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1. Introduction

The alkali-silica reaction (ASR) is a significant issue for concrete because it induces cracks and reduces mechanical properties. Structures affected by ASR may have serious issues in terms of serviceability and/or safety. To combat ASR, there have been many test methods developed to evaluate the reactivity of the reactive aggregates. These test methods have been developed to be consistent with the field performance of each country and/or region.

Current performance-based design enables engineers to select among many varieties of concrete to optimize structure performance. For different applications, performance testing of job-mix concrete is currently required to assess the alkali-silica reactivity or swelling potential of a wide variety of concretes (Thomas et al. 2006; Lindgård et al. 2012; Lindgård et al. 2013a; Lindgård et al. 2013b; Lindgård et al. 2016). Some sophisticated models have been developed to predict the expansive behavior of concrete structures using numerical tools (Multon and Sellier 2016; Grimal et al. 2010; Dunant and Scrivener 2010; Alnaggar et al. 2013; Saouma 2014; Kawabata et al. 2017). Recent studies proposed a model to extend predictions to systems with supplementary cementitious materials with consideration of alkali uptake by calcium silicate hydrates (Kawabata and Yamada 2015; Kawabata and Yamada 2017). Performance testing also provides useful data for these numerical models.

An appropriate testing protocol for obtaining reliable results to evaluate the reactivity of aggregate or swelling potential of concrete has been of international interest. The chemical test method was withdrawn from ASTM C290 in 2016. Current common knowledge is that the concrete expansion test is the most reliable laboratory test, while field-exposure tests and field experiences give the most valuable results (Thomas et al. 2006; Ideker et al. 2012a; Lindgård et al. 2010; Hooton et al. 2006). Recent studies place an emphasis on the importance of correlation between laboratory and field measurements (Ideker et al. 2012b; Fournier et al. 2012; Wigum and Einarsson 2016; Rajabipour et al. 2015). Even when the same concrete mix is used, expansion of field-exposed concrete block is frequently much larger than the laboratory test result. The gap between laboratory and field measurements has been discussed internationally.

One of the critical issues for concrete expansion tests is alkali leaching (Rogers and Hooton 1991; Duchesne and Bérubé 2001; Rivard et al. 2003; Rivard et al. 2007; Lindgård et al. 2013a). When concrete is stored over water in a sealed container, a significant amount of alkali is leached from the specimens. Since water condensation forms on the inner wall of container, water drops on partially dried concrete when the container is cooled before measurement. After measurement, the container is heated, generating water condensation on the concrete surface. As a result, alkalis in the concrete specimens diffuse out of the specimens, reducing the alkali content. There is a good correlation between the amount of remaining alkali content and expansion (Lindgård et al. 2013a).
Furthermore, drying of concrete with a low alkali content is a concern. When a concrete has a low alkali content, the equilibrium vapor pressure and resultant equilibrium relative humidity (R. H.) becomes higher due to the lower salt concentration, resulting in drying due to less water absorbing ability (Lindgård et al. 2013a; Yamada et al. 2016). Alkali leaching from the concrete surface may accelerate the drying of concrete.

These factors lead to failures in evaluating the potential expansion of concrete. Concrete expansion tests for detection of potential alkali reactivity of aggregates, such as RILEM AAR-3 and AAR-4 (Nixon and Sims 2016), allow the concrete specimens to have 5.5 kg/m³ of total alkali content; for these tests, abundant alkalis exist within the concrete and the equilibrium R. H. remains low resulting in relatively high water absorbing ability. However, in performance testing, the alkali amount is not boosted, and alkali leaching and drying have critical influences on concrete expansion. These issues should be taken into account, especially for concrete performance testing as well as expansion tests on cores extracted from existing structures. Leaching also induces a size effect depending on the ratio of surface to volume of the specimens (Lindgård et al. 2013a; Kawabata et al. 2016).

Recently, efforts have been carried out to address these issues. Bérubé et al. used several protective methods, such as silane coatings, sleeves, and aluminum foil, to eliminate the influence of alkali leaching for residual expansion tests on concrete cores (Bérubé et al. 2012). The results showed that aluminum foil was the most effective, but the measured test expansion was lower than the control specimen. Although the reason was not discussed, self-desiccation might cause less expansion. Lindgård et al. (2013a, 2016) tried tests with concrete specimens wrapped in wet cloth containing 1.5 mol/l NaOH solution. When the high pH wrapping was applied to concrete with low total alkali content (which would be non-expansive), the concrete showed greater expansion at 38°C. Alternatively, at 60°C, almost no expansion was observed for the same concrete with high pH wrapping (Lindgård et al. 2016). Therefore, Lindgård et al. (2016) concluded that special care must be taken when using this wrapping approach. Naranjo (2012) proposed a new testing method, the concrete cylinder test (CCT). In this test, a concrete cylinder mold is used to insulate the concrete specimen from alkali leaching. The concrete cylinder is shorter than the mold to allow water to pond on top of the concrete; additionally, filter papers are installed along the mold to allow water to access the concrete lateral surface. The CCT was shown to shorten the test duration to assess reactivity (Stacey et al. 2016). Therefore, the CCT is expected to be developed as a performance test.

