT \int_{p_g/p_0}^{p_g/p_0=1} \Gamma d \ln(p_g / p_0) \tag{5}$$

where Γ: layer thickness of adsorbed water, p/p_0: relative humidity, Σ: surface area of porous media, ρ: density of porous media, and E: Young's modulus of the matrix.

Shimomura (1992) modeled the shrinkage of cement paste or concrete with the following equations using the pore size distribution model:

$$\sigma_s = A_s \frac{2\gamma}{r_s} \tag{6}$$

$$\varepsilon_{sh} = \frac{\sigma_s}{E_s} \tag{7}$$

σ_s: capillary tension, A_s: area affected by capillary tension (assuming that it is equal to water content in the system), r_s: Kelvin radius, ε_{sh}: shrinkage strain, and E_s: compliance of concrete ($1/4E_c$ is used for concrete). More information will be introduced in section 5.2.

4.1.2.5 *Prediction of stress*

The stress distribution and stress history in a target member is generally predicted by solving the balance of forces among the target member and related members. The Finite Element Method (FEM), Boundary Element Method (BEM), and Rigid Body Spring Model (RBSM) are often used for solving stress-related problems, while, especially in the case of mass concrete, the Compensation Plane Method (CPM) is widely used in Japan (Tanabe 1986). This method is based on the assumption of linear strain distribution, which compensates the strain distribution due to temperature change and resultant restraint stress. CPM takes into account the effect of the bending restraint condition, and evaluates cracking from the upper fiber of the target member. CPM is covered in greater detail in section 5.1.

Evaluation of creep strain, which takes into account of the concrete type, w/c, loading age, and other factors, improves the accuracy of stress analysis in general. The guideline for controlling cracking of mass concrete of JCI (1986) adopts the effective Young's modulus method. The value range of 0.36-0.50 is proposed for when the temperature increases due to hydration-generated heat, and the value range of 0.63-1.67 is proposed for after the temperature has peaked. JSCE standard (2005b) also employs similar method.

Recently, as creep data at early ages has been accumulated, creep function taking into consideration the loading age is widely accepted, and a step-by-step method has also been applied for stress prediction (AIJ 2008). This step-by-step method is based on the linearity of creep in relation to stress, and the identification of compressive and tensile creep.

Creep behavior during the hydration process is a major concern for early age cracking. Bazant (1977) proposed the creep behavior of solidifying material taking into account the effect of newly formulated substances in a stress-free state.

Kawasumi et al. (1982) proposed a model of creep behavior at early ages based on the degree of hydration. This model assumed that the creep behavior of concrete is an inherent property of CSH, and the ultimate creep strain is determined by the amount of CSH in the concrete. This model shows good agreement with the creep behaviors of concrete at different loading ages as well as different w/c. Recently, a more quantitative approach was proposed by Lokhorst (1994), as well as DuCOM-COM3 (Asamoto et al. 2006).

Autogenous shrinkage in mass concrete cannot be neglected for stress analysis, especially in the case of using special binder, such as blast furnace slag (Dilgar et al. 1995). The new JCI guideline (2008) proposes an engineering equation of temperature dependent autogenous shrinkage.

4.1.2.6 *Evaluation of cracking*

Cracking behavior factors such as age at cracking, cracking width, and time-dependent cracking propagation are issues under study. Regarding the problem of cracking in mass concrete, Nagataki & Sato (1986) proposed a method for crack width prediction that solves the balance of forces between rebar and concrete with the given relation of stress in rebar, bond stiffness, and slip. Recently, the combination of CPM with FEM for the prediction of crack width has been proposed (Tanabe 1986). Further, RBSM taking into account the time-dependent fracture energy of concrete is also being used for this problem (Srisoros et al. 2007).

The risk of cracking has been experimentally evaluated by TSTM (Springenschmid et al. 1985), which is able to restrain concrete deformation perfectly and gives the emulated temperature history of members at real sites. This experimental equipment is widely employed in many countries for the evaluation of cracking risk.

Regarding cracking due to autogenous shrinkage, Maruyama et al. (2006) detected that micro-cracks around reinforcing bars are caused by autogenous shrinkage and that such cracks degrade bond stiffness in the transfer zone (Maruyama & Sato 2007), Additionally they proposed a time-dependent micro-crack model for evaluating the stress of concrete members including early age cracking.

4.2 *Durability Mechanics related to steel corrosion*

4.2.1 *Mechanisms of corrosion cracking*

The mechanism of deterioration due to steel corrosion is shown in Figure 6. After concrete casting, the processes whereby steel corrosion is induced and cracking occurs can be classified into passivation, depassivation, and cracking induction.

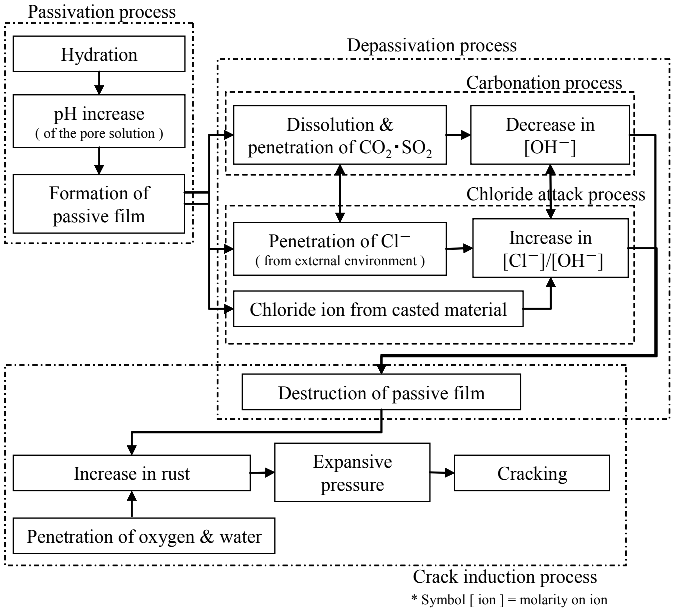

Figure 6. Mechanism of deterioration due to steel corrosion.

4.2.1.1 *Passivation process*

In the passivation process, the pore water becomes a highly alkaline environment with a pH of 12.5 or higher, and a dense oxide layer, called passive film, is formed on the surface of the steel by hydroxide ions resulting from the cement hydration.

$$\begin{aligned} &2Fe^{2+} + 4OH^{-} + 1/2\,O_2 \rightarrow 2FeO(OH) + H_2O \\ &2FeO(OH) \rightarrow Fe_2O_3 + H_2O \end{aligned} \tag{8}$$

The passive film protects the steel from further corrosion since it impedes the dissolution of steel.

4.2.1.2 *Depassivation process*

In a general environment, neutralization and chloride attack are well known causes of the destruction of the passive film.

Neutralization starts with the dissolution and penetration of carbon dioxide (CO_2) or sulfurous acid gas (SO_2) into pore water in concrete.

The dissolute carbon dioxide reacts with calcium hydroxide in cement hydrate, and then, drops the pH of pore water.

$$Ca(OH)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2H_2O \tag{9}$$

Chloride attack is a phenomenon whereby chloride ions destroy partially the passive film on the steel surface and induce pitting corrosion. Chloride ions originate from casted materials, sea water, or deicing salt. Although chloride ions are partially fixed to the cement hydrates, the free chloride ions penetrate through pore water to the interior of the concrete.

Destruction of passive film by chloride ions is strongly dependent on [Cl^-]/[OH^-] (molarity ratio of chloride ions to hydroxide ions) and occurs easily when this ratio increases.

Regarding combined action of neutralization and chloride attack, if the pH of the pore water is lower, destruction of the passive film occurs easily at lower chloride ion concentrations. Since a reduction of the pH level also causes the production of chloride ions by causing the release of fixed chloride, this accelerates the destruction of the passive film.

4.2.1.3 *Cracking induction process*

The conditions required for inducing corrosion cracking are the destruction of the passive film and the occurrence of dissolution in steel. Electrochemical corrosion occurs on de-passivated steel when the steel dissolves in the pore water for the anodic reaction and the sufficient oxygen are available for the cathodic reaction.

$$\begin{aligned} &Fe^{2+}+2OH^- \rightarrow Fe(OH)_2 \\ &4Fe(OH)^+ + O_2 \rightarrow 4FeO(OH)+4H_2O \end{aligned} \tag{10}$$

At the anode, chloride ions generate hydrochloric acid with water, causing a drop in pH, and also stimulate the anodic reaction. Ionized iron changes into $Fe(OH)^+$ and FeO(OH) and rust forms. Hydrochloric acid condenses under the rust layers, and the corrosion of the steel evolves into continuous pitting.

$$\begin{aligned} &Fe^{2+}+2Cl^- + H_2O \rightarrow (Fe(OH)^+ + 4Cl^-)+(H^+ + Cl^-) \\ &4Fe(OH)^+ + Cl^- + O_2 + 2H_2O \rightarrow 4FeO(OH)+4H^+ + 4Cl^- \end{aligned} \tag{11}$$

The volume of rust of $Fe(OH)_2$ is close to 4 times greater than that of steel consumed. The volume of $Fe(OH)_3$ is approximately over 4 times greater. If water is restricted, the volume of $Fe(OH)_3{\cdot}3H_2O$ is more than 6 times as that of the steel.

The volumetric expansion of rust due to corrosion is converted into forces that split the concrete surrounding the steel. These forces may cause compressive stress in the radial direction and tensile stress in the circumference direction. Cracking occurs if this tensile stress exceeds the tensile strength.

4.2.1.4 *Degradation of structural performance due to rebar corrosion*

Structural performance, such as stiffness and loading capacity, of reinforced concrete structures is degraded by corrosion of reinforcing steel bars.

The mechanical properties of a corroded reinforcing steel bar should be evaluated by an index related to the area of the cross section or its shape, but there is no effective method to measure or digitize such properties. Therefore, mechanical properties are often evaluated by another index, such as the ratio of corrosion weight loss, which is given by Equations (12) and (13) below.

$$C = \Delta w / w \times 100(\%) \tag{12}$$

$$\Delta w = w - w_2 \tag{13}$$

where w: weight of sound reinforcing steel, Δw: corrosion weight loss and w_2: residual weight after removal of the rust.

