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Strong Coupling of Freeze-Thaw Cycles and Alkali Silica Reaction - Multi-scale Poro-mechanical Approach to Concrete Damages -

Fuyuan Gong¹, Yuya Takahashi² and Koichi Maekawa³*

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Abstract

This paper aims to upgrade the poro-mechanical scheme to simulate concrete volume change and damages which are strongly coupled with both alkali silica reaction (ASR) and freeze-thaw cycles (FTC). The interaction of two impacts are modeled by considering ASR gel intrusion and ice formation in micro pores and crack gaps, gel movement and unfrozen water suction into entrained air, gel and water migration through cracks as well as equilibrium and mass conservation of both concrete skeleton and mixed pore substances. For the assessment how the proposed numerical scheme works, sequence of events on ASR and FTC is focused on. It shows that ASR can reduce the FTC expansion for non-air-entrained (non-AE) case, but increase the frost damage for air-entrained (AE) concrete. Similarly, the FTC damaged concrete will have a smaller ASR expansion for non-AE case, but a greater expansion when AE admixture agent is dosed. The simulated behaviors also agree well with past experiments of combined ASR and FTC. Finally, the analysis on short-term strength shows that the ASR damaged concrete has a higher residual compressive strength and ductility rather than FTC damaged one due to viscous ASR gel which stand for broken symmetry of damage fields.

1. Introduction

Deterioration process of concrete is of high complexity since structural concrete usually suffers from coupled mechanistic and multiple ambient actions, such as high cycle fatigue loads, alkali silica reaction (ASR), freeze-thaw cycles (FTC), carbonation and steel corrosion. Furthermore, those environmental impacts are usually interacted. For example, migration of chemical substances is significantly affected by the moisture in motion. ASR and steel corrosion will consume water on which FTC damage closely relies. In addition, once cracks are generated by any of those impacts, migration of substances (water, alkali, chloride ion, carbon dioxide etc.) is much accelerated so that other durability problems may get more serious.

Considering the complexity of durability problems in terms of the coupling effects in chemical, physical and mechanical processes, a multi-scale modeling system is necessary to provide a strong linkage between each process and concrete material itself. The system should start from the hydration stage in nano-scale, and then be upgraded to the physical and chemical equilibrium in porous media, and finally lead to the structural performance (Maekawa et al. 2003, 2013). Based on this platform, dual impacts have been well modelled and simulated based on poro-mechanics, such as the fatigue effect of condensed water under traffic loads (Maekawa and Fujiyama 2013), the steel corrosion and crack opening caused by corrosion gels (Gebreyouhannes and Maekawa 2016), as well as the ASR expansion and damage (Takahashi et al. 2016).

The FTC induced deformation and damage has also been modelled by the authors (Gong et al. 2015a, 2015b). The above studies deal with one or dual impacts of weak coupling, which are rather ideal to predict the real complex deterioration process in real life. Thus, it is necessary to enhance the comprehensive modeling system to take the strong interactive coupling of mechanistic and multiple environmental impacts into consideration. The first attempt of this study is the coupled FTC, ASR and condensed water motion accompanying crack kinematics.

The FTC and ASR damages take place together to concrete of many cases, and alternately in winter and summer seasons. In addition, the deicing salt has been widely sprinkled on roads and bridge decks where the frost damage could happen, the remaining salt will also accelerate the ASR in the summer season (Kawamura et al. 1994). Therefore, in the area which has both cold and warm seasons, the combined FTC and ASR damage is likely to occur. One problem is, when the coupled damage occurs in real structural concrete, it is difficult to distinguish how much proportion of damage comes from which impact, then making the assessment of current situation as well as the prediction of future performance difficult. Thus, it is essential to understand the mechanism of the interaction between FTC and ASR, and further develop a modeling and simulation system to predict the damage.

The deterioration mechanisms by each single event

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have been widely investigated in the past decades. The frost damage is caused by the ice formation in pores. Once the saturation degree exceeds a critical value (Fagerlund 2002), significant damage in the porous skeleton will occur due to several kinds of pore pressures (Powers 1945; Scherer and Vallenza II 2005; Coussy and Monteiro 2009; Gong et al. 2015a). This kind of internal damage will be cumulated during numbers of FTC and result in gradual degradation in material properties (Hasan et al. 2004; Gong et al. 2013). As a result, for concrete damaged by FTCs, the static and the fatigue strengths at room temperature will also be reduced (Ueda et al. 2009; Hasan et al. 2008).

During large numbers of FTCs, the additional water supply plays a crucial role in the damage accumulation (Fagerlund 2002). Past experiments under open (exposed to water) and closed (sealed) moisture condition shows very different damage phenomena. The open test by Hasan et al. (2004) up to 300 cycles was found to increase in the peak and residual strains, while in the closed test by Sicat et al. (2013), the expansive damage stops just after a few cycles. Although both tests used non-air-entrained specimens with fully saturated initial conditions, if additional water can fill the damage cracks, more ice can be formed in the next cycle, thus consequently results in a greater crack opening.

Different from the frost damage, of which the ice freezing and thawing is only a thermodynamic process, the gel by ASR comes from the chemical reaction first. However, if just focusing on the physical and mechanical behaviors after the gel is generated, it becomes similar to ice and can be treated under the framework of poro-mechanics. The expansive behavior of ASR and its modeling have been well studied recently (e.g. Kawabata and Yamada 2015; Sannoh and Torii 2014; Costa et al. 2014; Saouma 2014; Saouma et al. 2014; Multon et al. 2009; Bazant and Steffens 2000; Bangert et al. 2004; Liudat et al. 2015; Charpin and Ehrlacher 2014). Meanwhile, based on the multi-scale chemo-hygral computational system (DuCOM-COM3, Maekawa et al. 2008; Maekawa and Ishida 2002), the authors have modelled and simulated the ASR gel production by considering the multi-ionic equilibrium (Takahashi 2014; Elakneswaran and Ishida 2014), the mechanical impacts of ASR in multi-directional cracking system (Maekawa and Fujiyama 2013; Takahashi 2014), as well as the scale-dependent gel anisotropic expansion and migration (Takahashi et al. 2016).

For the major interactions between two impacts, there are several experimental facts which can help to draw the basic assumptions for the modeling in this study. First, the ice will get frozen first in bigger capillary pores according to the thermodynamic equilibrium (Scherer and Vallenza II 2005), while the semiliquid ASR gel around aggregates can also be intruded into large capillary pores by the expansive pore pressure (Muranaka and Tanaka 2013). Then, once the capillary pores are filled by ASR gel, the ice formation will be reduced. Thus, less frost damage may occur. In addition, previous experiments also show that the ASR gel can flow into the entrained air, which can delay or reduce the ASR expansion (Jensen et al. 1984) at early stage, but it will increase the risk of frost damage on the contrary. The ASR gel can also flow into the existing cracks (Maraghechi et al. 2012), which will affect the water permeation in the crack system. These events are so strongly and mutually coupled each other.

In this paper, the strong coupling between FTC and ASR will be modelled from the micro-structural level, considering the ice formation and ASR gel intrusion into capillary pores, as well as the effect of entrained air. Then, based on the poro-mechanics, the mixed pore pressure and deformation of concrete skeleton will also be formulated. The solid-liquid two-phase interaction model (Biot 1963) will be extended to the multi-phase case (several kinds of pore substances) with local coupling of each pore’s liquids (ASR gel and water). Finally, different sequences of combined FTC and ASR expansion will be simulated and discussed, considering the time-dependent nonlinear material properties. The strong coupling of FTC and ASR is extra combined with condensed liquid water in motion.