In this paper, a new performance testing protocol, Alkali-Wrapped Concrete Prism Test (AW-CPT), is proposed which will avoid alkali leaching and drying (Yamada et al. 2016; Kawabata et al. 2016; Yamada et al. 2017). This test has been developed to be applied to evaluation of the expansive potential of job-mix concrete as well as to detection of potential alkali reactivity of aggregates. This test is very similar to the wrapping approach by Lindgård et al. (2013a), but the difference is that the alkali concentration of the wrapping cloth mimics the pore solution. In this paper, the testing protocol of AW-CPT is presented, and the calculation method for determining the alkali concentration of the wrapping cloth is shown. Then, the applicability of the test as a performance test is discussed in terms of alkali threshold and alkali mass balance through the experiments.

2. Alkali-Wrapped concrete prism test (AW-CPT)

In order to avoid alkali leaching and drying, the method of wrapping concrete specimens with wet cloth containing alkali solution was developed; the alkali hydroxide solution concentration of the cloth matches the concrete pore solution concentration. The testing protocols for AW-CPT are summarized below.

2.1 Testing protocols

The test procedure for AW-CPT is described in this section. Although the general protocols are nearly identical to RILEM AAR-3 (38°C) / AAR-4 (60°C), the concrete specimens should be wrapped with wet cloth containing alkaline solution. The wrapping procedure is shown in Fig. 1. After de-molding the concrete specimens (75 × 75 × 250 mm), they are submerged in water for 30 minutes. During this submersion, 3 - 4% of alkalis in the concrete leach out according to Lindgård et al. (2013a) (70 × 70 × 280 mm). Other research has shown that the submersion has little influence on moisture content beyond 1 week of exposure (Lindgård et al. 2013b). However, the submersion process is adopted because cement initially hydrates quickly by absorbing water, but the absorption rate slows with time. Hence, when concrete is wrapped with wet cloth containing alkali hydroxide solution, a considerable amount of alkalis can be supplied by water imbibition of concrete. The alkali is inevitably supplied from the wrapping cloth, and this should be minimized as much as possible.

The concrete specimen is wrapped with a polypropylene non-woven cloth (355 mm × 425 mm, Crecia kimtex pops up white, Nippon Paper Crecia, Co., Ltd.). The wet cloth is recommended to be tolerant of alkaline solution. The wet cloth on a thin plastic film is placed on a table, and then the specimen is wrapped. One piece of cloth is sufficient to cover the entire surface of the specimen. 50 g of alkali hydroxide solution at a concentration matching the pore solution of concrete is added to the cloth. 50 g of solution corresponds to the maximum amount that can be absorbed by the cloth: the amount of solution was adopted from JASS 5N-T603 although that test method calls for only water. When the
wet cloth is picked up, in some cases droplets can fall from the bottom of the cloth. Therefore, to minimize loss of the solution, the cloth should be placed on a plastic film or a plastic bag before use so that all of the droplets can be contained within the cloth and plastic film. The cloth was secured by rubber bands to prevent detachment. Then, the wrapped specimen is covered with plastic film in order to avoid drying. Afterwards, three wrapped specimens are placed in a storage container over water, and the container is placed in a temperature-controlled chamber over water. The plastic film cannot be impermeable to water vapor, and it is necessary to store the wrapped prisms under humid conditions.

For the length change measurement, the storage container is moved to a room kept at 20°C and the specimens are cooled for 1 day. Special care should be taken to prevent the specimens from contacting the water at the bottom of the containers when they are moved to the room. After cooling, the length and weight of the specimen, as well as the weight of the cloth, are measured after slowly removing the cloth from the specimen.

Fig. 1 Wrapping procedure for AW-CPT.
After measuring the weight of the cloth, ion-exchanged water is added to the cloth to maintain the solution mass in the cloth at 50 g. This process is necessary to supply a sufficient amount of moisture for ASR. However, it is necessary to avoid adding an excess supply of alkalis from the wrapping cloth to the concrete specimen; this is the reason ion-exchanged water is used during the test. The same cloth is used throughout the test unless the cloth is heavily damaged.

Baseline measurements were taken after submersion of the specimens. The minimum reading of the comparator is 0.001 mm (1 μm), and the comparator reading is not always stable. The readings can increase or decrease when the specimen is rotated. It is recommended to read the minimum value, and the direction of placement should also be recorded. In order to check the repeatability, it is useful to place the prism in a reverse direction and measure the length. Both readings may have differences of a few μm. The electronic balances to weigh the specimen and wet cloth have the minimum reading of 1 g and 0.1 g, respectively.

### 2.2 Alkali concentration of wrapping cloth

One of the important issues is the method for determining the concentration of the solution for the alkali wrapping. A lower solution concentration will induce alkali leaching. In fact, using a wet cloth with pure water induces alkali leaching, but the degree of alkali leaching is less than an unwrapped sample (Yamada et al. 2014). If a higher alkali concentration is used, the wrap will supply alkali to the concrete, resulting in greater expansion. Lindgård et al. (2016) noted that when testing a low-alkali system, the concrete showed a larger expansion; this was attributed to alkali being supplied from the cloth at 38°C.