The yield strength of a corroded reinforcing steel bar is expressed by Equation (14) below using the ratio of corrosion weight loss. The yield strength is determined using the nominal cross sectional area of a sound bar.

$$y = 1 - k(C/100) \tag{14}$$

where y: f_{syc}/f_{syn}, f_{syc}: yield strength of corroded bar, f_{syn}: yield strength of sound bar and C: ratio of corrosion weight loss (%). Coefficient k differs with studies due to the difference in corrosion condition or bar diameter.

The flexural capacity of an artificially corroded RC member is decreased by corrosion of the reinforcements. According to most previous research, the decrease in flexural capacity due to corrosion can be evaluated to some extent by considering the cross-sectional loss and/or weight loss of reinforcements, as shown in Figure 7 (Oyado & Sato, 2005). However, opinions about the relationship between the decreasing rate in the flexural capacity and that in the cross section and weight of reinforcements differ among researchers. This is considered to be due to the flexural stress concentration caused by the localized corrosion of reinforcements. Since the distribution of the cross sectional area of corroded reinforcement is not uniform, the calculated flexural capacity of corroded RC members is dependent of the evaluation techniques for the distribution of the cross sectional loss and/or weight loss of the reinforcement.

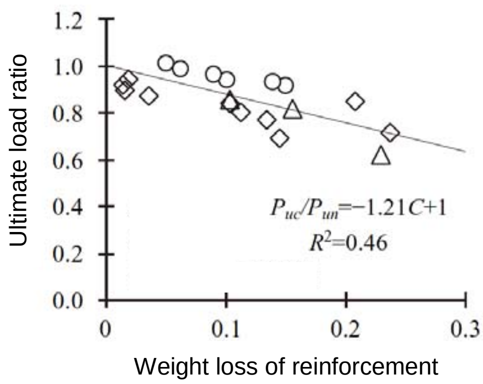

Figure 7. Flexural capacity vs. weight loss in experimental RC members.

4.2.2 Approach of Durability Mechanics

The models in the "Mandala for Durability Mechanics" for simulating corrosion cracking are shown in Figure 8.

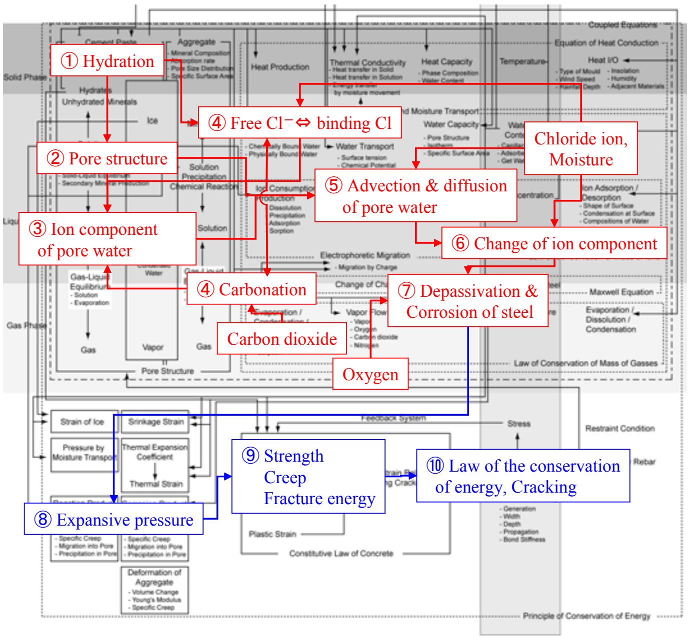

Figure 8. *Durability mechanics* related to crack due to corrosion of steel.

4.2.2.1 *Pore structure and liquid phase ion formation accompanying the hydration reaction*

Pore structures and ions in the micropore solution are formed during the cement in the concrete hydrates. These change with time as the hydration progresses. Pore structure has a significant effect on the ion transport associated with chloride attack and neutralization, while ion formation has a significant effect on the ability to protect steel from corrosion. The modeling of pore structure and ion formation is the starting point of the approach to the simulation of corrosion damage. Since this model is similar to the one described in section 4.1, further description of the model is omitted here.

4.2.2.2 *Free chloride ions and bound chloride*

Chloride ions, which are external factors of salt damage, come from the concrete materials or the environment. Some of these chloride ions are adsorbed and bound in cementitious material, while others exist in liquid phase as free chloride ions. The effect of the type of cement (including admixture) significantly affect on the binding capacity of chloride ions. Various approaches to the chloride binding mode have been taken in terms of experimental and analytical methods in Japan (Maruya et al. 1992, 1998, Hirao et al. 2005, Hosokawa et al. 2006, Ishida et al. 2008). For example, Hosokawa et al. (2006) studied the time-dependent behavior of chloride ions and hydroxide ions in pore solution through experiments and analyses, and they proposed a model describing the ratio of chloride ions in pore water to the hydroxide ions as,

$$\alpha_i(t) = \frac{\alpha_i^{\infty} \cdot k_i \cdot t}{1 + k_i \cdot t} \tag{15}$$

$$C_M(t) = \frac{m_r}{V_P + bP} \tag{16}$$

where $\alpha_i(t)$: reaction rate of mineral i at age t, α_i^{∞}: ultimate value of reaction rate of mineral i, k_i: constant indicating ability of reaction, $C_M(t)$: alkali ion concentration of pore solution at age t, m_r: mass of alkali ions (M^+) discharged up to age t.

4.2.2.3 *Formation of calcium carbonate and change of pore skeleton*

Carbon dioxide, which is an external factor of carbonation, is supplied from the external environment and is dissolved into pore water. By reacting with the calcium hydroxide, it forms calcium hydroxide carbonate and drops the pH of the liquid.

With regard to carbonation, there are three models to consider: consumption and production by carbonating reaction, chemical balance of solution in micro pores, and change of distribution of micro pores. Papadakis et al. (1991), Saetta et al. (1993a), Maeda (1989), Masuda & Tanano (1991), Saeki et al. (1991), Ishida et al. (2001, 2004, 2008), Ueki et al. (2003) and others have proposed models for simulating carbonation processes. For example, Ishida & Maekawa (2001) have presented the model coupling pore skeleton variation with mass transfer and conservation by carbonation. Recently, this model has been extended to consider the carbonated reaction of C-S-H gel (Ishida & Li, 2008).

Neutralization and chloride attack are interactively related. For instance, neutralization will reduce the binding capacity for chloride ions and increase in the concentration of free chloride ions in the liquid phase. Models that can describe such complex phenomenon are introduced in section 5.5.

4.2.2.4 *Advection and diffusion of pore water*

Ion concentration in the liquid phase changes due to diffusion and advection. For simulating ion transport, it is necessary to estimate effective diffusion coefficient or hydraulic conductivity while taking into consideration change of pore structures due to chemical reactions as well as hydration. For example, the tortuosity and constrictivity are used for representing the effect of characteristics of pore structure. It is also necessary to estimate phase transition by alternative drying and wetting process and the phenomenon of ion condensation. As for the chloride ion diffusion model, many methods have been proposed (Bažant 1979, Browne 1982, Maruya et al. 1992, 1998, Saetta et al. 1993b, Saeki & Niki 1996, Yokozeki et al. 2003, Ishida & Ho 2006).

Destruction of the passive film is dependent on the ion composition in the liquid phase surrounded by steel as described above. Although it is clear that the stability of passivity is affected by hydroxide ions and chloride ions in the liquid phase, its threshold is not clear and further investigation is necessary.

4.2.2.5 *Corrosion propagation and cracking*

The supply of both oxygen and water is essential for the continued corrosion of steel that has lost its passive film. To estimate corrosion process, it is necessary to predict the penetration of oxygen and moisture.

Rust, the product induced by the evolution of corrosion, dilates, and pressure around the steel occurs as a reaction force. As usual, this problem may be considered to be same as the initial strain problem. So, the force equilibrium equation based on the principle of virtual work will be dominant and can be generally given as

$$\int_V \delta\dot{\varepsilon}_{ij} D_{ijkl}\left(\dot{\varepsilon}_{kl} - \dot{\varepsilon}_{kl}^{cor} - \dot{\varepsilon}_{kl}^{0}\right) dV - \delta\dot{u}_i \dot{S}_i = 0 \tag{17}$$

where ε_{ij}, ε_{ij}^{cor} and ε_{ij}^{0} are total strain, i.e. the free expansive strain induced in the product and initial strain due to other factors. As for other factors, thermal change, drying shrinkage and autogeneous shrinkage can be considered. D_{ijkl} is a matrix related to stress and strain of the product, steel and concrete. To calculate pressure induced by expansion precisely, it is necessary to formulate both stiffness of rust and reduction of Young's modulus of steel after corrosion. In addition, u_i is a nodal displacement, S_i is an equivalent nodal force, and V is a volumetric domain. The dotted notation expresses time differentiation.

The condition at which cracking occurs in concrete is generally that maximum principal stress reaches tensile strength. However, to simulate the crack propagation, it is necessary to consider factors due not only to inner pressure caused by expansion of the steel but also the fracture energy, creep and shrinkage of the concrete.

Although the mechanical behavior after cracking will be considered as other cracking problems based on fracture energy or the theory of plasticity, the effects of crack width and depth on the corrosion rate should be considered. In other words, the coupling equations of force equilibrium and corrosion rate should be solved to allow rigorous investigation of the relationship between cracking and corrosion rate.

4.2.3 *Practical modeling on carbonation and chloride attack*

In Japan, since the degradation of concrete structures due to chloride attack in the marine environment as well as carbonation has been reported, practical modeling for simulation these deterioration process has also been studied. The following models have been installed on the standard specifications for concrete structures published by JSCE and used for durability verification in design (JSCE 2005a).

