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RESIDUAL MECHANICAL PERFORMANCE OF CONCRETE UNDER VARIOUS EXPANSION DETERIORATION STATES BASED ON CRACK MORPHOLOGY AND SUBSTANCE

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Abstract: This paper summarizes the authors' previous work on modeling and numerical simulation techniques for concrete residual mechanical performance evaluation, which has expanded owing to various factors, including alkali-silica reactions (ASRs), frost damage, and delayed ettringite formation (DEF). By varying the mechanical constitutive law and expansion strain proportion considered according to the different crack characteristics and time-dependent properties caused by each type of expansion deterioration as well as substance precipitation in the cracks, it is possible to perform numerical simulations that consider the differences in the concrete mechanical properties under various expansion states using a nonlinear finite element method. The relationship between the cracking characteristics and the mechanical performance of the expansive concrete was also verified experimentally. Regarding the ASR expansion, it has been successfully demonstrated via simulations that it is possible to rationally explain both cases, where the structural performance of reinforced concrete members improves after expansion and where it deteriorates, by considering the crack characteristics and reaction speed in the ASR.

1 INTRODUCTION

A large number of concrete structures suffer from cracking and deterioration owing to expansion within the concrete caused by chemical reactions and phase changes. Typical examples of concrete expansion and deterioration include alkali-silica reactions (ASRs) [1,2], freeze-thaw cycles (FTCs) [3,4], and delayed ettringite formation (DEF) [5,6]. To ensure the safe long-term service of structures, it is necessary to properly evaluate the structural performance of concrete structures subjected to expansion and deterioration. However, methods to properly evaluate the residual mechanical performance of concrete after expansion are still under development. This paper summarizes previous studies on the development of models to evaluate the mechanical performance of expansion-deteriorated concrete materials and members based on microscopic information, such as crack morphology.

2 SIMULATION SCHEME

2.1 Overall system

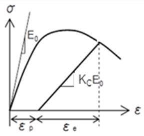
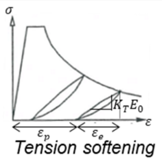
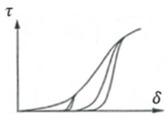
The authors' previous work has been conducted in the form of model implementation in a coupled material-structure response analysis system for concrete, DuCOM-COM3 [7]. This analysis system couples DuCOM, a coupled thermodynamic analysis system that considers hydration reactions, pore structure formation, water and ion migration, and equilibrium in concrete, with COM3, a structural analysis system that tracks the nonlinear structural behavior and fatigue degradation progress in concrete structures.

COM3 has been developed and implemented with the constitutive laws of compression, tension, and shear, as shown in Table 1, and a model that considers the fatigue evolution based on the stress history for each of them. Recently, a solid-liquid two-phase model [8] was implemented to consider cracks and pressure generation owing to water or secondary products in the pores or both, which allows for degradation where internal expansion occurs. However, the conventional damage model in constitutive law has mainly focused on crack initiation and damage propagation owing to external forces such as loading; therefore, the effects of expansion-degradation cracking and damage with different crack sizes, locations, and continuity cannot always be tracked perfectly. Accordingly, the authors investigated the multi-scale nature of cracks, the cyclic action of expansion stresses, and the mechanical contribution of materials to cracks.

2.2 Solid-liquid two-phase model

Figure 1 shows the computational flow of the solid-liquid two-phase model. The thermodynamic coupled analysis system incorporates a hydration and heat-generation model, a pore structure formation model, and a water movement/equilibrium model as basic models, and a scheme is constructed to add various ion movement/equilibrium models according to the calculation event. By inputting the concrete structure's dimensions, mix, and

Table 1: Constitutive laws and fatigue consideration in COM3 [7].

	Compression	Tension	Shear Transfer
Core-constitutive law	Normal stress-strain $\sigma = E_0 K_c \varepsilon_e$ $\varepsilon = \varepsilon_e + \varepsilon_p$  Elasto-plastic	Normal stress-strain $\sigma = E_0 K_c \varepsilon_e$ $\varepsilon = \varepsilon_e + \varepsilon_p$  Tension softening	Shear stress- Slip $\tau = \tau_0(\delta, \omega)$ 
Enhanced model for fatigue	$dK_C = \underbrace{\left(\frac{\partial K_C}{\partial t}\right) dt}_{\text{Time dependency}} + \underbrace{\left(\frac{\partial K_C}{\partial \varepsilon_e}\right) d\varepsilon_e}_{\text{Cyclic fatigue}}$	$dK_T = \underbrace{Fdt}_{\text{Time dependency}} + \underbrace{Gd\varepsilon_e}_{\text{Cyclic fatigue}}$	$\tau = X \cdot \tau_0(\delta, \omega)$ $X = 1 - \frac{1}{10} log_{10} \left\{ 1 + \int \lvert d(\delta/\omega) \rvert \right\}$

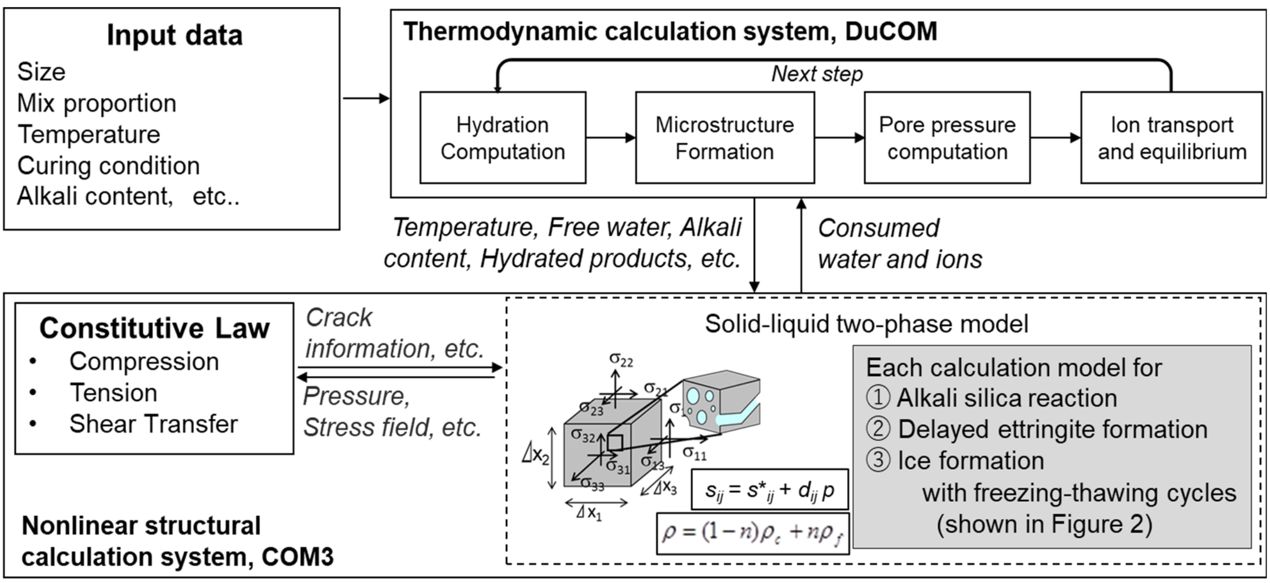


Figure 1: Coupled structural－material calculation system and solid-liquid two-phase model implementation