Therefore, the method for deciding the hydroxide ion concentration in the wrapping cloth is very important. The best approach may be to have the cloth wrap concentration be in balance with concrete pore solution (the alkali concentration of the solution in the cloth matches the pore solution). Nevertheless, a certain amount of alkali can be transferred by water uptake from the cloth to the sample, with increasing hydration and ASR over time. This alkali uptake from the cloth is inevitable, but the quantity transferred can be estimated by a mass balance between the cloth and the concrete.

One of the methods to decide the pore solution concentration may be to extract pore solution and analyze for the hydroxide ion concentration. However, the experiments strongly depend on procedures that have not been validated and are known to have significantly large variations. For example, the concentration of extracted pore solution was influenced by the pressure applied to the sample, but it had a lesser influence on the alkali concentration below 500 MPa (Lothenbach 2010; Duchesne and Bérubé 1994). In another source, it was claimed that concentrations in pore solution depend on the pressure applied (Chappex and Scrivener 2012).

Therefore, an alternative approach we have developed involves calculation of hydroxide ion concentration. Here, the method to calculate the hydroxide ion concentration is first reviewed, and then the method adopted in this test method is explained. Note that external alkalis are not considered here since the focus was placed on evaluating the potential performance of the concrete. Helmhuth (1993) formulated equation (1) to show the relationship between the alkali content of cement and OH\(^{-}\) concentration in pore solution.

\[
[OH^{-}] = 0.339 \times \frac{Na_{2}O_{eq}}{(W/C)} + 0.02 \pm 0.06, \quad (1)
\]

where \([OH^{-}]\) is the hydroxide ion concentration in the pore solution, \(Na_{2}O_{eq}\) is the equivalent alkali content of the cement, and \(W/C\) is the water to cement ratio.

Thomas et al. (2006) also formulated equation (2) based on the review of pore solution data from Nixon and Page (1987).

\[
[OH^{-}] = 0.7 \times Na_{2}O_{eq} \quad (2)
\]

These equations are formulated based on experimental results obtained from pore solution extraction and analysis of paste and mortar (Barneyback and Diamond 1981). According to a review on pore solution, however, there are large variations in hydroxide ion concentration (Vollpracht et al. 2016). The alkali concentration is strongly influenced by the content of water-soluble alkali as well as the total alkali content of the cement. Therefore, these equations strongly rely on the experimental results.

Recent progress on hydration analysis makes it possible to estimate the hydroxide ion concentration with thermodynamic modeling. Though thermodynamic modeling software, such as GEMS (Lothenbach et al. 2008; Lothenbach 2010; Kulik et al. 2013) and PhreeqC (Parkhurst and Appelo 1999; Hosokawa et al. 2011), has been under development, the calculation of alkali uptake by calcium silicate hydrate (C-S-H) gel remains controversial. Kawabata and Yamada (2015) calculated hydroxide ion concentrations of cement with various supplementary cementitious materials (SCMs), taking the interaction between C-S-H gel and pore solution into consideration. Since alkalis are distributed between the solid and liquid according to their electrostatic interactions, the total alkali content can be calculated by applying the conservation of mass:

\[
C_{alkali} = R_{d} C_{CSH} + R_{l} C_{fw}, \quad (3)
\]

where, \(C_{alkali}\) is the total alkali content per unit volume of cement paste (mmol/m\(^3\)), \(C_{CSH}\) is the C-S-H amount per unit volume of cement paste (g/m\(^3\)), \(C_{fw}\) is the free water per unit volume of cement paste (ml/m\(^3\)), \(R_{d}\) is the alkali content in solid C-S-H (mmol/g), and \(R_{l}\) is the alkali concentration in solution (mmol/ml). The distribution ratio, \(R_{d}\) (ml/g), may be described by:

\[
R_{d} = R_{l} / R_{i} \quad \text{and} \quad (4)
\]

\[
R_{d} = \alpha (Ca/Si)^{b}, \quad (5)
\]
where Ca/Si is the Ca/Si molar ratio of C-S-H gel and \( \alpha \) and \( \beta \) are constants. According to the experiments by Hong and Glasser (1999), the parameters were determined to be 2.5 and \(-3.1\), respectively (Kawabata and Yamada 2015). The alkali uptake by calcium aluminosilicate hydrate (C-A-S-H) gel is not considered in this calculation. The work by Hong and Glasser (2002) showed that C-A-S-H gel has a high capacity for alkalis. Chappex and Scrivener (2012), however, reported that the alkali uptake for C-A-S-H gel is not significant in realistic situations. Bach et al. (2013) also found that low levels of Al/Si substitution in a C-A-S-H gel has no significant effect on alkali uptake because the mechanism of alkali uptake can be explained by charge compensation of the C-A-S-H gel. In addition, L’Hôpital et al. (2016) reported that the presence of aluminum has a minimal impact on alkali uptake. Therefore, in the current model, only alkali uptake by C-S-H gel is considered. However, further investigation is necessary. The combination of hydration analysis and modeling described above leads to the equation for estimating the hydroxide ion concentration. As a result, a simple relationship between the alkali content of the cement and hydroxide ion concentration for a water-to-cement ratio of 0.50 was determined to be (Kawabata and Yamada 2015):

\[
[\text{OH}^-] = 0.89 \times \text{Na}_2\text{O}_{eq} \quad (6)
\]