Although it is principle to describe the actual phenomenon faithfully based on the concept of durability mechanics, the actual deterioration environment is too complex. In addition, there exist uncertain factors such as the affection of construction and widely varying qualities. Practical models applied to actual design are introduced in the following sections.

4.2.3.1 *Practical models of carbonation*

$$C = A\sqrt{t} \tag{18}$$

Constant A in this equation is called coefficient of carbonation rate and is decided by internal factors such as the quality of concrete and external factors such as environmental conditions. The formulae presented by Kishitani (1962), Morinaga (1986), Izumi (1991), Yoda (2002) and so on are well known in Japan and are verified with the results of accelerated carbonation test, exposure test and investigation of various real structures. For example, Yoda (2002) determined the coefficient based on the results of exposure tests conducted over forty years and considered the quality of construction. In the JSCE standard specifications for concrete structures, an analogous equation considering the degree of environmental influence has been used.

For judgment of steel corrosion in terms of carbonation depth C, the statistical quantification procedure using the difference between carbonation depths and cover thickness of concrete is widely employed. Here, 10mm of uncarbonated cover depth is usually considered in the standard specifications.

4.2.3.2 *Practical models of chloride attack*

$$C(x,t) = C_0\left(1 - erf\frac{x}{2\sqrt{Dt}}\right) + C(x,0) \tag{19}$$

This equation is one of the solutions of Fick's second law under fixed conditions, and is expressed as a function of concentration of chloride ions at the concrete surface C_0, apparent diffusion coefficient D, and initial concentration of chloride ion $C(x,0)$. C_0 is dependent of the environmental condition and D is dependent of the quality of concrete. In the JSCE standard specifications for concrete structures, the design value of diffusion coefficient of chloride ion D_d may be estimated by the following equation, which takes into account both the quality of concrete except in the cracking region and the influence of crack width

$$D_d = \gamma_c D_k + \left(\frac{w}{l}\right)\left(\frac{w}{w_a}\right)^2 D_0 \tag{20}$$

where γ_c: material factor for concrete, D_k: characteristic value of diffusion coefficient of chloride ions in concrete (cm^2/year), D_0: a constant to represent the effect of cracks on transport of chloride ions in concrete (cm^2/year), which is generally a value of 200 cm^2/year, w: crack width (mm), w_a: permissible crack width (mm), l: crack spacing (mm). The ratio of crack width over crack spacing may be generally estimated as

$$\frac{w}{l} = 3\left(\frac{\sigma_{se}}{E_s} + \varepsilon'_{csd}\right) \tag{21}$$

where σ_{se}: increment of stress of reinforcement from the state in which concrete stress at the portion of reinforcement is zero (N/mm^2), E_s: Young's modulus of steel, ε'_{csd}: compressive strain for evaluation of increment of crack width due to shrinkage and creep of concrete.

Judgment of corrosion of steel x at depth for chloride ion consistency $C(x,t)$ after t hours is made depending on whether the concentration of chloride ion exceeds the threshold value of chloride concentration for onset of reinforcement corrosion. In the JSCE standard specifications, the threshold value of chloride concentration for onset of reinforcement corrosion is defined as the mass of chloride ions containing fixed chlorine per unit volume, the value of which is 1.2 kg/m^3. This value is determined by the relation between chlorine concentration and corrosion state in real structures.

4.2.4 *Models for corrosion rate and expansion*

There are several models in which rate of corrosion, expansion of rust and resultant crack propagation around rebar, and the effect of corrosion induced crack on the structural behavior can be evaluated. In addition, experiments regarding those topics , especially, corrosion current system in concrete and structural performances are frequently conducted and these results are used for validation of the proposed models in Japan.

4.2.5 *Modeling of structural performance with corroded reinforcing bar*

For evaluating the mechanical performance of concrete structures with corroded reinforcing bars, several methods have been proposed. The changes of mechanical properties of reinforcing bar, concrete and their interactions need to be modeled based on the concept of analytical methods as mentioned in 4.2.1.4. Some of the recent research in Japan is introduced in this section.

Lee et al. (1996, 1998) calculated the load bearing behavior of reinforced concrete beams with reinforcement corrosion by finite element analysis. They considered the effect of reinforcement corrosion in terms of changes of mechanical properties of reinforcement and bonding between reinforcement and concrete (Lee et al. 1998). Instead of cross sectional area of reinforcement, they reduced Young's modulus and yield strength of corroded reinforcement.

The JSCE 331 Committee carried out case studies of numerical simulation of structural performance of concrete structures with reinforcement corrosion using a finite element program (Shimomura et al. 2006). They reported that modeling of deterioration in structures, such as corrosion of reinforcement and spalling of concrete cover, sometimes has a great influence on analytical results. Saito calculated the structural performance of RC members with reinforcement corrosion by RBSM. Making use of this simulation method, he carried out sensitivity analysis of the effect of degree and distribution of corrosion on structural performance.

Maekawa et al. proposed an integrated model of nonlinear mechanical analysis and time-dependent material analysis for simulating the overall performance of concrete structures over time under arbitrary conditions, as shown in Figure 9 (Maekawa et al. 2003, Toongoenthong & Maekawa 2005a, b). They proposed a multi-mechanical model to deal with materialized corrosive substances around steel bars and equilibrated damage in structural concrete. The multi-mechanics of corrosive product and cracked concrete are integrated with a nonlinear multi-directional fixed crack modeling so that corrosion cracks in structural concrete can be simulated in a unified manner (Toongoenthong & Maekawa 2005a, b). In addition, they discussed the fatigue behaviors of concrete structure with initial defects by the proposed path-dependent fatigue constitutive models (Maekawa et al. 2006a).

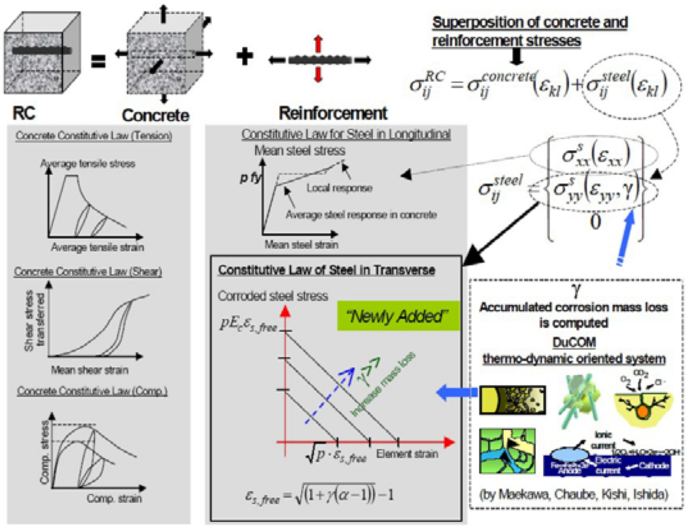

Figure 9. Constitutive models for reinforcement and concrete in RC considering corrosion.

4.3 *Durability Mechanics related to other degradations*

4.3.1 *ASR*

Alkalis (Na_2SO_4 and K_2SO_4) contained in cement are dissolved into a pore solution in a process of cement hydration, giving the solution strong alkalinity (pH 13~13.5), by forming sodium and potassium hydroxides (NaOH and KOH). Aggregate containing given siliceous minerals and carbonate rocks reacts with high alkaline solution in concrete and ASR gel is created as the reaction product. This reaction is called the alkali-aggregate reaction. The alkali-aggregate reaction is classified into alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). In Japan, damage caused by ASR has been mainly reported. The ASR gel absorbs the pore water, and the volume increases when concrete contains over a certain amount of pore water, with relative humidity usually over 80%. The expansive pressure degrades the concrete with micro cracks around aggregates and macro cracks in the structure.

It is known that the magnitude of performance degradation due to ASR is influenced by factors of concrete such as the type of cement and its alkali content, the type of reactive aggregate and its content, the mix proportions of the concrete (cement content, water cement ratio, air content, type of admixture and its content), factors of the concrete structure such as section dimensions of a member, steel ratio, restraint condition, factors of service condition and environmental conditions of concrete structures such as supply of water and alkalis, sunshine condition, and exposure to rain. In Japan, which experiences cold winters, it is known that ASR is accelerated by rock salt (NaCl) used as deicing salt. A number of ASR deteriorated concrete structures were reported in Japan prior to 1970, and a large number of ASR-damaged concrete structures were discovered in the 1980s. This led to the active investigation of measures to prevent such damage. In 1989, a testing method and ASR mitigation measure were established in the Japan Industrial Standards (JIS A5308), and there have been few ASR cases reported in newly constructed structures since 1990. Recently, fractures in reinforcing steel with large expansion due to ASR have been observed, giving rise to active studies on the structural performance of ASR damage.

The durability mechanical approach is classified into two stages. The first stage is the evaluation of ASR gel creation. The identification of the reactive mineral and calculation of OH^- ion content in pore water are required. The OH^- ion content is obtained by considering cement hydration, the amount of alkalis in the mineral, and the leaching process of alkalis. The second stage is the evaluation of expansive pressure and crack propagation. In order to evaluate the expansive pressure, both theories such as osmotic pressure and electric double layer and engineering methods based on the test are applied. It is noted that relaxation of the expansive pressure due to matrix creep is considered since pressure generation is a long-term behavior. In crack propagation evaluation, many mechanical behaviors such as the failure of the matrix around the ASR gel, the reduction of ASR gel stiffness due to water absorption, the restraint effect of reinforcing bars and so on, should be considered.

4.3.2 *Leaching*

Leaching is the deterioration of cementitious materials due to the dissolution of cement hydrates. It degrades the material performance such as strength, stiffness, conductivity and diffusivity. Although the rate of degradation is very slow compared to the other types of degradation, damage in hydraulic structures has been reported. Recently, the evaluation of calcium leaching from concrete as an engineered barrier in radioactive waste disposal has been investigated in Japan because the concrete for such applications is required to have long-term stability of several tens of thousands of years.