curing conditions, various state quantities and variables are calculated within each element, and these values can be transferred to COM3 for use. The models shown in Figure 2 are conceptual diagrams for each of the formation models of ice from water [3, 9] and secondary products (alkali silica gel [10] and secondary ettringite [5]) in cracks and pores. The models were used to calculate the change in the water state due to freeze-thaw action, ASR gel formation due to the ASR, and secondary ettringite formation due to DEF. According to the calculated product amounts and mechanical properties, the internal pressure and stresses in the concrete due to the internal products are calculated, allowing for expansion and crack propagation. Details of each chemical reaction and other modelling can be found in the literature [1–10].

3 DAMAGE MODEL CONSIDERING MICROSCOPIC PHENOMENA

3.1 Crack size (DEF case)

The consideration of microscopic matter in this study is presented next, discussing each degradation event. First, the compressive mechanical properties of concrete subjected to expansion owing to DEF are presented, in which macroscopic and microscopic cracks are classified into macroscopic strains using the finite element method [6].

The analysis was based on an experiment conducted by Brunetaud et al. [11] in which concrete specimens with compressive strengths

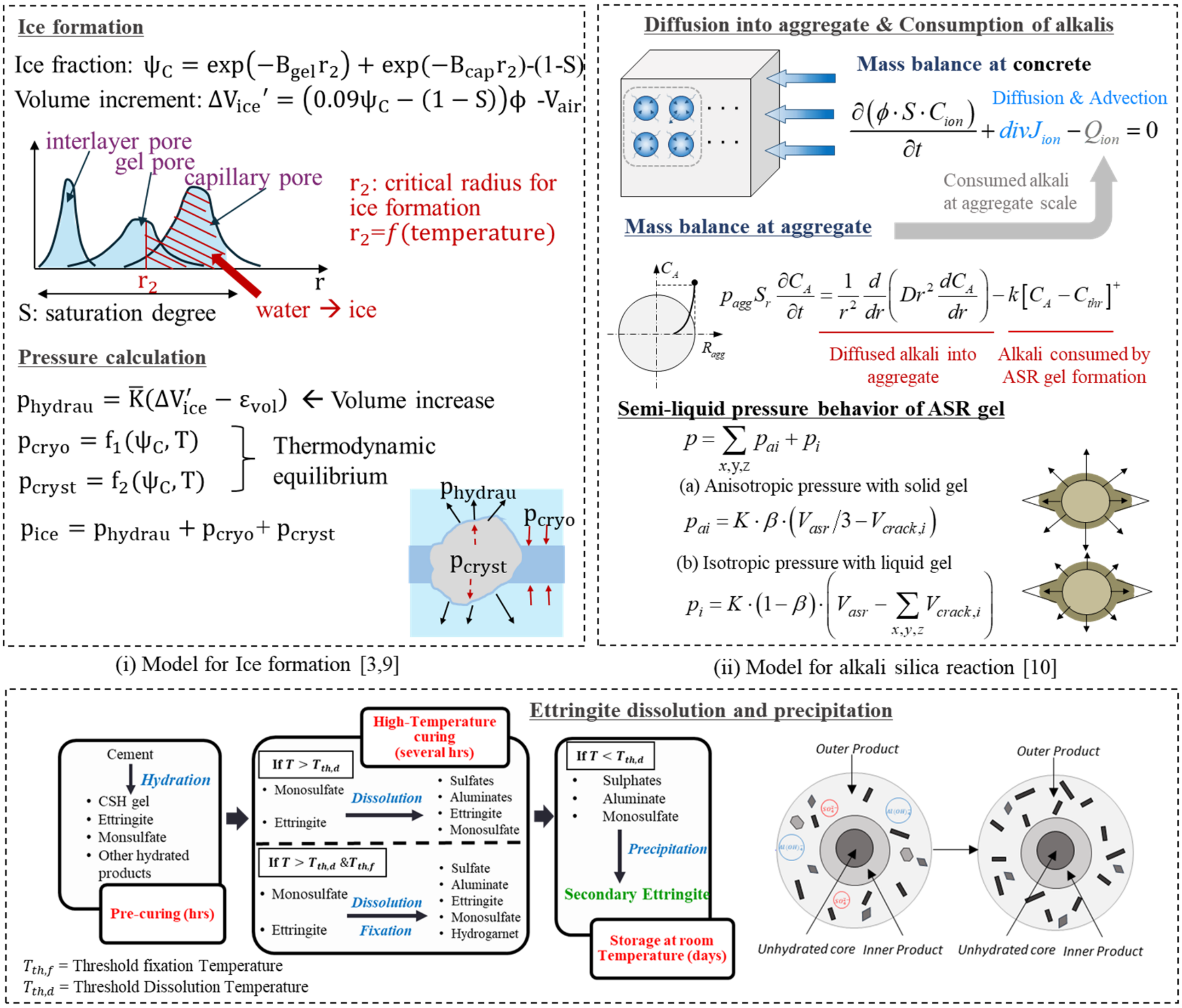


Figure 2: Models for ice formation, ASR, and DEF

of approximately 40 MPa were used. The specimens were subjected to compression tests after DEF expansions of 0.54% and 1.06%, and the load-displacement relationships were obtained.

We performed a replicate analysis of these tests. Figure 3 shows the behavior of concrete subjected to DEF in the compression test conducted by Brunetaud et al. [11] and the results of the replicated analysis. In the replicated analysis, the aforementioned solid-liquid two-phase model was used to calculate the DEF process, and compression simulations were performed after the same expansion degree was obtained. As shown in Figure 3, the expansion owing to DEF is generally a very large deformation, and applying it directly to a model that considers the cracking and damage degree to the existing constitutive law would result in excessive concrete mechanical performance degradation.