2. Analysis method and basic models

The multi-scale integrated simulation scheme has been briefly summarized in Fig. 1. Starting from the hydration stage at nano-scale, the formation of inner and outer products is simulated based on the hydration kinetics (Maekawa et al. 2008). Then, the hydration products together with the cement particles forms the micro pore structure, within which the moisture transport and equilibrium can be formulated. The multi-ionic transport and equilibrium for ASR, as well as the thermodynamic equilibrium of ice formation are considered also at this scale (Takahashi et al. 2016; Scherer and Vallenza II 2005). Since both the alkali silica reaction and the ice formation will cause volume increase in the pore substances, the mechanical interaction between pore substances (ice, water, ASR gel) and concrete skeleton will be considered for both non-cracked and cracked conditions. During the poro-mechanical modeling, the liquid water movement and ASR gel migration are also calculated according to the pressure gradient. Since the pore pressure by ASR is a long-time sustained load and the FTC will cause daily cyclic reloading and unloading, when considering mechanical response for the material, the time-dependent and cyclic nonlinearity should be adopted (Maekawa et al. 2006).

The basic models to calculate the ASR gel generation, ice formation, as well as the isotropic/anisotropic pressures induced by two effects are summarized in Figs. 2 and 3. The generation of ASR gel is formulated based on the chemical equations (Takahashi et al. 2014, 2015). The rate of ASR is formulated as a function of the alkali concentration, updated free water and the content of reactive aggregates. The environmental variable such as
the temperature and relative humidity have also been considered to affect the gel generation rate. As the reaction goes on, both alkali and water will be consumed, and the reduced alkali and water will affect the chemical reaction rate reciprocally. Since the chemical reactions are complex during ASR, a representative density $\rho_{gel}$ is chosen for the whole reaction product, including the newly create products as well as the volume reduction.

$$R_{ASR-x} = k \cdot C_{x} \cdot F_{water} \cdot VRG \cdot 1.0 \cdot E - 9$$

$\frac{d}{dt} = \frac{k_{RH} \cdot k_{R} \cdot R_{ASR-x}}{3}$

$\Delta Gel_{x} = \frac{R_{ASR-x} \cdot \Delta t \cdot M_{gel}}{\rho}$

$C_{x, ASR} = 2.0 \cdot \Delta Gel_{x} \cdot \rho \cdot 1.0 \cdot E + 6 \cdot M_{gel}$

$W_{x, ASR} = 8.4 \cdot \Delta Gel_{x} \cdot \rho \cdot 1.0 \cdot E + 6 \cdot M_{gel}$

$(r) \text{ Minimum pore size for gel absorption } [m]$

$Z: \text{ Coefficient } [m/Pa], \rho: \text{ gel pressure } [Pa]$

(a) Anisotropic pressure with solid part

$p_{ai} = \text{ stiffness} \cdot (1 - \beta) \cdot V_{crack} \cdot i$ ...

(b) Isotropic pressure with liquid part

$p_{i} = \text{ stiffness} \cdot (1 - \beta) \cdot V_{crack} \cdot i$ ...

$\text{ Stiffness} : \text{ Stiffness of matrix}$

$\beta: \text{ Solid ratio in ASR-gel (0.2)}$

$V_{crack}: \text{ Existing ASR gel volume}, V_{crack} \cdot i \cdot \text{ Crack width in } i \text{ direction}$
of intact aggregate. The representative density is determined through the sensitivity analysis based on experiments at this moment, which need to be investigated further. After the ASR gel volume is obtained, the deformation of concrete skeleton will be calculated through a poro-mechanical approach.

The generated ASR gel is thought as a semi-liquid substance and the total pore pressure is composed of both isotropic pressure by liquid gel and anisotropic pressure by solid gel. Driven by the high pore pressure, the liquid ASR gel will intrude into larger capillary pores, and the critical size of pores which the ASR gel can fill depends on the pore pressure and surface tension of liquid gel (same mechanism with mercury intrusion test). In order to express the solid-liquid coexisting states, parameter $\beta$ is introduced, which is the ratio of the solid phase to total ASR-gel. The proposed model has been sufficiently verified by ASR experiments, for both the uniform expansion under unconfined condition and the non-uniform expansion with confinements (Takahashi et al. 2016).

The pore pressure induced by ice formation is composed of three parts: the hydraulic pressure ($P_{\text{hydrau}}$) due to ice expansion (Powers 1945), the crystallization ($P_{\text{cryst}}$) and cryosuction ($P_{\text{cryo}}$) pressures due to the thermodynamic equilibrium between ice crystal and unfrozen water (Coussy and Monteiro 2009; Sun and Scherer 2010). The hydraulic pressure depends on the increased volume when ice forms and the deformation of pore skeleton; furthermore, the increased volume which can contribute to the volume expansion is also depending on the saturation degree and amount of entrained air. Here, the saturation degree ($S$) is defined for all the interlayer, gel and capillary pore, but not including the entrained/entrapped air system. Finally, the crystallization and cryosuction pressures only reply on the temperature due to thermodynamic equilibrium (Scherer and Vallenfa II 2005). This calculation scheme has also been verified by the mesoscale closed FTC test (Gong et al. 2015a) and macroscale open test (Gong et al. 2015b).

### 3. Modeling of coupling

As the main target of this study, the coupled FTC and ASR effect will be investigated from the micro pore structure level, and updated to the meso-scale level considering the space-averaged behaviors. Figure 4 illustrates the representative volume element (RVE) for this two-scale problem. Considering a RVE at meso-scale (1mm to 1cm) which contains aggregate, cement paste, entrained air and meso-cracks, the ASR gel will be created in and around aggregates, while the ice will form in meso-cracks (if the cracks are filled by free water). Not all the created gel will contribute to the volume expansion, because the liquid gel can be intruded into large capillary pores and even flow into the meso-cracks and entrained air bubbles (Jensen et al. 1984; Maraghechi et al. 2012). At the micro pore structure level (10 μm to 100 μm), the ice will forms starting from the larger capillary pores. Then, if the greater capillary pores are al-

$$P = P_{\text{hydrau}} + P_{\text{cryst}} + P_{\text{cryo}}$$

![Fig. 3 Calculation scheme of pore pressures during ice formation. (Gong et al. 2015a)](image-url)
ready occupied by ASR gel, the ice formation will be delayed and with less amount, and finally result in a smaller frost expansion.

However, when the entrained air bubbles are filled by the ASR gel, they may lose their function in preventing the frost damage. Finally, considering that the ASR gel intrusion is governed by the pore pressure and the pore pressure should always be within the limit of skeleton’s tensile strength, then if FTC causes damage first and decreases the skeleton’s strength, less liquid ASR gel can be consumed by the capillary pores so that the ASR expansion could become larger. The detailed quantitative formulation will be discussed in the following subsections.

The strong coupling between ASR and FTC is considered at both the global scale and local scale as shown in Fig. 4. For the coupling at global scale, the deformation of concrete matrix is interacted with the mixed pore pressures at the macro scale, while the pore pressures will push the pore substances into capillary pores and entrained air at micro scale, and this micro-events will affect the total pore pressures and matrix deformation reciprocally. Then, at the local scale of liquid flow in pores and cracks, different phases of flow are also coupled together.