The hydroxide ion concentration calculated with Eq. (6) is 27% higher than those with Eq. (2). The higher concentration calculated with Eq. (6) is likely reasonable because it was assumed in Eq. (6) that all of the alkalis were water-soluble. In fact, alkalis exist in some minerals, such as C\(_3\)A and C\(_2\)S as well as water-soluble alkali sulfate (Taylor 1997). Except for water-soluble alkali sulfate, the alkalis dissolve with increasing reaction ratios of C\(_3\)A and C\(_2\)S over time.

For cement paste without any supplementary cementitious materials, in this study, the parameters for Eqs. (3) - (5) were determined to be: C-S-H content = 790 kg/m\(^3\), w/c = 0.50, Ca/Si molar ratio of C-S-H = 2.0, and free water content = 0.270 L/m\(^3\): these parameters were adopted from the previous study, except for the Ca/Si molar ratio (Kawabata and Yamada 2015), to be consistent with the experimental data shown below. From these assumptions, the simple relationship can be described as follows:

\[
[\text{OH}^-] = 0.773 \times \text{Na}_2\text{O}_{eq} \quad (7)
\]

The calculated relationship between the alkali content of cement and hydroxide ion concentration is shown in Fig. 2: black solid line (calc.) is the calculated line in this study, with two dotted lines indicating ±0.2 mol/l of the calculation, and the results are compared with the experimental data; two colored solid lines are calculated using Eqs. (2) and (6), and some selected experimental data points are also included (Canham et al. 1987; Duchesne & Bérubé 1994; Shehata et al. 1999; Bérubé et al. 2004; Ramlochan et al. 2010; Chappex and Scrivener 2012). The calculated line (calc.) lies intermediate between those by Eqs. (2) and (6). Vollpracht et al. (2016) collected pore solution data and summarized them with a statistical evaluation. The potassium and sodium contents of the cement used in the study ranged between 0.76 - 1.03 wt% and 0.20 - 0.31 wt%, respectively. The gray zone shown in Fig. 2 notes the range of 95% of all measured concentrations. The calculated line (calc.) from the equations developed in this study passes nearly through the center of this zone. The selected experimental results in the figure are also within ±0.2 mol/l of the calculated result. Therefore, the hydroxide ion concentration with this calculation gives approximately the average value.

Finally, Eq. (8) is proposed in order to apply this calculation to various mixture proportions, especially for considering different water to cement ratios with reference to Eq. (1).

\[
[\text{OH}^-] = 0.386 \times \frac{\text{Na}_2\text{O}_{eq}}{\text{W/C}} \quad (8)
\]

Note that great care should be taken when applying this calculation to concrete with a low water to cement ratio since Eq. (1) was established for water-to-cement ratios over 0.45; lowering the water-to-cement ratio leads to self-desiccation as well as a change in hydration and thus may change the pore solution chemistry. For systems with supplementary cementitious materials (SCMs), see Appendix 1.

It should be noted that this calculation is focused on the hydroxide ion concentration supplied from the cement and NaOH (or sometimes KOH) added for boosting. The calculation was carried out with an assumption that pore solution of concrete is equivalent to that of cement paste. However, in real concrete, some minerals, such as clay,
may bind with a certain amount of alkali, which results in a lower hydroxide ion concentration (Kawabata and Yamada 2017), and alkalis can be released from alkali-bearing minerals over long time frames (Bérubé et al. 2002; Bérubé et al. 2008; Sims et al. 2012). The latter issue remains controversial whether alkali release really increases hydroxide ion concentration (Kawabata et al. 2018). The former issue would especially influence the hydroxide ion concentration in the early stage of testing, which is critical for proportional pessimum effect (Kawabata and Yamada 2017). For example, Duchesne and Bérubé (1994) reported that alkali concentrations were similar for cement pastes and mortars. This was contradicted by the experimental results of Leeman et al. (2011), who showed that the alkali concentration of the paste is higher than that of the mortar. Therefore, the calculated hydroxide ion concentration of the cement paste might be different from that of concrete when such aggregates are used. Alkali uptake by ASR gel is also important to estimate the time-dependency of alkali content in ASR-affected concrete.

Note that Eq. (8) can provide an estimate for pore solution alkali content but is not a perfect solution since it strongly depends on several concrete properties. As explained above, the alkali is inevitably supplied from the wrapping cloth since concrete absorbs moisture from the wrapping cloth. Assuming all the alkalis in the cloth are supplied to the concrete, the total alkali content increases to 1.27 times the initial content. One of the advantages of AW-CPT is that it enables estimation of the amount of alkalis supplied to the concrete; this can be thought of as a safety margin. In the case of conventional CPT, a higher safety margin is necessary because the amount of alkali leaching is unpredictable.