The damage overestimation can be attributed to the consideration of the total strain owing to the DEF for damage. When the crack patterns

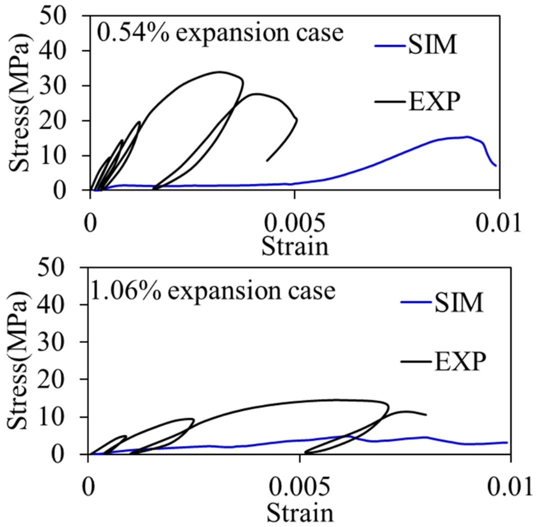


Figure 3: Compression after DEF expansion

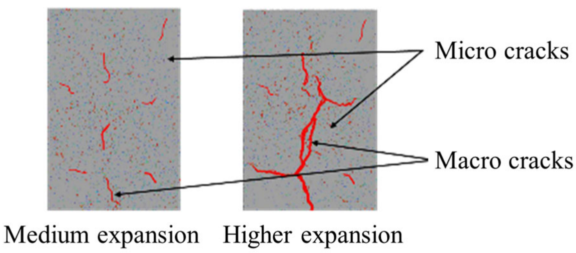


Figure 4: Micro- and macro-crack images after DEF expansion

of the DEF-affected concrete were observed, fewer visible cracks occurred with a medium expansion level. However, macrocracks developed from microcracks owing to concrete expansion, as shown in Figure 4. Therefore, the effects of partial macrocracks and changes in the constitutive damage model were introduced. To consider the effect of macrocracks, the total strain was divided into two parts, as follows:

$$\varepsilon_{total} = \varepsilon_{micro} + \varepsilon_{macro} \tag{1}$$

$$\varepsilon_{macro} = \mu \cdot \varepsilon_{total} \tag{2}$$

where ε_{total} is the total strain, ε_{micro} is the strain corresponding to the microscopic cracks, ε_{macro} is the strain corresponding to the macro cracks, and μ is the fraction of macro strain to total strain via expansion deterioration.

By using only the small strain corresponding to the macrocrack in the constitutive damage calculations, it is possible to consider that the mechanical performance will not be significantly degraded, even if a large expansion occurs due to DEF. Figure 5 shows the sensitivity analysis results for different strain rates corresponding to the macro cracks, showing that μ = 0.1–0.2 for a 0.54% expansion and μ = 0.5 for a 1.06% expansion will be appropriate to reproduce the experimental

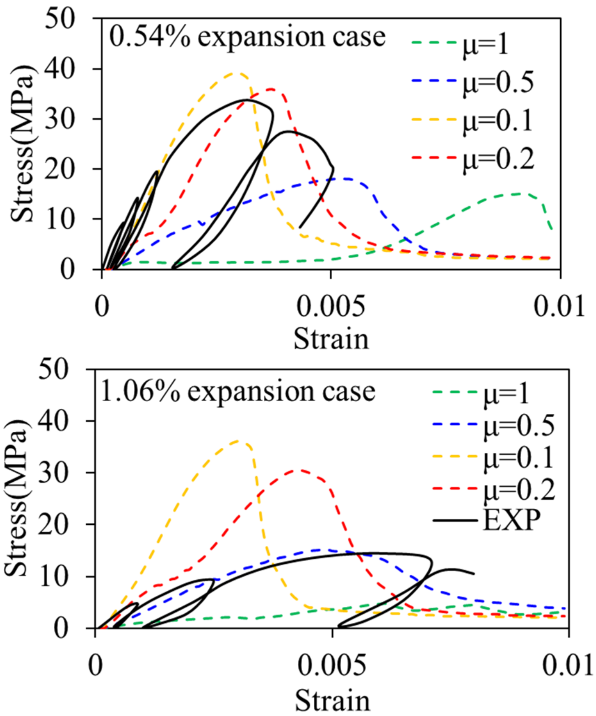


Figure 5: Consideration of macro- and micro-cracks due to DEF and their contribution to damage

trends. This behavior appears to capture the fact that as the DEF expansion progresses, the microcracks are mostly microcracks at the beginning but gradually increase and cause large mechanical damage. Further research is needed to determine the appropriate μ value for different DEF conditions through comparison with cracking observations.

3.2 Additional fatigue by substances (Frost damage case)

Next, we present a case study in which an additional damage model due to cyclic ice pressure was introduced for concrete damaged via FTCs [3]. Experiments were conducted on mortars with different water-cement ratios (50% and 75%) to measure the compressive mechanical behavior at several time points after expansion and cracking damage caused by the freeze-thaw action. Figure 6 shows the measured results of the expansion progress during the expansion development due to FTCs and the stress-strain relationship at compression tests [4]. For these experimental results, we performed a replicate analysis using the analysis system mentioned previously [3,9]. As shown in Figure 7, the results indicate that, although the mechanical performance degradation is well traced in the early stages, the analytical results overestimate the experimental results as a large FTC is reached.

Accordingly, a model for the fatigue degradation of concrete structures owing to cyclic ice pressure was introduced. As shown in