The leaching is usually evaluated by numerical simulation consisting of an equilibrium model and an ion transport model. Empirical models or geochemical models are widely used as equilibrium models. For the computation of ion transport, diffusivity, advection and electrical migration are considered. These have a strong relationship with the material properties including the amount of hydrate and micro pore structures. The modeling of such interactions is important for durability mechanics.

4.3.3 *Chemical attack*

Chemical attack may be the phenomenon that occurs when cement hydrates chemically react with some substances, forming soluble substances and degrading concrete, or it may be the phenomenon in which cement hydrates and some substances react to create expansive compounds, and the expansive pressure degrades the concrete.

Most of the instances of repairs or re-construction due to chemical attack in Japan according to frequency of occurrence involve deterioration due to sulfuric acid from sewage facilities. About 100,000 km of sewer pipes made of concrete have been placed all over Japan, and collapses accompanying deterioration have occurred frequently. Although the deterioration of concrete by acid water or reactive soil is restricted to specific areas, it occurs in no small numbers in hot springs and acidic rivers. Moreover, in recent years, deterioration by thaumasite has gained attention as one of the new kinds of sulfate deterioration in cold areas, but this kind of deterioration has not been confirmed in Japan.

The durability mechanics issue in chemical attack is a time-dependent and location-migrating phenomenon consisting of micro problems, such as changes in physical properties due to changes in hydrates, changes in volume of reaction products, and so on, as well as macro problems, such as reduced strength due to dissolution or cracks. The mechanism of chemical attack is extremely complex, and many of its problems have not been quantitatively evaluated.

4.3.4 *Fluctuation of air temperature and insolation*

After concrete is cast in a member, although the temperature inside the member rises to a high level due to heat hydration of the cement, as the outside air contacts the surface of the member, the temperature there does not rise as much as at the center of the member. In mass concrete structures with a large cross section, the temperature rises and falls are comparatively smooth without vibration through the balance between heat hydration of cement and heat transfer to the circumference. In the meantime, the temperature at the surface of the member changes with vibration owing to the effects of air temperature fluctuation, insolation, etc.

The fluctuation of air temperature is divided into yearly fluctuation through the change of seasons, and diurnal fluctuation through the change of air temperature between night and daytime. In Japan, which is a slender country that extends north and south, the yearly fluctuation greatly differs between regions. Comparatively large thermal stress occurs at the surface of concrete members that have a large cross section as the result of important yearly fluctuation of air temperature.

In a mass concrete structure with a large cross section, although the central temperature of the member is hardly affected by air temperature, the surface of the structure is greatly affected, and thus the diurnal fluctuation of air temperature needs to be considered. It goes without saying that structures with a small cross section are greatly affected by air temperature, and thus consideration of the diurnal fluctuation of air temperature is imperative for such structures.

In the verification of cracking at the construction stage, it is especially important to evaluate thermal cracking caused by thermal stress and the causes of cracks in the cover concrete for the re-bar. In such case, it is necessary to apply either the measurements in the area that is the closest to the in-situ or the estimated equation considering diurnal fluctuation.

4.3.5 *Frost damage*

Frost damage is an important problem that influences the appearance, durability, and safety of concrete structures in cold regions. It is reported that one of the causes of the collapse of the de la Concorde overpass in Quebec, Canada on September 30, 2006 was the use of low-quality concrete for the abutment, causing poor freeze-thaw behavior, compounded by the presence of de-icing salts (Johnson et al. 2007). Many prior studies about the mechanism of frost damage describe the fractural behavior of the matrix under freeze-thaw cycles only in the case of water saturated condition. The process of water uptake to reach the critical degree of saturation and the process of frost deterioration in the depth direction still have not been described.

A large number of factors such as type of aggregate, transport of water supplied from outside, deicing salt and coating with finishing materials in addition to temperature under freeze-thaw cycles, micro structure and air void system influence frost damage of concrete in complex ways. Frost damage should be taken as multiple deterioration with drying shrinkage, carbonation and salt attack, not as an independent deterioration.

In the approach of durability mechanics to the time dependence of concrete, we must investigate separately the water saturation process and the cracking process during freeze-thaw cycles considering the changes in the micro structure of concrete under natural conditions. A future task for the study of the durability mechanics of frost damage will be to establish a numerical model that can describe these processes including the water and weather conditions.

4.3.6 *Load*

Cracks occur in concrete members when the principal tensile stresses due to the action of loads exceed the tensile strength of concrete. From the viewpoint of fracture mechanics, the generation of cracks is explained as follows. A fracture process zone in which micro cracks concentrate locally is formed in the concrete. In this fracture process zone, tension softening in which stress is transmitted with increases in deformation arises. Finally, the fracture process zone opens completely and becomes a crack.

The generation of cracks by loads does not influence the safety performance degradation of a structure directly, because concrete is reinforced with steel bars. However, cracks promote mass transfer of various substances and deterioration of the concrete structure thereby. The diffusion coefficient of chloride ions into concrete proposed in Standard Specifications for Concrete (JSCE 2005b) is to estimate the average diffusion coefficient of chloride ions in cover concrete considering the quality of noncracked portions of concrete and the influence of crack opening. Furthermore, micro cracks are generated in concrete members besides structural cracks (Goto et al. 1971, Hsu et al. 1963). It has been experimentally made clear that internal cracks degrade the tightness of cover concrete and also promote the ingress of materials that corrode steel bars (Ujike et al. 1992, Igarashi et al. 2007).

4.3.7 *Creep*

Creep behavior is well known as time-dependent deformation under a sustained load. The mechanism of creep has not yet been fully elucidated, but a number of aspects such as the relationship between water content and creep strain, the linear relationship between stress and creep strain that exists when the loading stress is less than 1/3 of the concrete strength, and so on, have been clarified. For structural design, especially regarding pre-stressed concrete, creep phenomena have been spotlighted, and for mass concrete, creep under the hydration process and creep strain with stress inversion from compressive to tensile stress are under discussion in detail, while there are many engineering equations, that are based on the large amount of experiments, proposed for the design.

The durability mechanics issue of creep is precisely time-dependent and contributes to the evaluation of stress and crack, i.e. the generation of cracks, crack width, and the propagation of cracks.

5 TYPICAL EXAMPLES OF DURABILIT MECHANICS

This chapter introduces a number of examples of pioneering Japanese research activities regarding Durability Mechanics.

5.1 *Analysis of thermal stress for mass concrete structures using Compensation Plane method*

The Compensation Plane Method (CPM) was developed in 1985 as a calculation program that can be widely applied for thermal stress of mass concrete structures (Tanabe et al. 1986) as introduced in sections 4.1.2.5 and 4.1.2.6.

As shown in Figure 10, CPM assumes that a plane perpendicular to the longitudinal axis of a structure before deformation remains perpendicular to the axis after deformation as is commonly assumed in bending theory of beams. Under this assumption that a plane section remains a plane after deformation, structures to be analyzed should belong to the category that the length and height ratio is at least two or more. Denoting the axis deformation in compensation as axial strain $\bar{\varepsilon}$ and the gradient as curvature increment $\bar{\phi}$, the following equations yield $\bar{\varepsilon}$ and $\bar{\phi}$ using the distribution of initial strain $\varepsilon_0(x,y)$.

$$\bar{\varepsilon} = \frac{\sum_i E_i \int_{A_i} \varepsilon_0(x,y)\, dA_i}{EA} \tag{23}$$

$$\bar{\phi} = \frac{\sum_i E_i \int_{A_i} \varepsilon_0(x,y)(y-y_g)\, dA_i}{EI} \tag{24}$$

$$EA = \sum_j \int_{A_j} E_j\, dA_j \tag{25}$$

$$EI = \sum_j \int_{A_j} E_j (y-y_g)^2\, dA_j \tag{26}$$

where E_i: Young's modulus of concrete in cross section i, A_i: cross sectional area of concrete member A_i in cross section i, y_g: center of gravity in whole cross section. The initial stress in the cross section is shown by the sum of internally restrained stress that is derived from the difference between the compensation plane and temperature distribution curve, and the externally restrained stress caused by the force (axial force N_R and bending moment M_R for returning the plane after the deformation to the original restrained position).

N_R and M_R are given by the following equations using external restraining coefficients R_N and R_M, respectively.

$$N_R = R_N EA\bar{\varepsilon}, \quad M_R = R_M EI\bar{\phi} \tag{27}$$

The external restrained coefficients were derived from numerical calculation by the three dimensional finite element method. Finally, the initial stress $\sigma(x,y)$ is given by the following equation.

$$\begin{aligned}\sigma(x,y) = E_i\left\{\varepsilon_0(x,y) - \bar{\varepsilon} - \bar{\phi}(y-y_g)\right\} \\ + R_N E_i \bar{\varepsilon} + R_M E_i \bar{\phi}(y-y_g)\end{aligned} \tag{28}$$

Although CPM is one of the simple prediction methods that can be used to calculate thermal stress, the concept of internal restraint and external restraint, which were indefinite until now, are defined explicitly. The prediction accuracy of thermal stress was improved remarkably by CPM compared with the conventional simplified methods, and the application range was also expanded. Later, the external restraining coefficient was reviewed in 1998, and the application range of CPM was further expanded (JCI 1998).

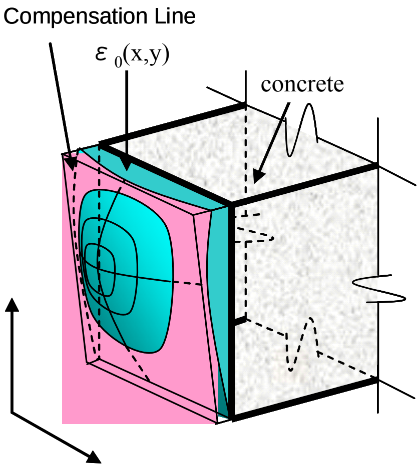

Figure 10. Compensation plane.