3. Experiments

Accelerated expansion tests were performed, with a focus on alkali mass balance and drying of concrete. The experimental details are described below.

3.1 Materials and mix proportions

Ordinary Portland cement with an alkali content of 0.61 wt% (Na2O: 0.37%, K2O: 0.36%) was used as the reference material. Two reactive coarse aggregates were used for testing. One is a highly-reactive andesite (designated “N”) in which the reactive phases are opal, cristobalite, and volcanic glass. The other is a chert (designated “T”) containing chalcedony and crypto-crystalline quartz as the reactive minerals. N has caused ASR damage in actual construction with a total alkali content ranging from 2.10 - 2.60 kg/m³ (Hayashi et al. 2009). In the affected structures, N was mixed with other coarse aggregate with lower reactivity. Therefore, in this case the mix of aggregates is believed to have caused the pessimum effect. To reproduce the material from a real situation, the reactive aggregate proportion was 30 wt% of N coarse aggregate. For the second material, the reactive aggregate proportion was 100 wt% T coarse aggregate.

| Total alkali content of concrete (kg/m³) | Alkali content of cement (wt%) | Concentration of NaOH solution (mol/l) |
|----------------------------------------|-------------------------------|---------------------------------------|
| 5.50                                   | 1.72                          | 1.33                                  |
| 4.25                                   | 1.33                          | 1.03                                  |
| 3.00                                   | 0.94                          | 0.73                                  |
| 2.50                                   | 0.78                          | 0.60                                  |
| 2.00                                   | 0.63                          | 0.48                                  |

Pure limestone (“LS”) from Kyushu was found to be a non-reactive coarse aggregate. Non-reactive limestone sand was also used.

Water content and water-cement ratio were 160 kg/m³ and 0.50, respectively; this mixture is commonly used in Japan. The total alkali content of concrete was boosted by adding NaOH solution to the mixing water. Hereafter, the concrete mix is expressed as “aggregate type-total alkali content.” For example, a mixture labeled N-3.00 notes the usage of aggregate N and 3.00 kg/m³ of total alkali content.

3.2 Alkali-wrapping

Alkali-wrapping followed the procedure described in Section 2. The concentrations of NaOH solutions for the various total alkali contents of concrete are summarized in Table 1.

3.3 Expansion test

Tests following the AW-CPT procedure described in Section 2.1 were performed. For each test, the sample length change was measured periodically. Expansion tests were performed using 3 specimens for each case, but the number of specimens was decreased with time in some cases as specimens were removed for additional analysis. The temperature for accelerating ASR ranged from 20°C to 60°C.

Control samples of concrete specimens without alkali-wrapping were also tested for comparison (hereafter, the conventional CPT). The basic protocol was performed at 40°C and 60°C in accordance with RILEM AAR-3/AAR-4, where three concrete specimens were stored inside each container. The samples without alkali wrapping were not submerged for 30 minutes in order to eliminate alkali leaching.

3.4 Alkali mass balance

For the tested specimens with the conventional CPT, the amount of alkalis leached from the specimens was measured. During testing, 1 ml of water from the bottom of the storage container was periodically extracted when sample expansions were measured. The OH⁻ concentration of the water samples was measured by neutralization titration using HCl solution, but the concentrations of Na and K were not measured directly. Simul-
taneously, the amount of water at the bottom of the container was measured. Finally, the amount of alkali leaching from a specimen was calculated by multiplying the amount of water and the OH- concentration, assuming that the concentration of alkalis is balanced with OH-.

For the AW-CPT test specimens, at some stages wrapping cloths were removed from specimens and prepared for elemental analysis. One piece of cloth was cut in small pieces (around 10 mm) and put in a plastic bottle. Then, 500 ml of pure water was added to the bottle, and the bottle was sealed. Finally, the bottle was boiled in a hot water bath for 6 hours. The solution was filtered and water was added to produce a 1 liter volume sample. This procedure was repeated five times, and 2 L of extracted solution was prepared for analysis. Around 90% of water soluble alkalis can be recovered by this process. The amount of residual insoluble alkalis was measured by immersing the cloth in 1 mol/l HCl solution. After triple extractions, the cloth was dried at 105ºC overnight and then weighed. At the last step, the remaining cloth was submerged in HF to extract Si from the cloth.

The solutions obtained were analyzed by atomic absorption spectroscopy for Na and K and by ICP-OES for Ca and Si. The OH- concentration of the solution extracted by hot water was measured by neutralization titration using HCl.

### 3.5 Field exposure test

A concrete block (400 × 400 × 600 mm³) was cast using the reactive aggregate N (described in Section 3.1). The reactive aggregate proportion was 30 wt%, which is the same reactive aggregate proportion as laboratory tests. The unit cement content was 300, 400, and 500 kg/m³, respectively. The total alkali content was boosted to various amounts as shown in Table 2.

The concrete blocks were exposed at the Ito Campus of Kyushu University in Fukuoka, Japan. Exposure tests were started on the 29th of March 2011. The meteorological history of the area, which was recorded by the Japan Meteorological Agency (2017), is presented in Fig. 3. Mean annual temperature and mean annual precipitation was 17 - 18°C and 1700 - 1900 mm, respectively.