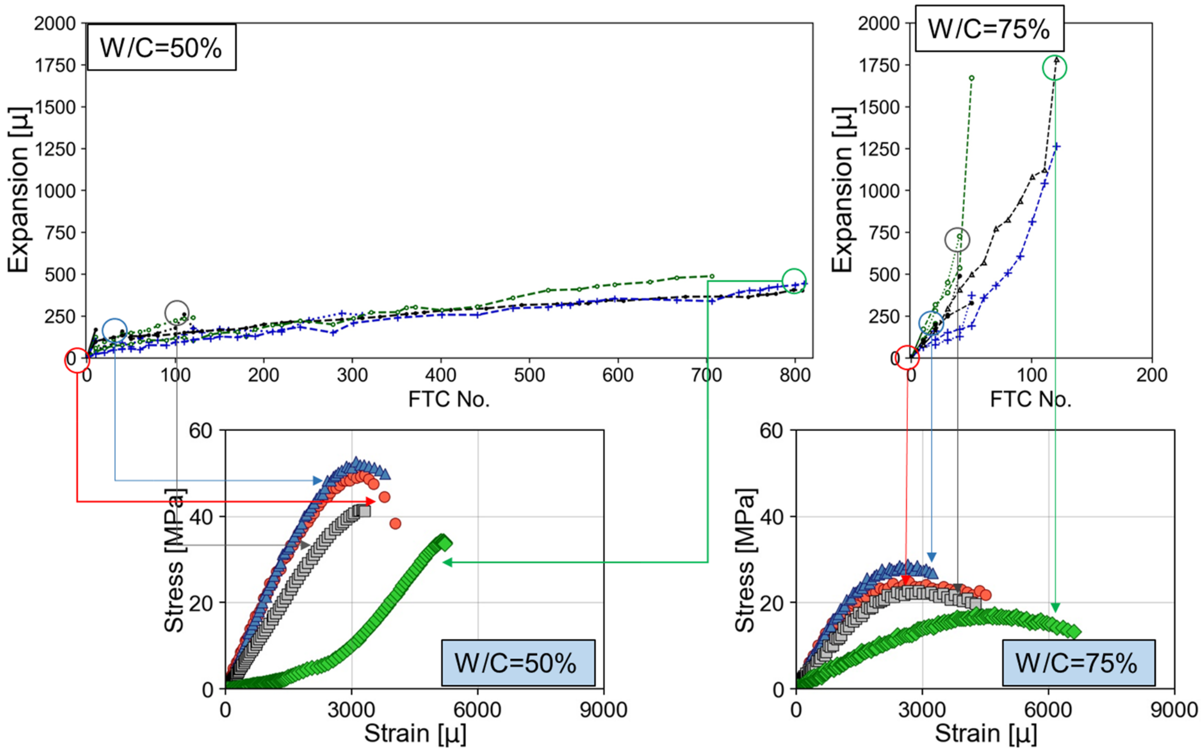


Figure 6: Expansion due to repetitive FTCs and compression behavior before and after FTCs [4]

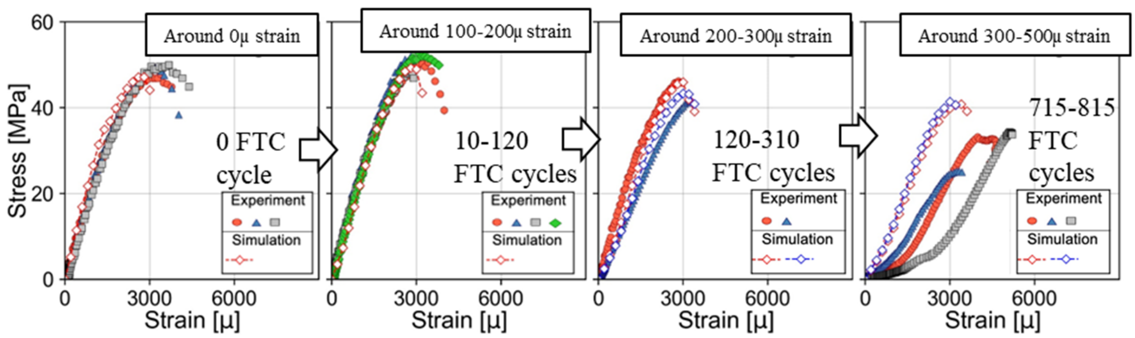


Figure 7: Reproduction analyses for FTC-damaged mortar specimens (W/C = 50%) [3]

the following equations, the existing model for the collapse process of concrete caused at the top of the concrete slab due to fatigue from liquid water pressure was extended to

$$dZ_{ice} = \left(-10^{n} \times \left(1 + f_{n\_ice}\right)\right) \times P_{ampl\_ice}{}^{f_{n\_ice}} \times d_{p\_ice} \quad (3)$$

$$dZ = dZ + dZ_{ice} \quad (4)$$

$$K = e^{-Z} \quad (5)$$

$$E = KE_{c} + \sqrt{K}E_{s} + (1 - K)E_{agg} \quad (6)$$

accommodate fatigue due to ice pressure.
where Z_{ice} is the parameter for ice pressure repetition and P_{ampl_ice} is the ice pressure amplitude. In this study, the value of f_{n_ice} was adjusted through simulations to control the damage level caused by the repeated application of ice pressure. K is a parameter that considers the reduction in the elastic modulus due to ice pressure fatigue. E, E_c, E_s, and E_{agg} are the elastic modulus fractions of the total material, concrete, steel, and aggregates, respectively. f_{n_ice} is a parameter that considers the effect of ice pressure. However, because there are no data to verify what value is appropriate, a value of approximately 3–3.3 was adopted from the sensitivity analysis. The compression simulation results using the ice fatigue model are shown in Figure 8. As can be seen, by including a fatigue model based on ice pressure repetitions, it is possible to appropriately consider the mechanical performance.

Figure 9 shows the contribution of constitutive damage by expansion strain and fatigue damage due to cyclic ice pressure on strength reduction, respectively. A W/C of 50% is subjected to more FTCs, and the contribution of fatigue to the mechanical performance degradation increases. Therefore, it is indicated

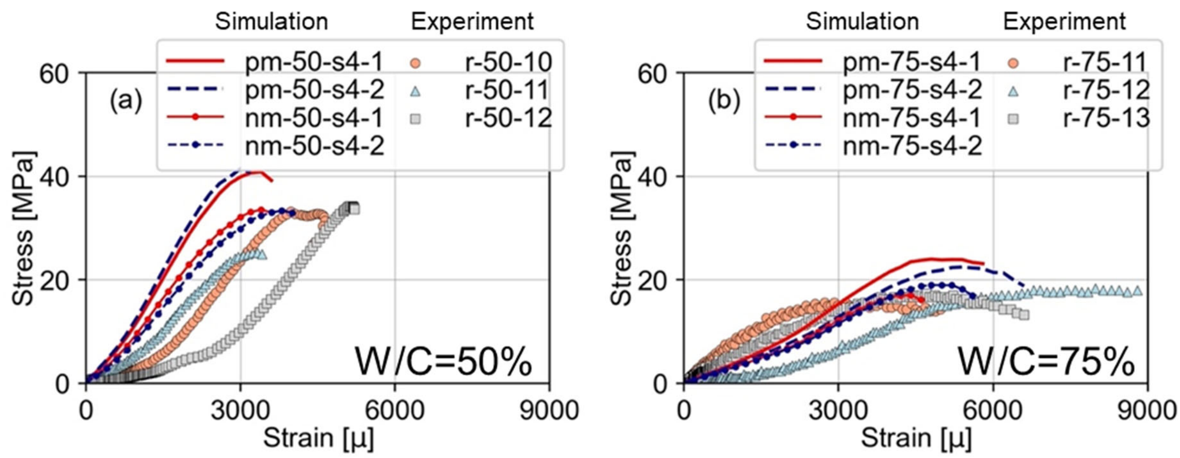


Figure 8: Compressive behavior with the ice pressure fatigue model [3]