3.1 Gel intrusion and ice formation in capillary pores

Due to different nature of the pore space in cement-based materials, the pore spaces can be divided into capillary pores (10^{-8} m to 10^{-4} m), gel pores (10^{-10} m to 10^{-9} m) and interlayer pores (less than 10^{-9} m) (Maekawa et al. 2008). The interlayer porosity (\( \phi_{lr} \)) (a structural part of the C-S-H gel) can be simply lumped with the porosity distribution of gel and capillary pores, because usually the physical or chemical events would not affect such small space. The general pore size distribution of capillary and gel pores can be conveniently described by a simplistic Raleigh-Ritz (R-R) distribution function. Then, the total pore size distribution is as follows (Maekawa et al. 2008):

\[
\phi(r) = \phi_{lr} + \phi_{gel} \left( 1 - \exp(-B_{gel} r) \right) + \phi_{cap} \left( 1 - \exp(-B_{cap} r) \right)
\]

where \( \phi(r) \) is the cumulated porosity whose radii are less than \( r \), \( \phi_{lr}, \phi_{gel} \) and \( \phi_{cap} \) are the porosity of interlayer, gel and capillary pores, respectively, \( B_{gel} \) and \( B_{cap} \) are the solo porosity distribution parameter for gel and capillary pores.

The critical radius (\( r_{ASR} \)) of the pore into which ASR gel can intrude under a gel pressure (\( p_{ASR} \)) can be determined by the Washburn equation as,

\[
r_{ASR} = \frac{2 \gamma_{ASR} \cos \theta_{ASR}}{p_{ASR}} = \frac{2 Z_{ASR}}{p_{ASR}}
\]

where \( \gamma_{ASR} \) is the specific energy of ASR gel and \( \theta_{ASR} \) is the contact angle between ASR gel and concrete skele-
ton. Since there is no report on the surface tension and contact angle of ASR gel, the parameter $Z_{ASR} \approx 0.4$ is determined based on the sensitivity analysis using the free expansion data from Muranaka et al. (2013). Different from the ASR gel, the ice occupation of different size of pores depends on the thermodynamic equilibrium closely related to the temperature (Scherer and Vallenza II 2005):

$$Z_{ICE} = \frac{2Z_{ICE}}{\Delta S_p(T_0 - T)} + \delta$$

(3)

where $Z_{ICE} = \gamma_{ICE} \cos \theta_{ICE}$, $\gamma_{ICE} \approx 0.04$ J/m$^2$ is the specific energy of ice/water interface, $\theta_{ICE} \approx 0$ is the contact angle between ice and pore wall, $\Delta S_p \approx 1.2$ J/(cm$^3$·K) is the molar entropy of fusion, $T_0 < 0^\circ$C is the local temperature in Celsius, $T_0$ is the freezing point of free water ($0^\circ$C), $\delta \approx 0.9$ nm is the thickness of unfrozen water layer between ice and pore wall. It is obvious that when ASR happens first, the ice will not start to form until $r_{ICE} < r_{ASR}$, when ice is formed first, the ASR gel can only penetrate pores smaller than $r_{ICE}$. The former situation is the usual case because the rate of ASR below $0^\circ$C will be too slow to be counted.

For many thermodynamic equilibriums related to the pore size distribution, the hysteresis phenomena are often observed, such as the water/nitrogen adsorption/desorption curves, ice freezing/thawing curves (Sun and Scherer 2010) and the ink bottle effect during mercury intrusion test. All these are because that the size of pore entries is usually smaller than the pore bodies, as shown in Fig. 5. Once the meniscus of ASR gel front achieved an equilibrium at the pore entry, it will stop to intrude into the pore body although its size is still larger than the critical radius. This part of the pore volume can be evaluated as (Maekawa et al. 2008):

$$S_{ink} = \int_{r_{min(ASR)}}^{r_{min(ASR)}} f(r) \Omega dr = \int_{r_{min(ASR)}}^{r_{min(ASR)}} \left( \frac{S}{V} \right) dV = -S_{ink}(S_{ink})$$

(4)

where $S_{ink}$ is the ratio of the trapped water to the total pore space, $\Omega$ is the normalized pore size distribution ($\int_0^\infty \Omega dr = 1$), $S_{ink} = \int_{r_{min(ASR)}}^{r_{min(ASR)}} \Omega dr$ is the equilibrium water content even when no water is trapped, $f = \frac{S}{V}$ is the probability that the water can be trapped by the ink bottle effect. It is obvious that $S_{ink}$ will depend on the minimum value of $r_{ICE}$ and $r_{ASR}$ (see Fig. 5).

As mentioned before, the ASR gel intrusion takes rather a long time compared to the cyclic freezing and thawing. Thus, it can be simply regarded that the ASR gel will occupy the larger capillary pore first, and then ice will form in the smaller pores. By defining $S(0) = \int_0^\infty \Omega dr$, we have the ASR gel saturation degree as,

$$S_{ASR} = 1 - S(r_{ASR}) - S_{ink} = 1 - S(r_{ASR}) + S(r_{ASR}) \ln[S(r_{ASR})]$$

(5)

and the ice saturation degree will be ($r_{ICE} < r_{ASR}$):

$$S_{ICE} = \{1 - S(r_{ICE}) + S(r_{ICE}) \ln[S(r_{ICE})]\} - S_{ASR}$$

(6)

For convenience, the ASR gel intrusion is assumed as an irreversible process because the created gel volume usually cannot decrease. In addition, as the time goes on, the liquid ASR gel may also crystalize and become more like solid phase. On the contrary, the ice freezing
and thawing is always reversible, thus, the differences between freezing and thawing curves have been considered (referring to the model by Maekawa et al. 2008):

\[
S_{ICE}^{\prime} = \begin{cases} 
1 - S(r_{ICE}) + S(r_{ICE_{-min}}) \ln[S(r_{ICE})] - S_{ASR} 
& (r_{ICE} \leq r_{ASR} \text{, freezing}) \\
[S(r_{ICE_{-min}}) - S(r_{ASR})] \ln[S(r_{ICE})] 
& (r_{ICE} > r_{ASR} \text{, thawing}) 
\end{cases}
\]

where \( r_{ICE_{-min}} \) is the minimum value during the freeze/thaw cycle.

Giving different water to cement ratio (w/c) for ordinary cement, and based on the hydration kinetics, the pore structures can be calculated by the DuCOM system (Maekawa et al. 2003). At 28 days, the hydration degree, each type of porosity, the pore size distribution parameters as well as the compressive strength are lined up in Table 1. The tensile strength \( f_t \) is estimated according to the ACI standard (ACI Committee 2008). Based on Eq. (7), if only considering the single freeze/thaw event, ice saturation during FTC can be calculated (Fig. 6). The computed ice volume is very close to the experimental measurements (e.g. Sun and Scherer 2010; Wang et al. 2016).

According to Eq. (1) and Eq. (2), the amount of ASR gel that can be intruded into the capillary pores depends on both the pore size distribution (w/c ratio) and the pore pressures, as shown in Fig. 7. Based on pore-mechanical theories, the exact pore pressure usually can be 2-4 times of the effective stress in the concrete skeleton. Then, if taking 3 times of the tensile strength under unconfined condition as the limit of pore pressures, the maximum capacity of ASR gel absorption can be estimated (Fig. 7). When FTC happens after ASR gel intrusion, the freezable water can be reduced, and as the w/c ratio becomes larger, the reduction effect will also become more significant. On the other hand, once the concrete material has been seriously damaged by FTC first, the maximum pore pressure which concrete skeleton can sustain will be largely reduced, then more ASR gel will contribute to the expansion and cause a bigger ASR damage.