Expansion was measured on the surfaces of the concrete blocks. The central 300 mm for vertical and 200 mm for horizontal expansions of 4 lateral sides (400 × 600 mm) were measured. Then the mean expansion was calculated.

### 4. Results

#### 4.1 Expansion and mass change of concrete tested by the conventional CPT

Expansion curves of the concretes using N aggregate (Type N concretes) without alkali-wrapping (conventional CPT) tested at 40 and 60°C are shown in Fig. 4. The higher total alkali content and the higher temperature led to greater expansion of concrete. At 60°C, the concretes having higher alkali contents showed rapid ASR expansion, and they reached a plateau after approximately 100 days. For the concrete with 2.48 kg/m³ of total alkali content, the sample showed slightly continuous expansion; however, the expansion at 105 days (15 weeks) and 182 days (26 weeks) was 0.026% and 0.034%, respectively. The concrete with 2.28 kg/m³ of total alkali content kept expansion below 0.02% during the test period. At 40°C, the expansions at 182 days were lower than those at 60°C for every alkali content. The concrete having 2.48 kg/m³ of total alkali content kept expansion below 0.02% during the test period. At 40°C, the expansions at 182 days were lower than those at 60°C for every alkali content. The concrete having 2.48 kg/m³ of total alkali content showed no expansion during the test period. Overall, results showed that expansion tended to reach a plateau at 182 days, which does not agree with actual ASR expansive behavior observed in the field (section 4.4).

Figure 5 compares the change in mass of Type N concretes using conventional CPT at 40 and 60°C. It is clear that the concrete with low total alkali content showed mass loss, suggesting possible drying of the concrete specimens. Significant mass loss was observed at an early stage of concrete testing with total alkali content less than 2.48 kg/m³, even though concrete speci-

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**Table 2 Field exposure test case.**

| Case | Water-to-cement ratio (%) | Cement content (kg/m³) | Reactive aggregate proportion (wt.%) | Total alkali content (kg/m³) |
|------|--------------------------|------------------------|------------------------------------|----------------------------|
| 1.95  | 0.53                     | 300                    |                                    | 1.95                      |
| 2.60  | 0.40                     | 400                    | 30                                 | 2.60                      |
| 3.25  | 0.32                     | 500                    |                                    | 3.25                      |

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**Fig. 3 Environmental conditions in Fukuoka."
mens were stored in a humid container. Assuming that all of the mass loss is attributed to moisture loss, 0.2% of mass decrease corresponds to a 6.5 g moisture loss.

The reason for mass loss may be related to equilibrium R. H., as R. H. becomes lower when NaOH solution concentration increases (Madge 1961). The equilibrium R. H. of 1.25 mol/l of NaOH solution is 96.13%, but it is reduced to 91.43% for 2.50 mol/l. The NaOH concentration of pore solution in concrete with 5.50 kg/m³ is approximately 1.33 mol/l, so the equilibrium R. H. is maintained at almost 96% at 40°C. Therefore, the highly-concentrated pore solution absorbs vapor moisture in the container, leading to positive mass gain.

When the total alkali content is reduced to 2.50 kg/m³, however, the concentration is reduced to 0.60 mol/l; this increases the equilibrium R. H. to above 98%. Increasing alkali leaching from concrete specimens also reduces the alkali concentration of concrete, especially at the surface of the specimens. This results in an increase in equilibrium R. H. at the concrete surface. Consequently, concrete specimens with low total alkali content tend to dry slightly, and thus ASR expansion is inhibited. This can be seen in the relationship between expansion and mass gain of Type N concretes (Fig. 6). The cases showing mass loss exhibit small expansions (less than 0.04%). Therefore, they may have a potential

![Fig. 4 Time vs. expansion curves at various alkali concentrations and temperatures. The values in the figures correspond to the total alkali content of concrete in kg/m³. (conventional CPT, Type N)](image)

![Fig. 5 Time vs. mass gain curves at various alkali concentrations and temperatures. The values in the figures correspond to the total alkali content of concrete in kg/m³. (conventional CPT, Type N)](image)

![Fig. 6 Expansion vs. mass gain data at various alkali concentrations and temperatures. The values in the figures correspond to the total alkali content of concrete in kg/m³. (conventional CPT, Type N)](image)
for expansion early in the testing, but when offset by drying and alkali leaching, expansion plateaued at a low level. This indicates that even when an aggregate is judged as non-reactive by the conventional CPT, there is a possibility of expansion in high moisture conditions.

For Type T concrete, similar trends to Type N concrete were observed. The concrete with 3.63 kg/m$^3$ of total alkali content showed almost zero expansion and 0.1% of mass loss. The trends were distinct in the concrete with 3.10 kg/m$^3$; 0.25% of mass loss and small traction were observed. Drying was found to be significant for Type T concrete, which is less reactive than Type N.