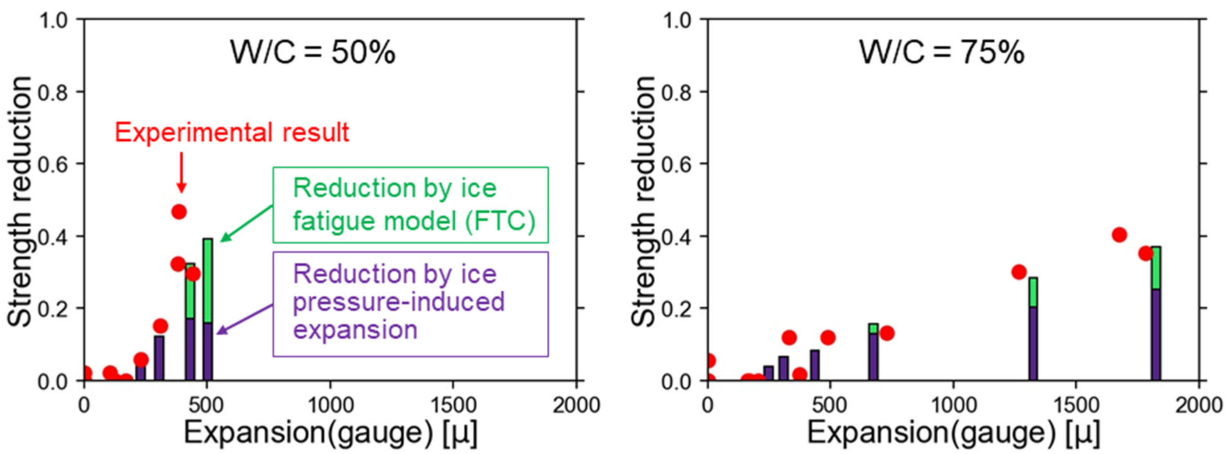


Figure 9: Contribution of damage by cracks and ice fatigue on strength reduction in the sumulations

that fatigue damage should be considered in addition to crack damage due to expansion under freeze-thaw conditions.

3.3 Effect of substances inside cracks (ASR case)

Finally, a case study of concrete subjected to expansion and degradation owing to the alkali-aggregate reaction is presented, considering the mechanical contribution of the material to the cracks as well as crack dispersion. Giaccio et al. [12] showed that the mechanical performance differs significantly when the rate of expansion is different, even for the same amount of ASR expansion, as in cases R2, R3, and R4, as shown in Figure 10. Also shown in Figure 11 [13] are experimental results in which the mechanical performance recovered with time when the specimens were stored for a long period of time with the same amount of ASR expansion. Based on the microscopic mechanisms, the results shown in Figures 10 and 11 suggest that the cracking morphologies are different at different expansion rates, the macrocrack fraction mentioned in Section 3.1 changes, and the chemical composition and mechanical properties of the ASR gel occupy the crack

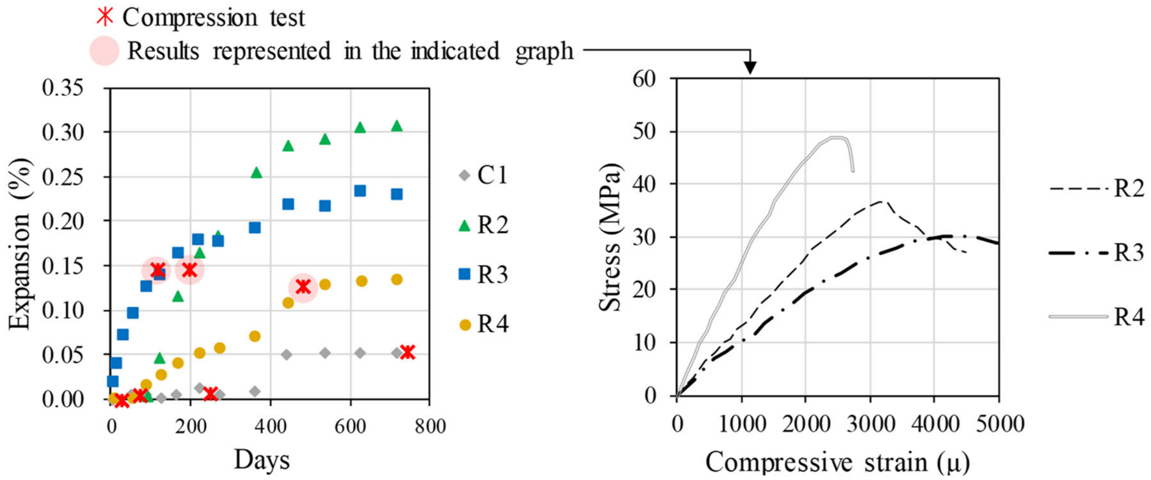


Figure 10: Compressive behavior of concrete after different ASR expansion rates [12]