### Table 1 Parameters of pore volume and size distribution in cement paste.

<table>
<thead>
<tr>
<th>w/c</th>
<th>Age (day)</th>
<th>Hydration Degree</th>
<th>Total Porosity</th>
<th>Interlayer Porosity</th>
<th>Gel Porosity</th>
<th>Capillary Porosity</th>
<th>( B_{gel} ) (m(^{-1}))</th>
<th>( B_{cap} ) (m(^{-1}))</th>
<th>( f_t ) (MPa)</th>
<th>( f_t' ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>28</td>
<td>71%</td>
<td>0.3050</td>
<td>0.0954</td>
<td>0.1159</td>
<td>0.0938</td>
<td>6.54E+7</td>
<td>1.32E+7</td>
<td>77.6</td>
<td>5.5</td>
</tr>
<tr>
<td>0.50</td>
<td>28</td>
<td>86%</td>
<td>0.3943</td>
<td>0.0946</td>
<td>0.1144</td>
<td>0.1853</td>
<td>6.57E+7</td>
<td>5.36E+6</td>
<td>40.6</td>
<td>4.0</td>
</tr>
<tr>
<td>0.65</td>
<td>28</td>
<td>92%</td>
<td>0.4750</td>
<td>0.0859</td>
<td>0.1037</td>
<td>0.2855</td>
<td>6.57E+7</td>
<td>2.73E+6</td>
<td>19.6</td>
<td>2.7</td>
</tr>
</tbody>
</table>

\* \( f_t' = 0.623(f_t)^{0.5} \) according to ACI standard.

### 3.2 Function of entrained air under coupled effect

The original purpose of entrained air is to reduce or prevent the frost damage (Powers 1949), because ice will crystallize in the entrained air and the water in the surrounding pores will be sucked into the air bubbles so that the ice volume increase in the pore system can be avoided. The effect of entrained air on the ASR expansion has also been discussed for years. Jensen et al. (1984) observed that the entrained air can be fully occupied by the ASR gel, and 4% entrained air can reduce the ASR expansion by about 40%. But, there are some other long-term exposure tests which show that the entrained air has little effect on the ASR expansion (Fournier et al. 2009). This difference might attribute to the condition of tests. In laboratory tests as Jensen et al. (1984), ASR was accelerated and the gel can be easily intruded into entrained air while it stays as a liquid phase. But for the in-situ exposure test, the reaction rate is generally slow so that the ASR gel may be solidified with the presence of calcium ion before flow into the air bubbles. In this study, the authors focus on the accelerated case in order to clarify the interaction of these effects.

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![Fig. 6 Ice freezing and thawing curves considering the ink bottle effect (without ASR gel).](image-url)

![Fig. 7 Amount of ASR gel intrusion into capillary pores under different pore pressures.](image-url)
The air content measured after casting will not all contribute to the frost resistance or ASR gel absorption, because most of the air volume is attributed to the large air bubbles \( r > 255 \mu \text{m} \) with very limited number as shown in Fig. 8. According to Powers’ spacing factor model (1949), those big bubbles have little effect on the averaged distance of the air system. Similar to the unfrozen water movement to the entrained air, ASR gel flow is also driven by the gel pressure. Thus, ASR gel will also first flow into air bubbles closely around aggregates, and the smaller distance between two bubbles is, the easier gel flow can reach. Therefore, a simplistic rate-dependent model considering the differences in accessibility is assumed as:

\[
V_{\text{ASR-AIR}} = k_{\text{AIR}} \cdot (1 - \beta_{\text{ASR-AIR}}) \cdot p_{\text{ASR}} \cdot \text{Air}
\]  

(8)

where \( V_{\text{ASR-AIR}} \) is the speed of gel flow into air bubbles, \( k_{\text{AIR}} \) is a constant which can be determined by the sensitivity analysis \((3 \times 10^{-9} \text{Pa}^{-1} \text{s}^{-1})\), \( \beta_{\text{ASR-AIR}} \) is the ASR gel occupying ratio in the air bubbles (0 to 1), \( \text{Air} \) is the total air content (entrained and entrapped air).

For the frost resistance, only the smaller air bubbles with a small average distance is functional, which is around 10% of the total air volume based on Fig. 8. On the other hand, these 10% air bubbles can also be easiest filled by the ASR gel. Thus, once \( \beta_{\text{ASR-AIR}} \) becomes bigger than 0.1, the air bubbles will fully lose functions in the frost resistance. Then, when temperature falls down below 0°C, the increased volume by ice which will contribute to the damage \( (\Delta V_{\text{ICE}}) \) is:

\[
\Delta V_{\text{ICE}} = \Delta V_{\text{ICE}} - Q = 0.09 \phi \cdot \psi_{\text{cp}} - (0.1 \text{Air} - V_{\text{ASR-AIR}})
\]

(9)

where \( \Delta V_{\text{ICE}} \) is the original volume increment when ice forms, \( S_{\text{ICE}} \) is the ice saturation calculated from Eq. (7), \( \phi \) is the total void ratio of cement paste, \( \psi_{\text{cp}} \) is the volume ratio of paste in concrete, \( Q \) is the volume consumed by the effective air bubbles.

**3.3 Mixed pore pressure and migration of pore substance**

The governing equations of the poro-mechanical equilibrium together with the pore flow has been discussed in previous studies (Maekawa et al. 2008), which was originally based on Biot’s two-phase model (1963). For this study, there are two pore liquids which will both contribute to the skeleton deformation, and reversely, the deformation of skeleton will also affect both liquid flows. Therefore, the governing equations should be extended to the multi-phase flow case. Fortunately, the liquid ASR gel and water have rather great differences in nature (such as permeability and viscosity). In addition, the difference in the specific surface energy will provide a clear interface between two fluids (see Fig. 9), so that the two liquids will hardly be merged unlike mixed gases. These characters make the coupling formulation simpler because the one liquid phase can be regarded as the pore wall made by the other phase. The friction at the interface between two liquids may also be assumed similar to the pore wall for convenience. Then, by following the formulation scheme of Biot (1963) and Maekawa et al. (2008), we have the averaged density \( (\rho) \) as,

\[
\rho = (1 - n) \rho_s + \sum_{i=1}^{N_1} f_i n \rho_i + \sum_{i=1}^{N_2} f_i n \rho_i
\]

(10)

where \( 1 - n \) and \( \rho_s \) are the volume ratio and density of concrete skeleton, \( f_i \) is the proportion of each solid/liquid substance in pores and \( \sum_{i=1}^{N_1} f_i = 1, N_1 \) is the total number of pore substances, \( N_i \) is the number of liquid phase in pores, \( \rho_i \) is the density of each pore substance.