5.2 *Autogenous shrinkage*

Autogenous shrinkage has been known as a property of concrete for a long time through several reports by Davis (1940), etc. However, autogenous shrinkage has not been taken into account for control of cracking and the design of concrete structures, because it is much less pronounced than drying shrinkage in the case of ordinary concrete. As high-strength concrete has recently come into wide use, autogenous shrinkage is now being recognized as an important factor of cracking.

It was found experimentally by Paillère et al. (1989) that high-strength silica fume concrete has full depth cracks at an early age when deformation is restrained. This phenomenon, which was observed even in specimens without evaporation, was attributed to intense autogenous shrinkage.

Tazawa & Miyazawa (1992, 1995) observed autogenous shrinkage of cement paste with a water-cement ratio ranging from 0.14 to 0.70, and found that autogenous shrinkage increased as the water-cement ratio decreased, and might be no less than 4000×10^{-6} (Figure 11). Depending on the water-cement ratio and the dimension of specimens, shrinkage was observed even when the specimens were stored under water, which was explained by the development of self-desiccation in the inner part of the specimens. From experimental data for cement paste with various types of cement, a prediction model for autogenous shrinkage was proposed as a function of the mineral composition of cement. It was also proved that autogenous shrinkage was increased by the addition of silica fume and fine blast-furnace slag, and that it was decreased by the addition of shrinkage reducing agents and expansive additives. The work of Tazawa & Miyazawa includes observation of autogenous shrinkage stress in RC members with steel ratios ranging from 1.05 to 4.97%, in which shrinkage was restrained by embedded reinforcing bars (Tazawa & Miyazawa,

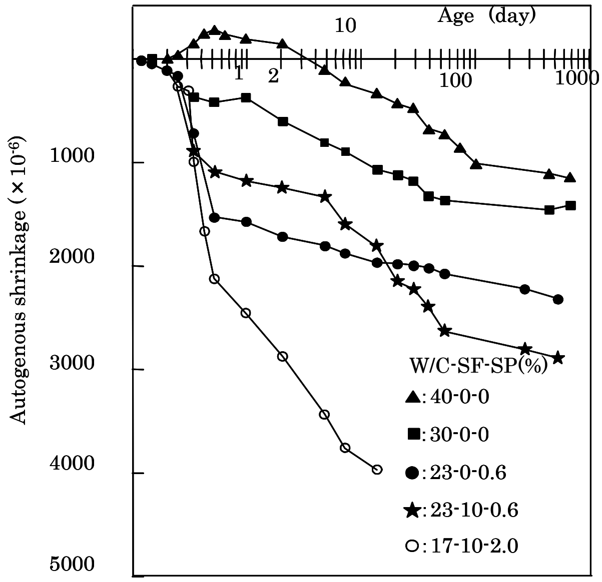

Figure 11. Influence of water-cement ratio on autogenous shrinkage of cement paste.

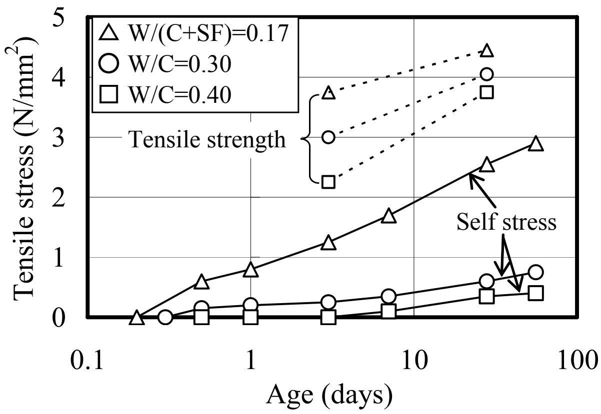

Figure 12. Restraint stress in RC beam specimens (100x100x1200mm, Steel ratio: 2.77%).

1993). From the experimental results, it was proved that autogenous shrinkage stress increased with decreases in water-cement ratio (Figure 12) and could be the cause of full depth cracks.

After the above mentioned reports, studies on autogenous shrinkage have been conducted by many researchers. Nasu (1994) pointed out the importance of autogenous shrinkage as a cause of early age cracking in a real structure (large piers). and Takahashi et al. (1996) studied the mechanism of autogenous shrinkage with focus on the transformation of ettringite to monosulfate. Ishida et al. (1999) succeeded in predicting autogenous shrinkage and drying shrinkage on the basis of a model of cement hydration. Sato et al. (1997) analyzed initial stress in RC members taking into account the volume change due to autogenous shrinkage and temperature change. Standard Specification for Concrete Structures (2002 edition) introduced a prediction model (Tazawa & Miyazawa, 1999) for autogenous shrinkage (JSCE 2005a), and it was specified that autogenous shrinkage should be taken into account in stress analysis for mass concrete structures (JSCE 2005b).

5.3 *Prediction of expansion strain*

The shrinkage of concrete is one of main issues as explained in section 4.1. The use of expansion additive is effective to reduce the shrinkage of concrete. Furthermore, the introduction of chemical prestress by using a large amount of expansion additive can improve the performance of a concrete structure. The evaluation of the distribution of expansive strain and chemical prestress produced in the members is necessary for the promotion of the use of expansion additive. For example, Muguruma (1968) proposed a prediction method based on the concept of free expansion, and Okamura & Kunishima (1973) proposed a composite model based on the concept of potential expansion. The accuracy of the estimation of material properties such as Young's modulus and creep coefficient greatly affects the results in these models.

Tsuji (1980) proposed a prediction method based on the concept of the work performed on restraining reinforcement by expansive cement concrete (Figure 13). The value of the work is calculated by the following equation.

$$U = \frac{1}{2}\sigma_{cp}\varepsilon = \frac{1}{2}pE_s\varepsilon^2 \qquad (29)$$

where U: work performed by expansive cement concrete per unit volume on reinforcement, σ_{cp}: chemical prestress, ε: expansive strain, p: restraining reinforcement ratio, E_s: elastic modulus. Firstly, the method assumes that expansive strain in the axial direction is linearly distributed within the cross section. Secondly, it assumes that the work performed by expansive cement concrete on restraining reinforcement is a constant value regardless of the quantity and method of arrangement of reinforcement when the mix proportions and curing methods of the concrete are same. Then, the distributions of expansive strain and chemical prestress of the members are calculated by using the results of the reference specimen as the basis for calculating the value of work. The details of the specimen are determined in JIS A 6202. Because this method does not include constants such as the modulus of elasticity and creep coefficient of expansive cement concrete, it has a great advantage for the evaluation of the various structures in the practice. Through verification with a lot of experimental data, it was shown that errors between the estimated and measured values were approximately 20% at most. Recently, applicability to new structure such as the hybrid structures of steel and expansive cement concrete and concrete structures using FRP reinforcement were also verified.

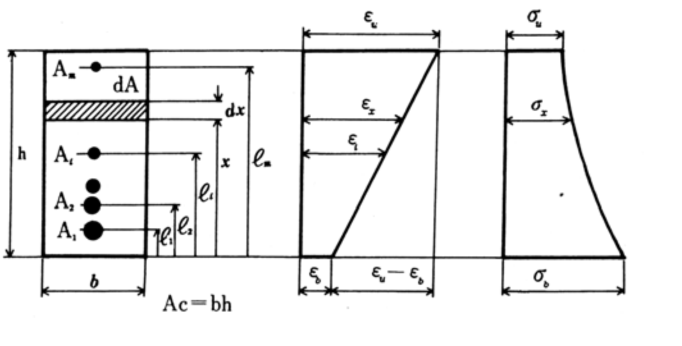

Figure 13. Estimation of distributions of expansive strain and chemical prestress.

5.4 *Model for moisture transport and drying shrinkage based on micro pore structure*

The mechanism of moisture transport in concrete and drying shrinkage of concrete has been studied from the viewpoint of the structure of the hardened cement paste and microscopic behavior of water there. On the other hand, since high-performance computers became generally used in 1980s, they have been applied for the analysis of the behavior of material and structures. Shimomura developed a numerical simulation method for moisture transport in concrete and drying shrinkage of concrete based on the modeling of pore structure of concrete and the microscopic behavior of water (Shimomura & Maekawa, 1993). The pore structure of concrete was represented by a statistical pore size distribution function. Classical models were employed to describe the behavior of water, such as the capillary condensation theory expressed by Kelvin's equation, the capillary tension expressed by Laplace's equation, and a state equation for ideal gas and molecular diffusion in porous media (Figure 14). Characteristics of moisture transport and drying shrinkage of concrete are reasonably evaluated as a function of pore size distribution of concrete (Figure 15).

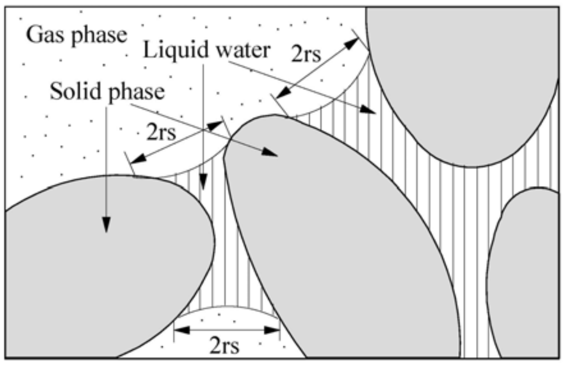

Figure 14. Modeling of pore structure of concrete and behavior of water in pores.

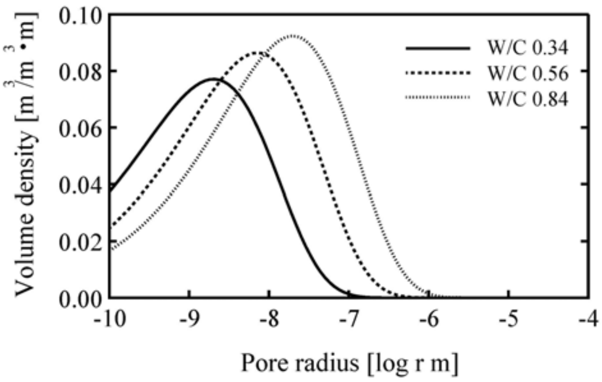

Figure 15. Assumed pore size distribution for calculation of shrinkage of specimens.