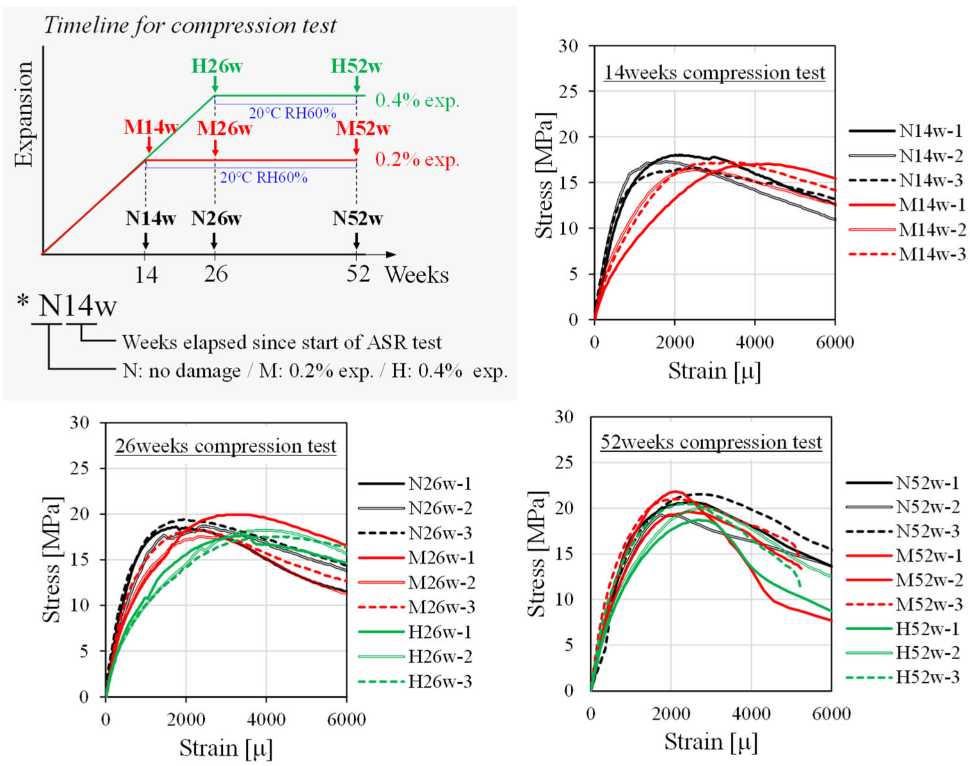
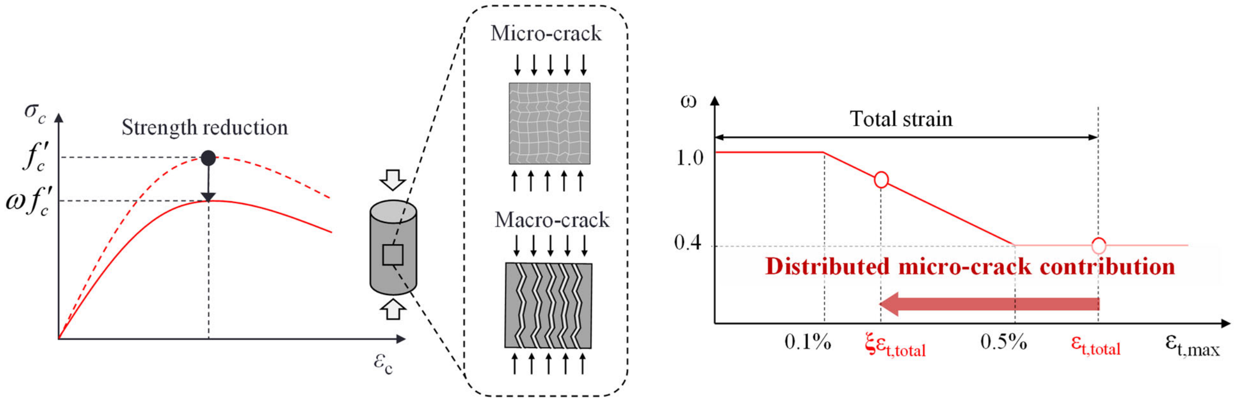


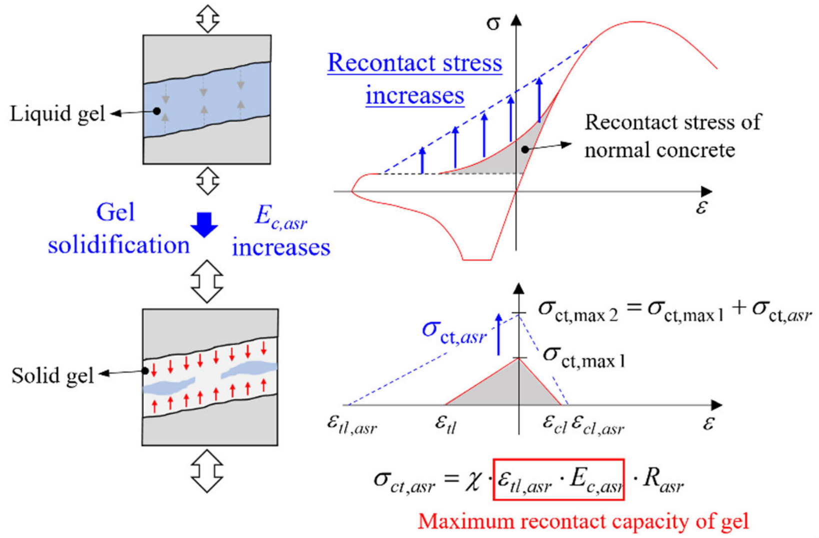
Figure 11: Time-dependent mechanical properties with different material ages [13]

space change, causing a mechanical contribution.

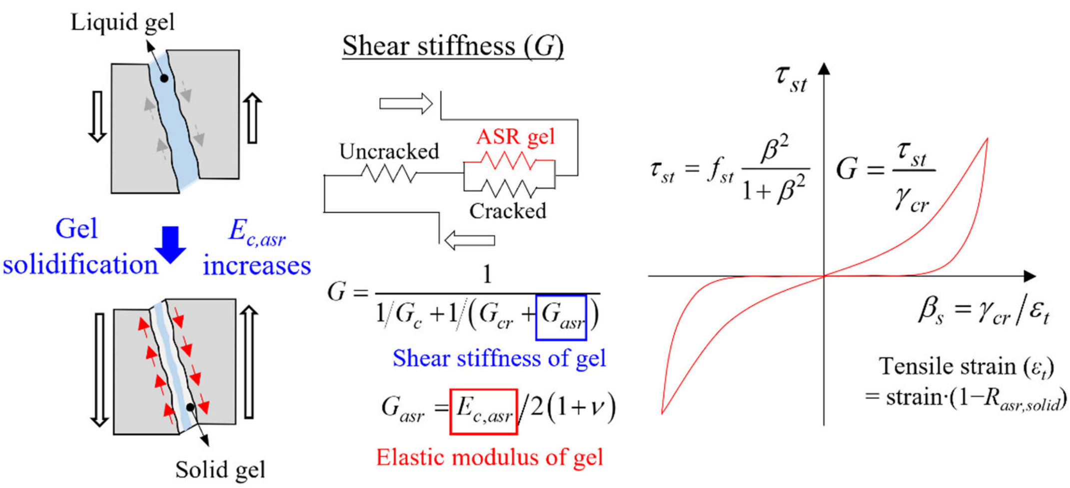
Therefore, a model is proposed to account for these effects in the mechanical constitutive law [1]. An overview of the proposed model is shown in Figure 12. The influence of macrocrack fraction on the total strain was considered in the compression softening model to prevent excessive compressive strength reduction (Figure 12(a)). Additionally, the occupation of the ASR gel in cracks and their stiffness depending on the chemical