In this study, the motion of pore liquids is defined by the relative displacement from the solid matrix. Then, the movement of each pore liquids denoted by \( U_{ij}^{(r)} \) is expressed by the space-averaged displacement of concrete skeleton \( u_i \) and the substantial relative displacement of each pore liquid phase \( (w_i^{(r)}) \) as,

\[
U_{ij}^{(r)} = u_i + w_i^{(r)} f_i n
\]

(11)

The pore substances can be either liquid or solid, which will generate isotropic liquid and anisotropic solid pressures, respectively. Thus, a term \( (s_{ij}) \) represent-

![Fig. 8 The size distribution of entrained/entrapped air (redraw from Promentilla and Sugiyama 2010), and the cumulated air content of \( r < 255 \mu \text{m} \) (a) plain concrete (b) air-entrained concrete.](image-url)
ing the stress tensor caused by all the solid pore substances is added to the total stress \( \sigma_{ij} \) as,

\[
\sigma_{ij}^* = \sigma_{ij}^0 + s_i + \delta_j p
\]

(12)

where \( \sigma_{ij}^* \) is the effective stress tensor defined on the concrete skeleton, \( \delta_j \) means the Kronecker’s delta \( (\delta_{ij} = 0 \text{ if } i \neq j; \delta_{ii} = 1 \text{ if } i = j) \), \( p \) is the total isotropic pore pressure by liquid pore substances, which is a sum of all the partial pressures of each liquid phase (here, considering a local strong coupling) as,

\[
p = \sum_{r=1}^{N_s} p_{ij}^{(r)}
\]

(13)

This assumption of pore liquid isotropy inside capillary pores of concrete may hold before cracking. Then, this is applied to the liquids inside capillary pores. In formulating the dynamic equilibrium equations of the concrete skeleton and each pore liquid in cracks, the interacting term between two phases is needed. Assuming that different kinematics of each phase may create mutual interacting forces, the governing equations can be formulated with the term of dragging forces rooted in the permeability \( (k_i^{(r)}) \) of pore liquid in each i-direction through concrete pore and crack gaps as,

\[
\sigma_{ij} = \rho(u_i - g_i) + \sum_{r=1}^{N_s} \rho_{ij}^{(r)}
\]

(14)

\[
p_{ij}^{(r)} = \rho_i (u_i - g_i) + \rho_{ij}^{(r)} (f \cdot n) + (1/k_i^{(r)}) w_{i}^{(r)}, \quad r = 1...N_i
\]

(15)

where \( g_i \) is the gravity and the last term of Eq. (15) represents the dragging action of each pore liquid based on Darcy’s law. The subscript \( t \) and \( tt \) denotes the first and second degree differentiations with respect to time.

The total liquid and solid pore pressure in pores and crack system can be calculated as an extension of previous models (Biot 1941, 1963; Maekawa et al. 2008; Gebreyouhannes and Maekawa 2016) as follows.

\[
p = \bar{K}_f \sum_{r=1}^{N_s} \sum_{i=1}^{N_i} w_{ij}^{(r)} + (1 - \beta) \varepsilon
\]

(16)

\[
s_i = 3\delta_{ii} \bar{K}_f (a_{ii} + \beta \varepsilon)
\]

(17)

\[
\bar{K}_f = \left( \frac{1 - n}{K_s} + \sum_{r=1}^{N_s} \frac{f_r}{K_r} \right)^{-1}
\]

(18)

where \( \bar{K}_f \) is the average bulk modulus of the whole composite assuming a volumetric linearity, \( \varepsilon \) is the strain of concrete skeleton based on the space averaged path and time dependent constitutive equation rooted in the multi-directional crack modeling (Maekawa and Fujiyama 2013; Maekawa et al. 2003), \( a_{ii} \) is the amount of all generated solid pore substances, \( \beta \) is the ratio of the solid phase of pore substances. Thus, \( \sum_{r=1}^{N_s} \sum_{i=1}^{N_i} w_{ij}^{(r)} + (1 - \beta \varepsilon) \) represents the volumetric strain of liquid phases inside concrete, while \( a_{ii} + \beta \varepsilon \) means the one-dimensional strain of solid pore substances.

The shear stiffness of the liquid phases is assumed zero. From a strict point of view, the porosity \( n \) is not constant but varies with the concrete micro-structure.
and crack opening and closure. However, considering that the range of strain for porous media \(\left(\sum_{i=1}^{N} w_i \varepsilon_i + a_i + \varepsilon_a\right)\) is at most one percent and negligible in case of engineering practice, the averaged porosity in the governing equations can be treated as the initial one of constant. Throughout this formulation, the mechanical interaction of multi-phase pore substances and cracked concrete skeleton can be consistently installed in the framework of continuum mechanics. The overall framework of the multi-phase poro-mechanical modeling is summarized in Fig. 9.

The anisotropy of cracking can affect both liquid pore pressures and the liquid permeability, as discussed and formulated in Maekawa et al. (2013). That is, once the cracks are generated, the liquid pore substances (water, liquid ASR gel) are located within thin crack opening, and the interaction with cracked concrete is rather anisotropic. Therefore, the liquid pressure inside the crack gaps will act perpendicularly to a pair of parallel crack planes (Fig. 10) as,

\[
\sigma_y = \sigma_y^* + s_y + \delta_y l, p
\]

(19)

where \(l\) is the unit directional vector normal to a crack plane. Here, the anisotropic liquid pore pressure will be considered only after complete formation of connected planes through the fracture process zones.

The crack opening will also result in an anisotropy in the permeation of pore liquids (Fig. 10). This anisotropy has been discussed for several pore liquids such as water (Maekawa et al. 2013), steel corrosion gel (Gebreyouhannes and Maekawa 2016) and the ASR gel (Takahashi et al. 2016) as a single pore media. For example, with a parallel cracking plans as shown in Fig. 10, the permeability along the other two directions will be significantly enlarged (1 and 2) while 3 will not be changed. Experimental studies of the averaged water permeability with single (Wang et al. 1997) and multiple cracks (Lepech and Li 2005) show that the original permeability of un-cracked concrete is around \(10^{-10}\) to \(10^{-9}\) cm/s of isotropy, but can be significantly magnified up even to \(10^{-3}\) cm/s for more (see Fig. 10). For a multi-directional cracking system, the permeability enlargement depends on the crack opening width of other two directions, which has been proposed as (Maekawa et al. 2013),

\[
k_i = k_i \left[1 + \left(\frac{\varepsilon_{ij} + \varepsilon_{kk}}{a}\right)^b\right]
\]

(20)

where \(k_i\) is the permeability in direction \(i\), \(k_0\) is the intrinsic permeability for different kinds of liquid, \(\varepsilon_{ij} + \varepsilon_{kk}\) is the transverse in-plane strain of projection, \(a\) is a constant meaning the threshold of the crack opening (=100μ in this study), \(b\) is a constant related to the liquid type. Based on the experimental data from Wang et al. (1997), \(k_0=10^{-9}\) cm/s, \(b=4\) for liquid water, while for the liquid ASR gel, the sensitivity analysis (Takahashi et al. 2016) based on measured ASR expansion shows \(k_0=10^{-18}\) cm/s, \(b=2\). As discussed above, although there are two liquids (water and liquid gel) in the pore and crack system, they can transport rather independently and may not be mixed together. Upon this assumption, once the cracks are partially filled with ASR gel, the actual spacing for the water permeation will be reduced. On the other hand, the ASR gel flow may not be affected much by the existing water in cracks, because the gel flow is much slower than that of water so that we have enough time to expel water out when the ASR gel flows through the cracks. Thus, the permeability of each liquid phase can

Fig. 10 Anisotropy of stress and permeability induced by cracking, considering the interactive effect of ASR gel and ice in cracks.
Table 2 Curing and exposure conditions of each group.

<table>
<thead>
<tr>
<th></th>
<th>NaOH (mol/l)</th>
<th>Curing</th>
<th>Stage 1</th>
<th>Stage 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASR+FTC</td>
<td>1.64</td>
<td>28d, 20 °C, 99.9%</td>
<td>ASR: 152d, 40 °C, 99.9%</td>
<td>FTC: 10d, T(17), in water*</td>
</tr>
<tr>
<td>FTC+ASR</td>
<td>1.64</td>
<td>28d, 20 °C, 99.9%</td>
<td>FTC: 10d, T(0), in water</td>
<td>ASR: 152d, 40 °C, 99.9%</td>
</tr>
<tr>
<td>FTC alone</td>
<td>0</td>
<td>28d, 20 °C, 99.9%</td>
<td>FTC: 10d, T(0), in water</td>
<td>-</td>
</tr>
</tbody>
</table>

*: In air, RH=99.9%; *: FTC temperature history; *: Open (unsealed) or closed (sealed) condition

be expressed as follows.

\[
K_{\text{Air}} = K_{\text{Air}}^0 \left(1 + \left(\frac{\varepsilon_{\text{Air}} + \varepsilon_{\text{Air}}} {a} \right)^2 \right) \quad (21)
\]

\[
K_{\text{ASR}} = K_{\text{ASR}}^0 \left(1 + \left(\frac{\varepsilon_{\text{ASR}} + \varepsilon_{\text{ASR}}} {a} \right)^2 \right) \quad (22)
\]

where \(0 \leq R_{\text{ASR}} \leq 1\) is the ASR gel occupying ratio of the crack spaces.