5.5 *Integrated modeling of salt damage and carbonation*

As described in section 4.2, carbonation affects chloride ingress. For example, Theophilus et al. (1984) suggested the increase in the chloride ion concentration associated with the release of fixed chloride due to carbonation based on the diffusion theory. Kayyali & Haque (1988) reported a significant increase in chloride ions in the pore solution as a result of carbonation. Kobayashi (1991) revealed the mechanism of the effect of carbonation on chloride ingress by the immobilization and release of chloride ions in cement hydrates. He clearly verified this by using the Electron Probe Micro Analyzer (EPMA) and also reported the phenomena in real structures.

Maruya & Tangtermsirikul et al. (1992) proposed a numerical model for simulating chloride ion transport considering moisture movement under wetting and drying conditions and carbonation. In this study, total chloride in concrete is considered to be composed of fixed and free chlorides. The ion transport model simulates the diffusion of free chloride ions according to the concentration gradient, and the moisture transport model simulates moisture movement according to the vapor pressure gradient. The relation between total and fixed chloride contents was modeled based on the experimental data obtained from various mortar and concrete specimens. Here, the measured soluble chloride content was converted into the free chloride content because the measurement of soluble chloride is easier.

For considering the effect of carbonation, the amount of free chloride released by carbonation is defined to be linearly proportional to the degree of carbonation (carbonation factor, β_c), as follows:

$$C'_{free} = C_{free} + \beta_c C_{fixed} \qquad (30)$$

where C'_{free}: free chloride contents after carbonation, C_{free}, C_{fixed}: free and fixed chloride contents before carbonation, respectively. The degree of carbonation was simply assumed to vary with the humidity in concrete pores for qualitative study, as shown in Figure 16. The applicability of the proposed model was verified using the experimental results. Figure 17 shows an example of verification. Maruya & Tangtermsirikul et al. (ibid.) also showed the efficiency of the integrated approach to real structures.

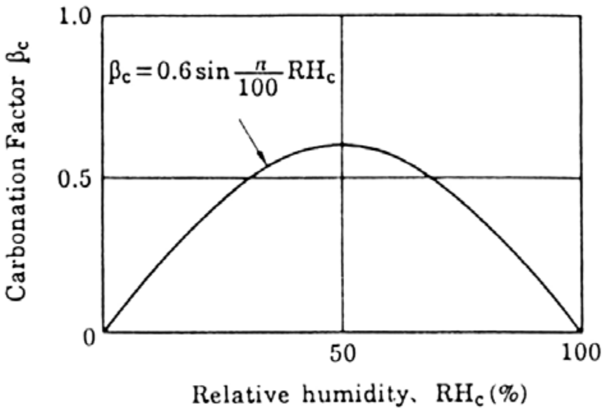

Figure 16. Relation between relative humidity and carbonation factor.

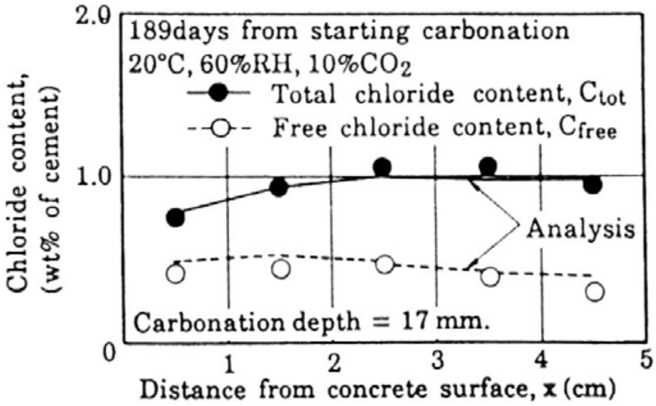

Figure 17. Chloride condensation by carbonation (result of accelerated carbonation test and analysis).

Saeki et al. (2002) created a model for predicting the deterioration process of concrete due to the compound interaction of salt damage and carbonation through an investigation into the immobilization of chloride ions in cement hydrates and their release when degradation of cement hydrates occurs due to carbonation. They referred to the research findings of Kobayashi for the mechanism of concrete degradation due to chloride ions ingress and carbonation.

The available capacity of cement hydrates to immobilize chloride ions was determined by adding NaCl to artificially synthesized cement hydrates that were immersed in an artificial pore solution of concrete; the release of chloride ions accompanying the carbonation of cement hydrates was determined by introducing CO_2 to Cl^- containing cement hydrates that were also immersed in the artificial pore solution of concrete. The experimental results can be seen in Figure 18. Saeki et al. (ibid.) formulated the relation between the release of chloride ion and the pH of pore solution based on these experiments.

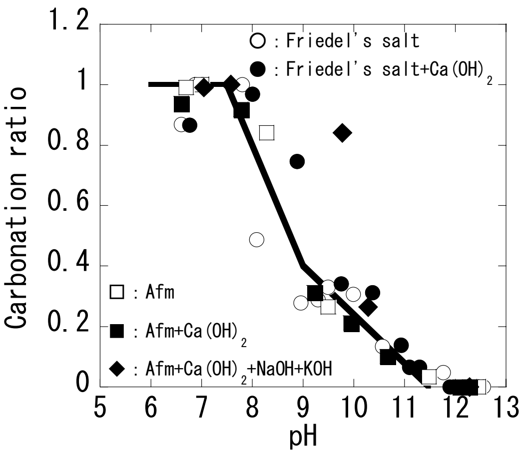

Figure 18. Relationship between pH and carbonation ratio.

Models for characterizing the process of immobilization and release of chloride ions occurring in concrete were established and their validity verified by comparing calculated data with the data from the tests on cement paste and cement mortar specimens subjected to the compound interaction of chloride penetration and carbonation. Finally, by combining the above model with the models for characterizing the transportation of CO_2 and chloride ions in concrete, an approach to evaluate the durability of concrete constructions that are subjected to both chloride damage and carbonation was proposed. Figure 19 shows an example of the prediction results.

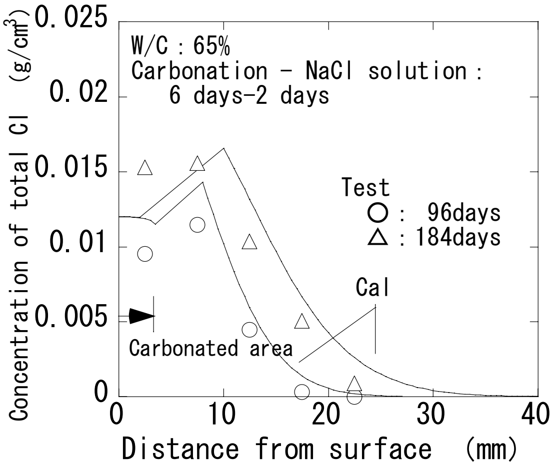

Figure 19. Prediction results of Cl- distribution under salt damage and carbonation condition.

5.6 *Interaction between shrinkage and structural performance*

Evaluation of shrinkage of concrete with regard to the structural performance of RC structures is an import issue in concrete engineering as previously mentioned, and several methods for evaluating the structural performance in terms of concrete shrinkage have been proposed. For example, Ulm et al. (1999) simulated cracking of concrete structures due to drying shrinkage. Martinola et al. (2001), van Zijl et al. (2001), Meshke & Grasberger (2003) and others also proposed numerical models.

In Japan, Hasegawa & Seki (1984) discussed the influence of cracking caused by drying shrinkage on structural performance by using FEM analysis. Maekawa et al. (2003, 2006) proposed integrated modeling of material and structure for the evaluation of the effect of material degradation on structural performance. Nakamura et al. (2006) proposed the RBSN-TRUSS networks model for simulating time-dependent structural performance considering mass transfer.

Drying shrinkage of concrete is a major factor that induces not only cracking but also the time-dependent increase of crack width. For example, Sato et al. (1998) computed the effect of drying shrinkage on flexural crack width of reinforced concrete members under sustained load by considering the bond stress-slip relationship, creep of concrete and bond. Figures 20 and 21 shows crack propagation with an increase in width over time.

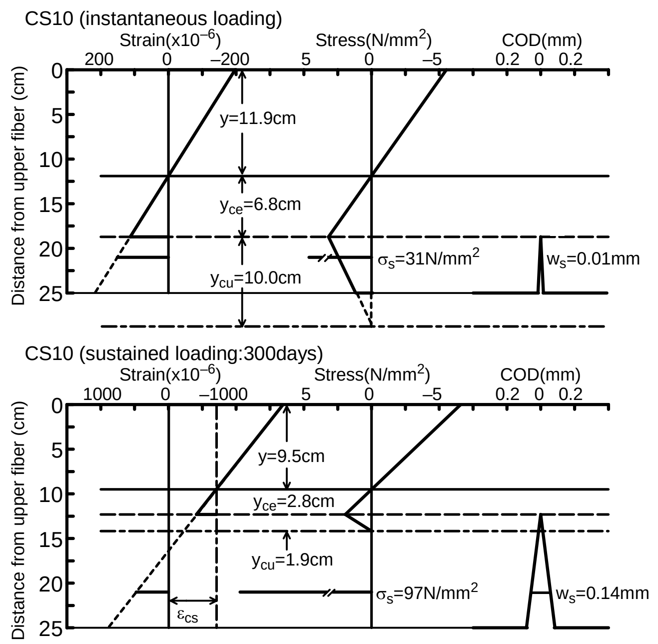

Figure 20. Computed distributions of strain, stress and COD at cracked section.

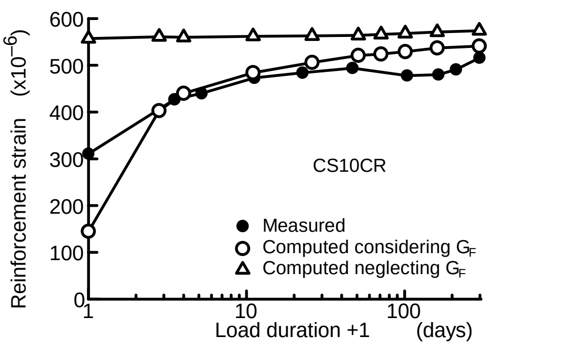

Figure 21. Comparison of measured and computed time-dependent change of maximum strain in tension reinforcement.