(a) Compression model considering the effect of microcrack



(b) Recontact model considering the mechanical contribution of gel



(c) Shear model considering the mechanical contrivution of gel

Figure 12: Consideration of ASR expansion crack characteristics and gel-filling effect on the constitutive laws [1]

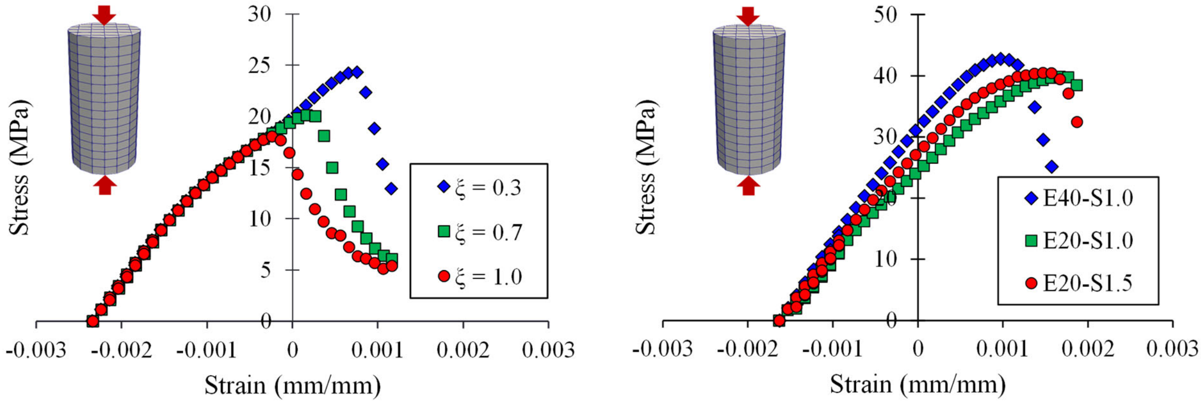
composition were considered in the crack re-contact and post-crack shear transfer models (Figures 12(b) and 12(c)).

The ASR mechanical contribution in the cracks was determined by considering the gradual chemical composition changes. As a result of these considerations, the macroscopic compressive strength and Young's modulus of the concrete cylinder specimens varied, as shown in Figure 13.

Finally, with the introduction of these models, it is possible to reproduce the time-dependent recovery of the mechanical performance of concrete after ASR expansion in the authors' experiments, that is, the compressive behavior of concrete after ASR expansion (Figure 14). With the time-dependent stiffness increase in the ASR gel, the macroscopic Young's moduli of the concrete cylinders recovered in the simulations.

4 STRUCTURAL MEMBER SIMULATIONS

Based on the aforementioned microscopic mechanisms considerations in the mechanical model, a case study of a reproducible structural



(i) Effect of macro crack ratio (ii) Effect of gel stiffness and solidified gel ratio

Figure 13: Effect of each model on the concrete cylinder compression behavior [1]

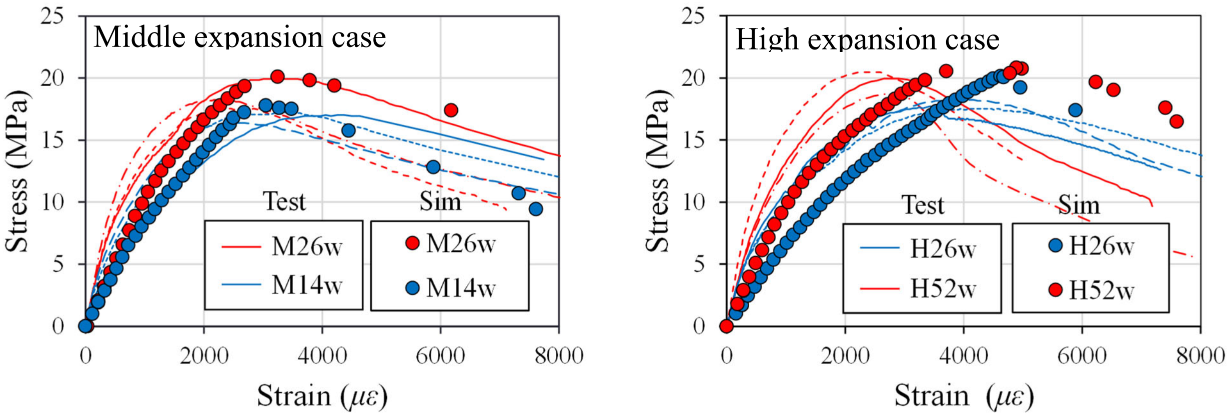
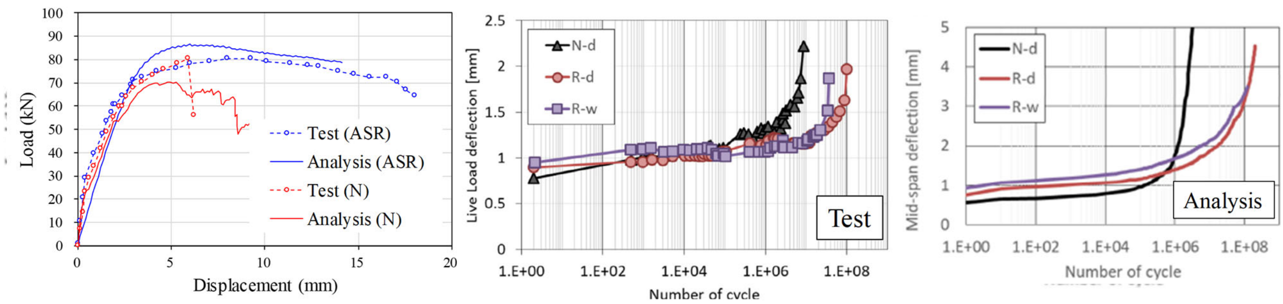


Figure 14: Compressive simulation of ASR-expanded concrete after model modifications [1]



(i) Bending behavior of RC beams [14] (ii) Fatigue behaviors of RC slabs [15]

Figure 15: Improvement of the mechanical properties of RC members after ASR expansion [14,15]

performance test analysis for a reinforced concrete (RC) member subjected to ASR expansion is presented. Figure 15 shows examples of the reproduced analyses of the bending and fatigue of RC structures [14, 15]. These cases show that the proposed model can adequately reproduce these behaviors, although the results indicate that the performance is better in the case of ASR expansion than in the case of no ASR expansion. It was found that crack propagation is suppressed by the preceding randomly oriented ASR expansion cracks [14], and that the mechanical contribution of the ASR gel present in the cracks suppresses crack opening and displacement, which are important in the performance evaluation [15].