4. Simulations and discussions

The FEM analysis is conducted by using DuCOM- COM3 for the sole and coupled ASR and FTC expansion. 10cm cubic concrete samples are used for all the cases in order to address the basic expansion behavior, and the deformation is space-averaged similar to the experimental methods by using transducers or embedded sensors of “finite” sizes (see Fig. 11). Three different w/c ratios (0.35, 0.5 and 0.65) and three air contents (0%, 1.5% and 4.0%) are considered to make a comprehensive investigation. Air=0% represents an ideal case completely without any entrained and entrapped air, which is only used for the parametric analysis in this study. The usual concrete without any air- entraining agent may still contains some air bubbles around 1% to 2%. Then, the case Air=1.5% is chosen as representing the ordinary non-AE concrete in the following analysis. Finally, for AE concrete, 4% of air content is chosen in the following analysis. In order to provide the same amount of generated ASR gel, the content of reactive aggregates is kept constant (1165 kg/m³ gravel and 777 kg/m³ sand) for all cases. Finally, the initial NaOH concentration is set as 1.64 mol/l.

The curing and exposure conditions are listed in Table 2. After 28 days of curing (20 °C, RH=99.9%), 152 days of ASR exposure and 10 days of FTC are conducted with different sequences. The temperature history for each FTC has four equal duration (6 hours): (i) first goes down from 5 °C to -20 °C with a constant cooling rate (-4.17 °C/h); (ii) kept constant at -20 °C; (iii) goes up to 5 °C (4.17 °C/h); (iv) kept constant at 5 °C. During the FTC, the moisture boundary conditions are considered either closed (sealed) or open (exposed to water). The single FTC event is simulated with pure water as a control group, to eliminate the effect of ion concentration on freezing point and ASR during curing stage. The mix proportion and exposure conditions are chosen to provide a similar magnitude to damage level for both effects, so that the interaction between two effects can be analyzed clearly.

4.1 Single event and influential parameters

The reliability of the proposed models for the single ASR or FTC events (Fig. 2 and Fig. 3) has already been verified in previous studies (Takahashi et al. 2014, 2015, 2016; Gong et al. 2015a, b). Thus, the influential parameters of each single event without coupling of others are discussed directly here. Figure 12 shows the effects of air content and w/c ratio on the pure ASR expansion during 180 days. According to the proposed model in Fig. 5, the created ASR gel can be first consumed by the capillary pores, and also as the w/c ratio increases, the capillary porosity becomes greater (Table 1). Therefore, when the created gel amount is the same, concrete with higher w/c ratio can absorb more ASR gel in the pore system so that the deformation (crack opening) will become smaller (see Air=0% cases in Fig. 12).

For AE concrete, ASR expansion can be reduced, and reduction ratio in Fig. 12 also agree well with experiments of Jensen et al. (1984). It can also be seen that concrete with lower w/c ratio has a greater reduction effect from the entrained air, this is because the driving

![Fig. 11 FEM mesh and the equivalent embedded sensor.](image1)

![Fig. 12 Effect of w/c ratio and air content on the free ASR expansion.](image2)
force (ASR gel pressure) of gel flow into air bubbles in high strength concrete can be larger. Thus, the effect of w/c ratio on the magnitude to ASR expansion may vary with the air content. Actually, the w/c ratio can also affect the magnitude of ASR expansion in terms of the reacting water, as reported in Stark (1995), that the high strength concrete may has a lower ASR expansion due to the largely reduced water transportation from surface inward.

However, when the sample size is small and RH is very high (as in this simulation), the reacting water for ASR can always be enough, thus the ASR expansion of low w/c can be higher than the high w/c, since the generated ASR amount are the same, but more gel can be absorbed by capillary pores in high w/c concrete. The sole ASR expansion for all cases of w/c ratio and air content is shown in Fig. 13, where smaller expansion can be found when the higher w/c ratio and the air content.

The initial saturation degree defined not including the isolated air bubbles is set 100% for all the cases when simulating the FTC expansion. In order to eliminate the effect of ion concentration on the drop of the freezing point, pure water is used for the single FTC event. It is well known that the continuous water supply during FTC is a crucial factor for the damage accumulation, because once additional water fills the crack gaps generated in previous cycles, more ice will develop and cause greater expansion in the following cycles. Therefore, two moisture boundary conditions are considered here with (open condition) and without (closed condition) water supply. The FTC deformation for the ideal 0% entrained air is shown in Fig. 14. Here the expansion still means the averaged deformation similar to the measured strain as shown in Fig. 11. The quantitative verification of FTC expansion has been done in Gong et al. (2015b). In this study, the results in Fig. 14 can catch the general FTC behavior well: higher w/c ratio has a greater FTC damage; damage and expansion can be accumulated only when additional water can be supplied. The reason of this accumulated plastic deformation can be explained by referring to Eq. (16), that once more ice forms as w increases, in order to achieve an equilibrium between pore pressure p and the material’s tensile capacity, more crack spacing is needed, and resulting in increased strain. Figure 15 shows the non-uniform deformation and damage development from the surface inward, because the condensed water can come from outside to concrete block and the corner and surface will be more damaged.

Figure 16 shows the effect of air content on the FTC expansion. The ideal referential case (Air=0%) has a
much greater expansion than the real one ($Air=1.5\%$). This phenomenon was also found in Sun and Scherer (2010) by filling all the air bubbles with water by using vacuum saturation. When 4% air is introduced, there is no macro-scale expansion and cracking, but some micro damage may occur due to the suction and unfrozen water in motion, which will be discussed in Section 4.3. The final free expansion after 10 FTCs (days) are shown in Fig. 17, from which the general conclusion can be made, that is to say, lower $w/c$ ratio and higher air content can reduce or prevent the FTC expansion, and much more serious damage will be caused when the additional water would be supplied.

4.2 ASR expansion followed by FTC

After achieving the free expansion under a sole event as discussed in previous section, the mutually coupled event is discussed from this section. First is how the

![Image](image1.png)

Fig. 15 Non-uniform expansion on surface and cross section during FTC ($w/c=0.5$, $Air=0\%$, in water).

![Image](image2.png)

Fig. 16 Effect of air content on the free FTC expansion ($w/c=0.5$) (a) under closed (sealed) condition (b) under open (submerged in water) condition.