### 4.2 Expansion and mass change of concrete tested by AW-CPT

Expansion curves of the Type N concrete tested at 20°C, 40°C, and 60°C are shown in Fig. 7. At 60°C, higher total alkali content leads to greater concrete expansion. Due to the high reactivity of the aggregate, the concrete started expanding with a very short latency time after the test began. The concrete specimens with a total alkali content of 5.50 kg/m$^3$ reached over 0.10% expansion at 35 days. Even concrete having only 2.50 kg/m$^3$ reached an expansion of greater than 0.04% at 35 days. After 35 days, the rate of expansion tended to decrease.

It is apparent that concrete specimens tested by AW-CPT showed continuous expansion due to ASR. According to the test results, even concrete with a low total alkali content of 2.00 kg/m$^3$ also has an expansive potential.

It should be noted that although expansion of concrete specimens with a higher total alkali content was higher at the beginning of the tests, overall expansion behavior during the test period was complicated. At 637 days and 40°C, expansion of concrete with 4.25 kg/m$^3$ was the lowest, while that of 3.00 kg/m$^3$ was the highest. At 20°C, the expansion in the 2.50 kg/m$^3$ case was highest after 300 days. It has generally been assumed that there is more expansion when the total alkali content is higher. The expansion behavior of concretes obtained from AW-CPTs was quite different from the results of conventional CPTs.

The change in mass of Type N concretes tested by AW-CPT is summarized in Fig. 8. It is significant that concrete with a higher total alkali content and at high temperature has a low increase in mass. At 60°C, the mass gain of concrete with 5.50 kg/m$^3$ remained almost constant up to 300 days, indicating no water uptake by the ASR gel although the concrete showed significant expansion. The concrete tested by AW-CPT showed positive mass gains and no mass loss was observed. Especially in the case of lower total alkali content samples at 20°C, mass gain but no expansion at early age (before 50 - 100 days) was confirmed. This mass gain is expected to be caused by cement hydration. Therefore,
AW-CPT would avoid drying concretes with a lower total alkali content during the test period.

The relationship between expansion and mass gain is summarized in Fig. 9. There are various correlations that depend on the temperature and the total alkali content. A positive correlation exists between water uptake and ASR expansion for the cases with lower total alkali content and lower temperature. For the fastest ASR expansion cases (higher temperature and higher total alkali content), on the contrary, from the beginning the water uptake changed very little with ASR expansion (e.g., 4.25 - 5.50 kg/m³ at 60°C), which may be attributed to loss of ASR gel inside the concrete specimens. This point will be discussed in the next section.

Similar trends of expansion and mass gain were observed for concretes using T aggregate (Type T concretes), as shown in Figs. 10 and 11. The potential for expansion of Type T concrete is less than that of Type N. The rate of expansion was higher when temperature and the total alkali content were higher. However, expansion of concrete with 5.50 kg/m³ at 40°C was larger than that at 60°C. Interestingly, at 40°C there was no considerable difference in expansion behavior among the various total alkali contents of the measured concretes. At 20°C, no expansion was observed over one year, but after that a relatively slow (in comparison to higher temperature tests) but significant expansion began. At 60°C, similar to the case of Type N concrete, the lower the total alkali content, the higher the mass gain. The mass gain of concrete of 5.50 kg/m³ at 60°C remained almost constant after 28 days, although expansion slowly increased. The relationship between expansion and mass gain is shown

Fig. 9 Expansion vs. mass gain at various alkali concentrations and temperatures. The values in the figures correspond to the total alkali content of concrete in kg/m³. (AW-CPT, Type N)

Fig. 10 Time vs. expansion at various alkali concentrations and temperatures. The values in the figures correspond to the total alkali content of concrete in kg/m³. (AW-CPT, Type T)

Fig. 11 Time vs. mass gain at various alkali concentrations and temperatures. The values in the figures correspond to the total alkali content of concrete in kg/m³. (AW-CPT, Type T)
in Fig. 12. Similar to Type N concrete, the data of concrete subjected to severely-accelerated conditions are shown in the lower right of Fig. 12, indicative of loss of ASR gel from the prisms. Decreasing the acceleration temperature led to positive slopes between expansion and mass gain even for concretes with high total alkali content.

4.3 Alkali mass balance

(1) Alkali leaching (conventional CPT)

Measurements of alkali leaching from specimens with 5.50 kg/m³ at different temperatures over time are illustrated in Fig. 13. The OH⁻ concentration is inevitably influenced by carbonation, so the amount of alkalis leached might be slightly higher than measured. As shown in Fig. 13, the amount of alkali leaching increased over time. It can also be seen that a higher temperature leads to more alkali leaching. This trend is consistent with the results of previous research (Fournier et al. 2004; Ideker et al. 2010). The amount of alkali leaching at 60°C was approximately three times higher than that at 40°C. Figure 14 shows the initial total alkali content and the amount of alkali leaching. For Type N concretes at 60°C, there is a positive correlation. At 40°C, the amount of alkali leaching was almost zero for concrete with less than 3.10 kg/m³, but leaching increased with an increase of the initial total alkali content. For Type T concretes, no clear relationship was found, but the amount of alkali leaching was more than 10% of the initial total alkali content.