While there are cases where structural performance improves by ASR, there are also cases where the mechanical performance degrades owing to ASR expansion as shown in Figure 16. We conducted a replicated analysis of these cases by considering various crack dispersions and gel contributions. Figure 17 shows the results of simulation study, in which "Normal" represents sound RC slab with no ASR damage, while "ASR-A" and "ASR-L" cases denote the ASR-damaged members with distributed (Pattern 1) and localized (Pattern 2) crack patterns, respectively. In addition, for ASR-L, two simulations, namely, with and without considering the gel resistance, were conducted. The analysis of ASR-L-GO (with localized cracks and gel resistance) was conducted to check how effective the gel-filling effect is even in the case of localized cracks. The results indicate that when the ASR expansion cracks disperse, the bearing capacity increases with a bending failure, whereas when the cracks are intentionally dispersed and localized, the cracks reach their final stage via

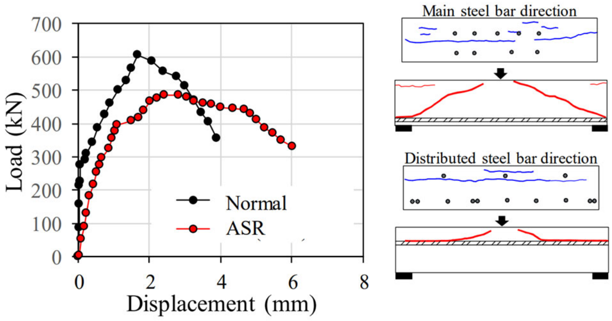
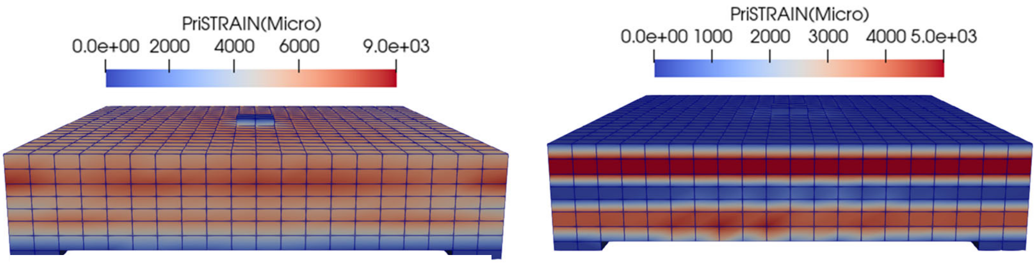


Figure 16: Punching shear of slab specimens [16]



(a) Pattern 1: Distributed crack pattern (b) Pattern 2: Localized crack pattern

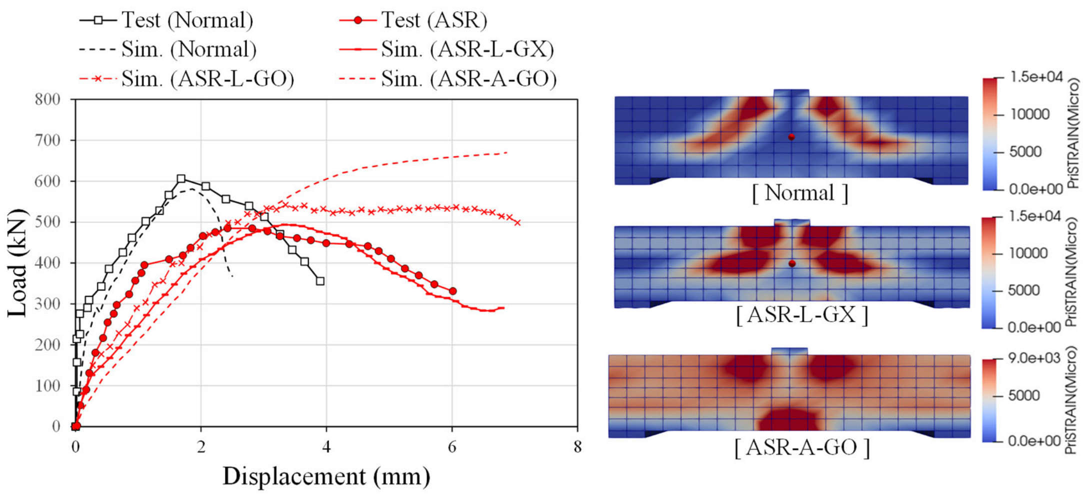


Figure 17: Structural behavior of RC slabs after ASR expansion with different crack locations and gel-filling effects

shear failure, and the bearing capacity decreases after ASR expansion. The results of this study successfully reproduced the bearing capacity reduction in the case of ASR expansion with such large and localized cracking. Additionally, it was shown that when these localized cracks open wide, the mechanical contribution of ASR to the cracks in the previous section is rather absent, which adequately reproduces the structural behavior.

As described above, the mechanical performance of RC structures subjected to expansion cracking can be properly modeled by properly understanding the cracking conditions (e.g., dispersion and directionality) as well as the mechanical properties of the precipitates in the cracks. Furthermore, the time-dependent behavior (e.g., mechanical property changes due to chemical composition changes and cyclic pressure generation such as FTC) of precipitates in cracks are considered to be important.

5 CONLUSIONS

This paper presents a numerical investigation of the mechanical performance of concrete subjected to expansion cracking owing to various chemical reactions and phase changes, and the modeling of microscopic mechanisms within concrete. It is necessary to consider that the expansion cracking and expansion strain due to these factors have different mechanical contributions than those assumed by conventional constitutive laws. Expansion cracks are generally associated with microdamage; therefore, at the same strain level, the damage degree is likely to be less than that predicted by the conventional mechanical constitutive law. Additionally, depending on the cause of expansion, the mechanical contribution of precipitates in cracks may further improve mechanical performance. However, if cyclic action of internal products occurs, damage may develop above the strain level. It is necessary to evaluate the residual performance of concrete structures that have undergone expansion and deterioration by considering the appropriate damage conditions depending on the expansion factor.

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