Sato et al. (Tanimura et al. 2007, Sato & Kawakane 2008) also proposed a clear-cut approach for considering the effect of autogenous shrinkage on the bending and shear behaviors of RC members using high-strength concrete. The outline of these investigations will be introduced.

5.6.1 *Influence of autogenous shrinkage on flexural behavior of RC members using high-strength concrete (HSC)*

Tanimura et al. (2007) investigated the flexural serviceability performance of RC beams made of HSC with various shrinkage/expansion properties. Experimental results demonstrated that autogenous shrinkage of HSC significantly affects the increase in crack width and deformation of RC beams, while low-shrinkage HSCs markedly improving serviceability performance. From the design equation point of view, Tanimura et al. (2007) also investigated and proposed a new concept for evaluating flexural crack width and deformation of RC beams considering the early age deformation of concrete before loading, which has been incorporated into the equation for maximum crack width in the JSCE design code (2005a). This concept taking into account strain change in tension reinforcement, as shown in Figure 22, is effective in explaining the effects of shrinkage and expansion of concrete before loading on the crack width of RC members. In addition, a general evaluation method for predicting the flexural deformation of RC members, which takes into account curvature change at the cracked section caused by autogenous shrinkage/expansion induced stress, was proposed (Tanimura et al. 2007). Effective flexural stiffness, modified by incorporating the shrinkage/expansion effect into flexural stiffness at the cracked section, improves prediction accuracy compared with the conventional equation.

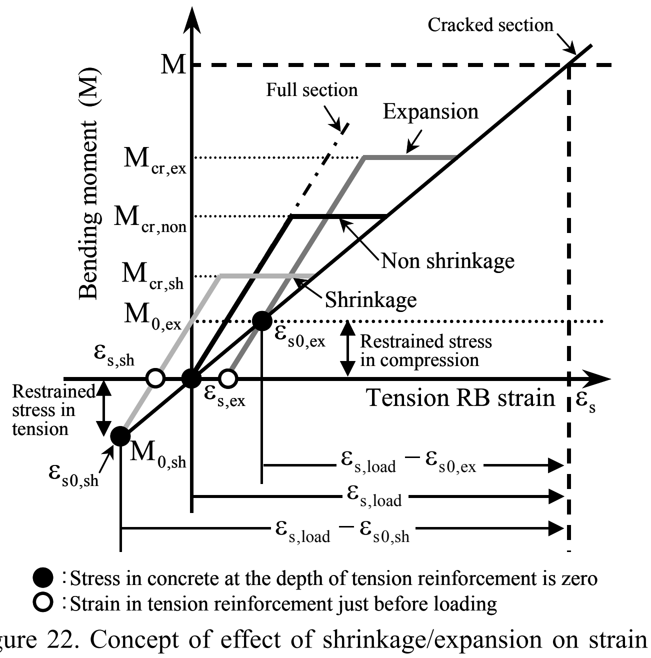

Figure 22. Concept of effect of shrinkage/expansion on strain change in tension reinforcement.

5.6.2 *Influence of autogenous shrinkage on shear behavior of RC members using HSC*

The tension reinforcement ratio is generally one of the major factors of design equations for predicting shear strength at diagonal cracking. Performance of shear transfers along cracks as well as in the concrete compression zone should decreased when the shrinkage effect is remarkable, because flexural cracking moment deteriorates due to shrinkage induced tensile stress in concrete, and flexural crack width is increased by strain changes in tension reinforcement from compression to tension before and after loading. This fact must mean that the tension reinforcement ratio substantially decreases under the effect of shrinkage.

The shrinkage effect on the diagonal cracking strength of reinforced HSC beams was investigated by using shear beams with various effective depths (Sato & Kawakane 2008). The size effect on diagonal cracking strength, as shown in Figure 23, is obviously different depending on shrinkage, and the powers of the effective depth for high-shrinkage HSC (HAS) and low-shrinkage HSC (LAS) beams are -1/2.04 and -1/2.59, respectively. Moreover a new generalized design equation independent of the magnitude of shrinkage was proposed, by applying the concept of the equivalent tension reinforcement ratio based on the strain change in tension reinforcement before and after loading.

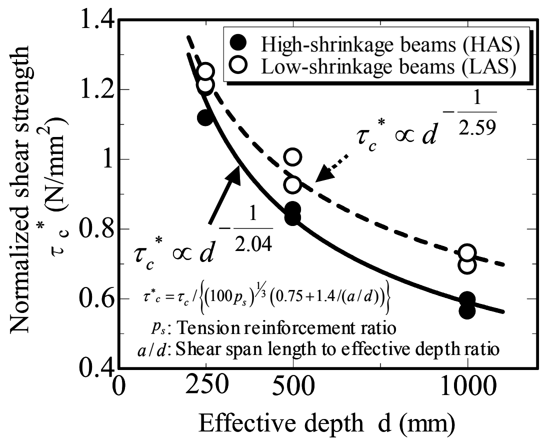

Figure 23. Dependence of size effect on shrinkage for diagonal cracking strength.

5.6.3 *Influence of autogenous shrinkage on bond behavior*

Maruyama et al. (2006, 2007) detected the cracking around reinforcing bar due to autogenous shrinkage of ultra high-strength concrete (Figure 24), and from the comparison of self-induced stress in RC prism with different autogenous shrinkage, it is concluded that this crack degrades bond stiffness. This experiments indicates that the effective concrete cover of high performance of concrete may be reduced due to autogenous shrinkage, and this bond deterioration may affect on the larger flexural crack width as well as shear behavior.

Additionally in order to evaluate self-induced stress of RC prism, time-dependent micro-crack model is proposed, whose schematic representation is shown in Figure 25. This model is based on the smeared model by Bazent & Oh (1983) with 1/4 tension softening model by Rokugo et al. (1989).

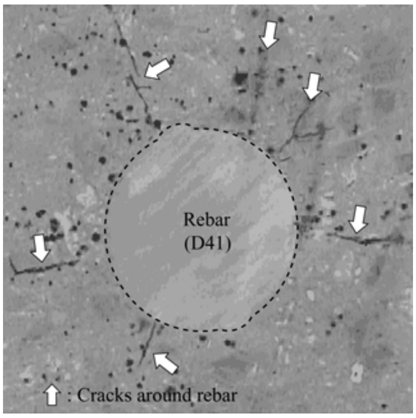

Figure 24. Cracking around reinforcing bar due to autogenous shrinkage.

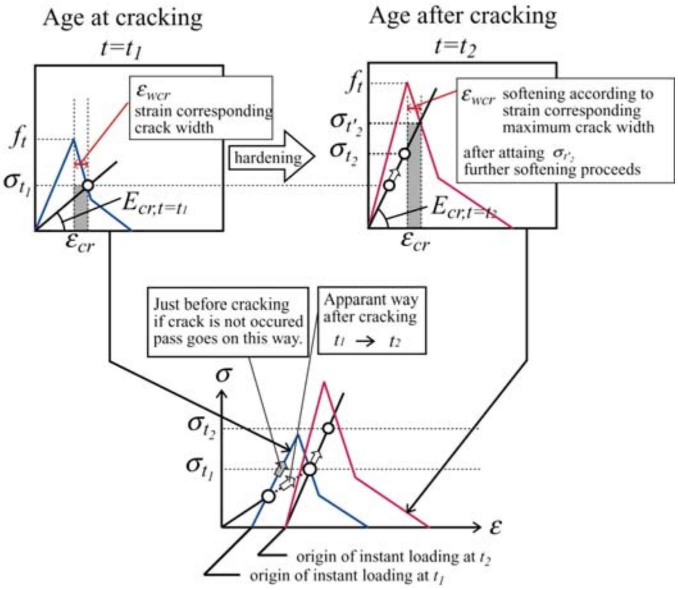

Figure 25. Time-dependent micro-crack model.

5.7 *Influence of internal cracking on durability*

Internal cracking formed around a deformed tension bar deteriorates the tightness of cover concrete and promotes the ingress of materials corroding the steel bar, as explained in section 4.3.6. Figure 26 shows examples of deterioration of cover concrete by internal cracking (Ujike & Sato 2006). It is clearly shown that the air permeability coefficient of concrete with internal cracking depends on the stress of the reinforcing bar and the ratio of the concrete cover to the bar diameter, and the diffusion coefficient of chloride ions is also increased by the generation of internal cracking. Therefore, when carrying out verification of the performance of concrete cover to protect reinforcements subjected to tensile force, it is necessary to examine performance by using the effective concrete cover, which is obtained by subtracting the length of 1.5 times the bar diameter from the actual cover.

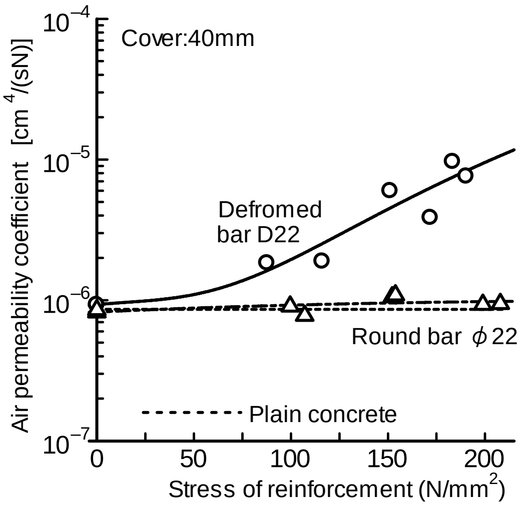

Figure 26. Increase in air permeability coefficient of cover concrete with deformed bar.