![Image](image3.png)

Fig. 17 Final free FTC expansion ($\mu$) (10 cycles) depending on $w/c$ ratio and air content (a) under closed (sealed) condition (b) under open (submerged in water) condition.
ASR will affect FTC expansion, that is, after curing stage, conducting ASR exposure for 152 days at 40 °C and then followed by 10 cycles (5 °C to -20 °C) of freeze-thaw expansion. The deformation histories of 0% entrained air as a reference are shown in Fig. 18, for both closed and open moisture conditions. There are some slight differences in the ASR expansion between closed and open conditions. This is natural and mainly due to the randomness on multi-directional crack opening under rather uniform field of stresses before cracking and the broken symmetry is simply reproduced by using parallel computing process (Gebreyouhannes and Maekawa 2016). After ASR exposure, the FTC expansion has the similar tendency to the sole FTC event, but the amplitude become smaller. In addition, since more ASR expansion but less FTC expansion will be caused for lower w/c ratio concrete, the total expansion after two process may have different tendency depending on which process is more dominant (Fig. 18 (b)). Here, although the large crack opening has been caused after ASR exposure in the open test, this crack space will not increase the water permeation because it is filled by ASR gel (see also Eq. (21)). Thus, the cyclic increasing in expansion in Fig. 18 (b) still depends on how much water can flow into the newly created cracking space.

The net FTC expansion after ASR in Fig. 18 is compared with the sole FTC case as shown in Fig. 19. Although the FTC expansion before and after ASR are not strictly equivalent due to the nonlinear tension-softening in material property, the general tendency can still be found. The effect of ASR intrusion in capillary pores on the FTC expansion can be found from Fig. 19 (a). Concrete with higher w/c ratio can absorb more ASR gel so that the reduction in freezeable pore water is also higher, and greater decrease in the net FTC expansion can be found in Fig. 19 (a). For the FTC under open conditions (Fig. 19 (b)), the main mechanism for the cyclic increasing expansion derives from the additional ice formation computed in crack gaps. If the residual crack opening can be kept smaller at the beginning (like w/c = 0.35 in Fig. 19 (b)), the more reduction can be guaranteed. Then in Fig. 19 (b), w/c = 0.35 has the most significant reduction in the final FTC expansion.

Similar analysis is also conducted for the AE concrete

![Fig. 18 Expansion under combined ASR (first) and FTC (last) for different w/c ratio (Air=0%) (a) under closed condition (b) under open condition.](image-url)
(Air=4%) as shown in Fig. 20. Without ASR, 4% of entrained air can totally avoid expansion for all w/c ratios under both closed and open conditions (Fig. 17 (a)). However, once a part of the effective entrained air is filled with ASR gel, the risk of frost expansion increases, as shown in Fig. 20. Although the same reduction in the freezable water can happen after ASR gel occupies part of the capillary pores, the negative effect from the entrained air is more dominant clearly in the FTC expansion. The experiments by Bérubé et al. (2002) can also verify this modeling result (see Fig. 21). With air content of 6.4% and 2.4%, concrete cannot likely have expansion under FTC. But with the ASR exposure, air bubbles will lose their functions to prevent the FTC expansion. It is difficult to quantify the exact experimental conditions in Bérubé et al. (2002), but the experimental phenomena can still prove the findings of this study. Finally, the net change in the FTC expansion comparing with non-ASR cases is shown in Fig. 22. It can be found that the net expansions are quite similar between Air=0% in Fig. 19 and Air=4% in Fig. 22, which means the air bubbles almost totally lose functions during FTC.

Fig. 19 Reduction of FTC expansion after ASR compared to the single FTC effect alone (Air=0%) (a) under closed condition (b) under open condition.

Fig. 20 Expansion under combined ASR (first) and FTC (last) for different w/c ratio (Air=4%) (a) under closed condition (b) under open condition.
4.3 FTC followed by ASR expansion

The cases that FTC goes first and followed by ASR are simulated in this section. Figure 23 shows the full strain history of Air=0% under closed and open conditions. There are two effects caused by FTC damage which will affect ASR expansion. One is that the damaged concrete will get a lower tensile capacity (if without any confinement) so that the amount of gel which can be intruded into pores will decrease. The other is that the crack space caused by FTC can be filled by ASR gel when the ASR begins. Then, ASR expansion can be postponed. In the closed test (Fig. 23 (a)), the first event is dominant because the residual expansion after FTC is not large enough compared to the total ASR expansion. Since less gel can be consumed by capillary pores, more ASR expansion will take place (Fig. 24 (a)). As w/c ratio gets higher, the FTC damage becomes greater so that the tensile capacity will be more reduced. At the same time, non-damaged concrete with higher w/c ratio has a smaller ASR expansion (Fig. 12 (a)). Finally, the negative effect by FTC is larger when w/c ratio gets higher (Fig. 24 (a)). While in the open test (Fig. 23 (b) and Fig. 24 (b)), the positive effect (more cracking space) is more dominant. Thus, net ASR expansion can be reduced for all cases of w/c ratio.

The slight shrinkage during the initial stage of ASR in Fig. 23 (b) and Fig. 24 (b) is mainly because of the negative water pressure. That is, when the FTC period ends, the residual crack space is not fully filled by water, then it will result in a negative pore pressure which will absorb free water from the surface until the crack space gets saturated. At the same time, the cracked concrete matrix has a much smaller stiffness so this negative pore pressure will also cause a significant shrinkage, and the weaker material is (like w/c=0.65), the bigger shrinkage will happen. Nevertheless, this temporary small shrinkage would not affect the following ASR expansion significantly.

When 4% of air is introduced, there is no obvious FTC expansion even under the open condition (Fig. 25). It does not provide any pre-cracking before ASR starts. However, when looking at the net ASR expansion after FTC, it is still affected slightly. Although there is no heavy expansive damage, some small damage resulting from the uneven temperature distribution during FTC can still occur, which will slightly reduce the material strength near the corner and surface. Therefore, the ASR expansion can be a little enlarged after

![Figure 21 Experimental data of AE and non-AE concrete under combined periodical ASR and FTC (a) AE concrete (b) non-AE concrete (redraw from Bérubé et al. 2002).](image)

![Figure 22 Increasing of FTC expansion after ASR compared to the sole FTC effect alone (Air=4%) (a) under closed condition (b) under open condition.](image)
FTC for all the cases.

4.4 Combined damage effect

In order to achieve the general conclusions about strongly coupled ASR and FTC events, aforementioned cases are summarized together. The final residual expansion denoted by $\varepsilon_{\text{w/c, Air}}$ of each single and coupled cases are used for the evaluation of the general accelerated/ decelerated damage effects. Then for each w/c ratio, air content and the moisture conditions (open/closed), $\varepsilon_{\text{ASR}}$, $\varepsilon_{\text{FTC}}$, $\varepsilon_{\text{ASR} \rightarrow \text{FTC}}$, $\varepsilon_{\text{FTC} \rightarrow \text{ASR}}$ represent the final residual strain of single ASR case (152 days), FTC alone (10 cycles), ASR followed by FTC and FTC followed by ASR, respectively. Then, we define the damage ratio as,

$$R_{\text{ASR} \rightarrow \text{FTC}} = \frac{\varepsilon_{\text{ASR} \rightarrow \text{FTC}}}{\varepsilon_{\text{ASR}} + \varepsilon_{\text{FTC}}}$$

(23)

$$R_{\text{FTC} \rightarrow \text{ASR}} = \frac{\varepsilon_{\text{FTC} \rightarrow \text{ASR}}}{\varepsilon_{\text{ASR}} + \varepsilon_{\text{FTC}}}$$

(24)

where $R_{\text{ASR} \rightarrow \text{FTC}}$ and $R_{\text{FTC} \rightarrow \text{ASR}}$ mean the relative acceleration/deceleration of the damage by two sequences of combination compared to the simple summation of each single impact. Then, $R > 1$ means that the coupled condition will cause more damage than the independent process, and $R < 1$ means that the coupled effect can be beneficial. The damage ratios of all cases are plotted in Fig. 26. The experimental data from Bérubé et al. (2002) is also added for the comparison. Considering the uncertainties in the material and environmental variables, the predicted coupled effects are in a good agreement with the experiments.