5.8 *Multi-scale modeling for material and structural interactions*

Simulation of the whole behavior of a concrete structure during its service life is one of the goals of Durability Mechanics. This simulation has to consider venomous phenomena in and around concrete structures such as chemical and physical reactions and their interactions from the casting stage of concrete. This approach is becoming reality with the development of the technique of nonlinear analysis and the quickly rising performance of computers.

One of the pioneers of the numerical system simulating the time-dependent behavior of concrete at the material level is van Brugel (1991). His HYMOSTRUC can simulate the hydration process from a quantitative microstructure development model based on the cement particle growth concepts. Bentz (1997) also proposed CEMHYD3D as a computational system for simulating the hydration process. In Japan, DuCOM (Kishi & Maekawa 1994, Maekawa et al. 1999), CCBM (Maruyama et al. 2007) and other systems have been proposed.

Furthermore, Maekawa and his colleague extended their DuCOM system for predicting the long-term durability of concrete materials and also integrated it with the nonlinear mechanical system, COM3 (Okamura & Maekawa 1991, Maekawa et al. 2003), for evaluating the performance of concrete structures over time (Ishida & Maekawa 2000, 2001, Maekawa et al. 2002, 2003). The resulting integrated system can evaluate the time-dependent performances of concrete structures for arbitrary environmental and mechanical actions through multi-scale modeling (Figure 27).

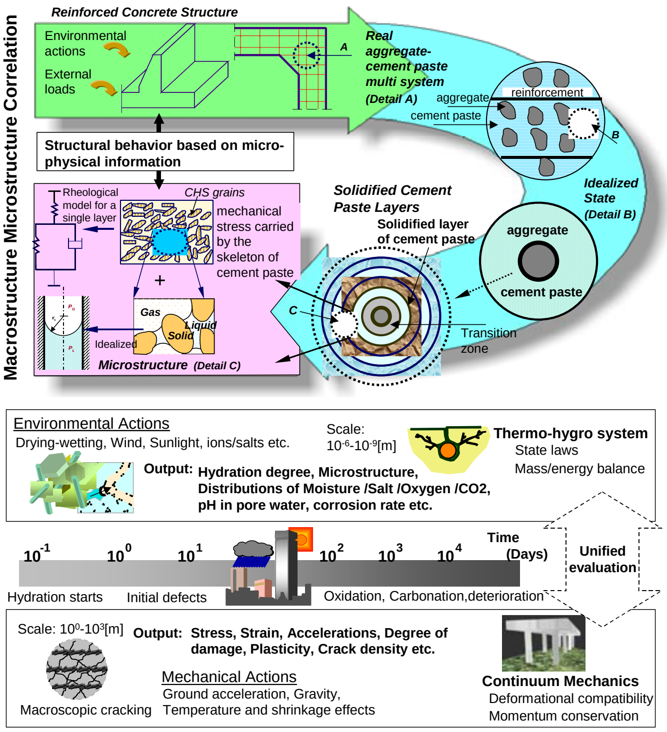

Figure 27. Multi-scale scheme and lifespan simulation for materials and structures.

The thermodynamic analytical system called DuCOM was originally developed by integrating the multi-component hydration model (Kishi & Maekawa, 1995) and the moisture transport model coupled with the microstructure formation (Chaube & Maekawa, 1995) rooted in the drying shrinkage model based on micro pore geometry and hygrothermal state equilibrium (Shimomura & Maekawa, 1993). This system aims to simulate the entire thermo-mechanical states of early age cementitious materials having various mix proportions and materials under arbitrary curing and environmental conditions. Furthermore, it has been extend for simulating the long-term deterioration process regarding the corrosion of reinforcement due to salt damage and carbonation (Ishida & Maekawa, et al., 2001) and calcium leaching (Nakarai & Ishida et al., 2006a). In addition, the target of the simulation has been extended to soil materials (Nakarai & Ishida et al., 2006b). Figure 28 shows the distributed object-oriented scheme of DuCOM.

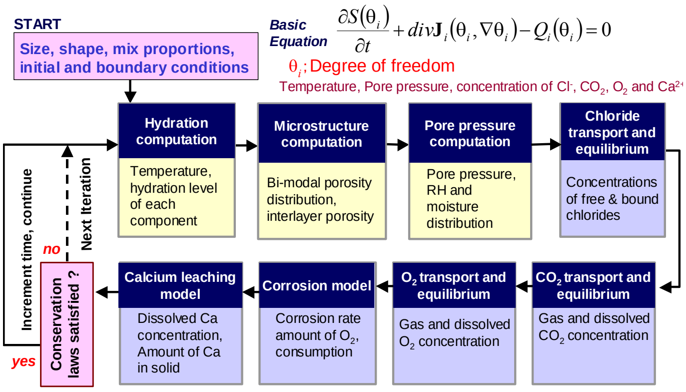

Figure28. Sub-structure platform of Concrete Model for Durability -DuCOM-

In parallel, a totally integrated system of material information calculated by DuCOM and mechanical behavior calculated by COM3 nonlinear analysis has been developed (Ishida & Maekawa 2000, Maekawa et al. 2002). This integrated modeling allows the performance evaluation of concrete structures during their service life. So far, the applicability to the ex tended evaluation of concrete structures deteriorated by corrosion, shrinkage, creep, fatigue, and the coupling of these various factors, has been presented (Toongoenthong and Maekawa, 2005a, b; Maekawa et al. 2006a, b; Asamoto et al, 2006; Gebreyouhannes et al., 2008). Figure 29 shows the scheme of the simulation of corroded RC structures.

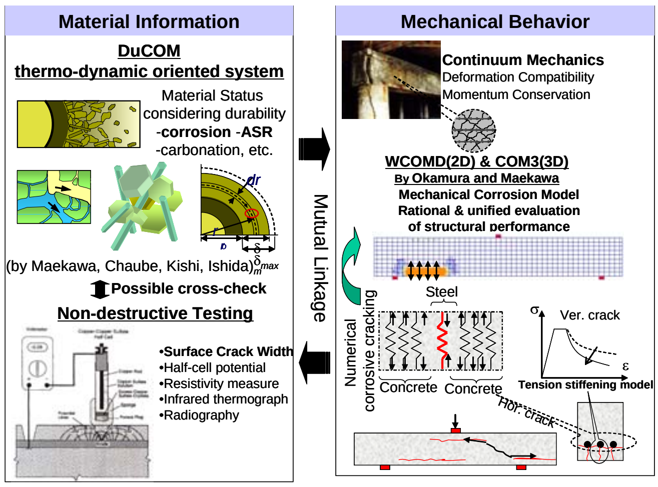

Figure 29. Structural performance assessment of corroded RC.

Nakamura et al. proposed the RBSN-TRUSS networks model for simulating time-dependent structural performance considering mass transfer (Nakamura et al. 2006). Mass transfer can be represented in various scales from the micrometer scale of pore structures to the millimeter scale of cracks. On the other hand, structures also have several mechanical scales such as crack, specimen and member. In the RBSN-TRUSS networks model, the crack scale was selected as the target scale because it is an important route of mass transfer and a mechanical feature of concrete structures. RBSN (Rigid-Body-Spring Networks), which is one of the discrete approaches, was used as structural analysis, since it makes it easy to deal with crack propagation of concrete directly. The truss networks model was used for mass transfer analysis to adjust the concept of structural analysis, since RBSN does not require continuality.

The model is a unified analytical method with load applying analysis for short-term behavior and mass transfer analysis for long-term behavior under multi-actions in consideration of drying shrinkage due to moisture transfer and rebar corrosion caused by chloride ion penetration (Figure 30). The advantage is that the truss networks are set between rigid body nuclei and on boundaries (Figure 31). The mass transfer through the crack can be considered in addition to mass transfer through the bulk concrete, in which a different diffusion coefficient from that of the concrete material is assumed.

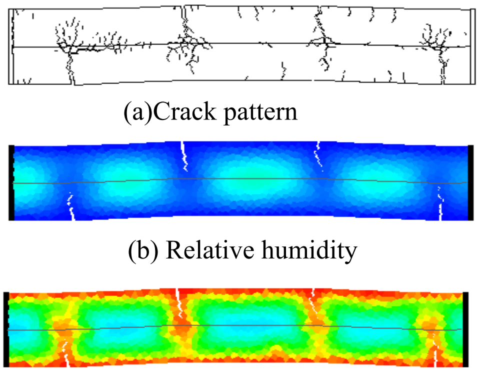

Figure 30. Combined analysis of drying shrinkage and corrosion.

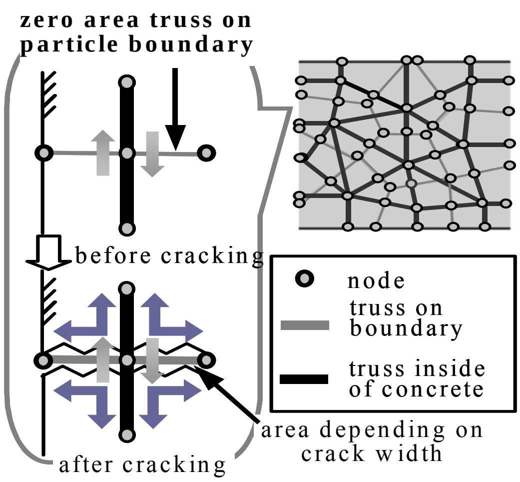

Figure 31. Truss networks.

6 CONCLUSION

This paper has provided a summary of the activities of the Working Group on Durability Mechanics (WG3) within the JCI Technical Committee on Time Dependent Behavior of Cement-Based Materials. A re-definition of and new approach to durability mechanics aimed at integrating the huge body of research regarding material and structural issues by using a platform named "Mandala for durability mechanics" are proposed. By integrating related research activities, this approach helps clarify the characteristics of phenomena such as similarities of degradation and the existence of interactions. It also highlights the need to standardize methods, the modeling of considerable interactions, and the provision of experimental data for verification. This approach to durability mechanics is an ambitious research topic covering all fields of concrete engineering as well as an essential topic for solving the problem of durability of concrete structures. Our working group calls for strong involvement in this research topic *of durability mechanics* from all over the world.

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