From Fig. 26 (a) and Fig. 26 (b), when ASR comes first, the total damage can be similar or slightly reduced for non-AE concrete (Air < 1.5%), but for AE concrete, coupling may weaken the function of air bubbles and result in greater damages. This acceleration effect is higher when both the w/c ratio and air content increases.

![Fig. 23 Expansion under combined FTC (first) and ASR (last) for different w/c ratio (Air=0%)](image-url)
When FTC comes first (Fig. 26 (c) and Fig. 26 (d)), both the expansive FTC damage (non-AE concrete) and damages in micro structures (AE concrete) will reduce the tensile capacity of the material under unconfined condition, so that more ASR gel will contribute to the expansion. However, if more cracking space is generated after FTC (non-AE in open test), ASR gel must first fill the residual cracks by FTC. Then, total expansion will be reduced (Fig. 26 (d)).

The above discussion mainly deals with relative acceleration/deceleration by the combined effect, which may not reflect the real damage level. For example, the effectiveness of entrained air may be reduced under the combined effect, like Fig. 26 (a), (b) and (d). However, the entrained air may still be beneficial for controlling the total expansion. Therefore, the total damage (expansion) is summarized in Fig. 27. Generally speaking, the entrained air is still beneficial for the concrete under sole and coupled ASR and FTC, but the function can be largely reduced. For all the sequences of combinations in Fig. 27, lower w/c ratio with higher air content can result in a smaller total expansion, which still obeys the common understanding of high strength concrete and entrained air.

Finally, the coupled effect on the strength change is also discussed qualitatively. In order to provide the similar damage levels for single and coupled exposures, the case with w/c ratio of 0.5 and 0% air content under open moisture condition is selected as summarized in Table. 3, and the stress-strain curves are shown in Fig. 28. Although the residual strain after single ASR event (4666 μ) is even greater than that after the sole FTC (3409 μ), the ASR damaged concrete still shows a greater stiffness, strength and ductility than those of the FTC damaged concrete. This difference comes from the strengthening effect of ASR gel in the crack system, because the semi-liquid ASR gel can bear compressive forces, enhance the tension-softening and shear capacity of crack gaps. For the coupled damage, when ASR takes place first, the following FTC will cause new cracks

<table>
<thead>
<tr>
<th>Table. 3 The residual strain after exposure and residual compressive strength.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undamaged</td>
</tr>
<tr>
<td>Residual strain (μ)</td>
</tr>
<tr>
<td>Comp. strength (MPa)</td>
</tr>
</tbody>
</table>

Fig. 24 Change of ASR expansion after FTC compared to the sole ASR effect alone (Air=0%) (a) under closed condition (b) under open condition.

Fig. 25 Expansion under combined FTC (first) and ASR (last) for different w/c ratio (Air=4%) under open condition.
which are not filled by ASR gel. Then, the stiffness and strength will be slightly reduced.

On the contrary, when FTC damage occurs first, the following ASR can significantly strengthen the pre-damaged concrete, even though the expansion becomes larger, because all the cracks gaps may be filled by ASR gel. There is also another interesting finding. By comparing the ASR damage with/without pre-FTC damage in Fig. 28, the stiffness and ductility are the same but the strong coupling of these events has a greater compressive strength. In view of the nonlinear stability, so called broken symmetry cannot be avoided when ASR gel induced cracks are first introduced like the case of corrosion around reinforcing bars (Gebreyouhannes and Maekawa 2016). The following FTC brings about ice formation accompanying the further volumetric expansion. In this case, the compressive strength under room temperature is kept lower.

When FTC damage happens first accompanying the broken symmetry and the following ASR gel is generated, viscous gel is computationally injected into crack spaces. This coupling is to stabilize the damaged solid of concrete and broken symmetry of cracking profiles is mechanically treated by coupling the motion of semi-liquid media which is hardly in motion compared to the condensed water.

The frozen ice can have the similar strengthening effect as the ASR gel, when the compression test is conducted below 0 °C. For example, the stiffness and strength at -20 °C after FTC alone are larger than those at room temperature. However, the residual properties are governed by both the strengthening effect of pore substances and the matrix damage, which is a plus/minus effect. Thus, because of the higher non-uniformity of expansion, the ice strengthened concrete has a much lower compressive strength than the ASR strengthened one.

5. Conclusions

Expansive damages caused by combined ASR and FTC are modeled through a poro-mechanical approach, by considering the strongly coupled physical events of the gel intrusion and ice formation in pores, gel movement and unfrozen water suction into entrained air, as well as the gel and water migration through damage cracks. Furthermore, based on the nonlinear mechanics of concrete materials with cracks, deformation and cracking under mutually coupled effects are simulated in accordance with several sequences of combination, under different moisture states (sealed or exposed to water).

The strong coupling model of ASR and FTC has been developed for both macroscopic cracked concrete skeleton and meso-scale physics developing in cracks and capillary pores. The gel intrusion and ice formation in micro pores are formulated together by considering the

Fig. 26 Relative acceleration/deceleration (R) by the coupled effect (a) ASR followed by FTC (closed) (b) ASR followed by FTC (open) (c) FTC followed by ASR (closed) (d) FTC followed by ASR (open)
pore size distribution and so called ink bottle effect, so that the saturation degree of ASR and ice can be estimated theoretically. The poro-mechanical model has been extended from two-phase (pore liquid and solid skeleton) to a multi-phases problem, which can take the both solid pressures (solidified ASR gel and ice) and the liquid pressure and transportation (highly viscous liquid ASR gel and water) into consideration. This model also makes the further studies such as the coupled steel corrosion gel easier.

The FEM simulation results show that ASR may reduce the FTC expansion for non-air-entrained concrete by replacing the freezable water in capillary pores, but for the air-entrained concrete, ASR gel will also fill the air system and disable its function for the frost resistance, which will lead to a much greater FTC damage. On the other hand, the FTC damaged concrete has lower capacity of pore pressure, thus less ASR gel can be absorbed by capillary pores. It is expected to result in a greater ASR expansion. But at the same time, the FTC created crack space may postpone the ASR expansion, logically. Considering the final total damage under different situations, the entrained air is thought to be still beneficial for controlling the total damage, but with less

Fig. 27 Total expansion (μ) by the coupled effect (a) ASR followed by FTC (closed) (b) ASR followed by FTC (open) (c) FTC followed by ASR (closed) (d) FTC followed by ASR (open)

Fig. 28 Residual compressive strength after different exposure conditions
efficiency. This shall be investigated experimentally and verified in future.

Mechanically speaking, ASR and FTC expansion have different effects on the residual compressive strength, because the ASR gel in the crack gaps may strengthen the damaged material by solidification with calcium ion in pore solution. When ASR is activated computationally after FTC damage, viscous ASR gel fills the gaps of damages induced by FTC and the crack assembly is made stable. As a result, it is computationally foreseen that the risk of local failure is reduced, and the apparent reduction of compressive strength of damaged concrete is suppressed. This is also one of the derived predictions by strong coupling.

There are predictions of interest on the combined ASR and FTC events. Some of the findings are already verified with previous experiments, but some are still un-certified. More detailed experimental verification is also needed, which will be quantitatively conducted in future.

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References
ACI Committee, (2008). “Building code requirements for structural concrete (ACI 318-08) and commentary.” American Concrete Institute, and International Organization for Standardization.
reactive aggregate in NaCl solution.” Cement and Concrete Research, 24(4), 621-632.