(2) Alkali supplying (AW-CPT)

The alkali contents in the wrapping cloths around various concrete specimens were measured after 45 weeks of AW-CPT. The results are summarized in Table 3 and Fig. 15. The table also shows the total alkali content of concrete after 45 weeks of AW-CPT. The total alkali content of the specimens after 45 weeks was calculated using the simple assumption that all alkalis lost from the cloth have transferred to the concrete. The increased alkali content is defined as the ratio of transferred alkali content to the initial value. It also should be noted that a small but negligible amount of alkalis were detected (<0.4%) in the container water, possibly due to seepage of the solution through the plastic film. According to material balance calculations, the maximum amount of alkali supplied to the sample is 27% (see Section 2.2). Over 95% of the Na in the wrapping cloth was recovered by hot water extraction, while recovery of K by hot water extraction was less at 60°C. The overall trend showed that K content was higher when Na content was higher. Except for concrete with 5.50 kg/m³ at 40°C, all cases showed the total alkali content increase after 45 weeks of testing. The increased alkali content was clearly higher when the initial total alkali content was lower. The maximum alkali increase was 21.0% for Type T.
concrete with 3.00 kg/m³ alkali at 60°C. For the same mixture and temperature, the alkali increases for Type T are higher than that of Type N. There is no clear relationship between temperature and the increased alkali content. During the test, due to consumption of alkalis by the reaction, the alkalinity of the pore solution is reduced. Therefore, there is a difference in alkali concentration between concrete and wrapping cloth, resulting in a driving force for alkali diffusion. Another key point is that the hydration of cement reduces the concrete water content and thus the concrete specimen tends to absorb water from the wrapping cloth. It is also interesting that the K content in the wrapping cloth was higher when Na content was higher, except for Type N concrete at 60°C where a peak was observed at 3.0 kg/m³ of alkali content.

Additional analysis shows that a considerable amount of Ca and Si were detected in the wrapping cloth (see Table 4). The Ca and Si contents were higher at higher temperatures. Fig. 15 shows the comparison of total alkali content initially and after 45 weeks.

Table 3 Alkali content in wrapping cloth and the total alkali content of concrete after 45 weeks of AW-CPT. (Type N, 3.00 kg/m³ alkali)

| Aggregate | Temp. (°C) | Initial (kg/m³) | Na  | K  | Na  | K  | Na  | K  | Increased alkali content (%) |
|-----------|------------|-----------------|-----|----|-----|----|-----|----|-----------------------------|
| N         | 60         | 5.50            | 801.1 | 34.5 | 172.9 | 44.0 | 974.0 | 78.5 | 5.99 | 8.9 |
|           | 4.25       | 620.9           | 26.4 | 64.7 | 116.5 | 142.9 | 685.6 | 115 | 4.64 | 9.3 |
|           | 3.00       | 321.8           | 26.4 | 14.6 | 48.7 | 175.1 | 336.4 | 110 | 3.38 | 12.6 |
|           | 2.50       | 212.9           | 28.8 | 6.4 | 62.0 | 90.8 | 219.3 | 112 | 2.90 | 16.2 |
|           | 2.00       | 98.5            | 23.1 | 2.5 | 18.1 | 41.2 | 101.0 | 110 | 2.41 | 20.7 |
| T         | 60         | 5.50            | 1546.4 | 114.7 | 61.4 | 30.1 | 1607.8 | 144.8 | 5.34 | -2.8 |
|           | 4.25       | 1068.7          | 106.4 | 24.4 | 17.6 | 1093.1 | 124.0 | 4.26 | 0.3 |
|           | 3.00       | 545.5           | 105.2 | - | - | 545.5 | 105.2 | 3.22 | 7.2 |
| N         | 40         | 5.50            | 1281.0 | 138.6 | 13.3 | 6.8 | 1294.3 | 145.4 | 5.64 | 2.6 |
|           | 4.25       | 784.0           | 105.4 | 11.4 | 5.2 | 795.4 | 110.6 | 4.56 | 7.2 |
|           | 3.00       | 389.8           | 82.6 | 7.3 | 3.9 | 397.1 | 86.5 | 3.37 | 12.3 |
|           | 2.50       | 270.8           | 63.8 | 6.3 | 3.7 | 277.1 | 67.5 | 2.86 | 14.5 |
| T         | 40         | 5.50            | 1061.5 | 77.5 | 65.0 | 39.3 | 1126.5 | 116.8 | 5.82 | 5.8 |
|           | 4.75       | 535.3           | 55.0 | 9.0 | 20.9 | 562.5 | 75.9 | 5.43 | 14.4 |
|           | 4.00       | 426.5           | 65.7 | 7.9 | 5.9 | 434.4 | 71.6 | 4.61 | 15.2 |
| N         | 60         | 5.50            | 1546.4 | 114.7 | 61.4 | 30.1 | 1607.8 | 144.8 | 5.34 | 9.9 |
|           | 4.25       | 1068.7          | 106.4 | 24.4 | 17.6 | 1093.1 | 124.0 | 4.26 | 17.7 |
|           | 3.00       | 545.5           | 105.2 | - | - | 545.5 | 105.2 | 3.22 | 20.2 |
| T         | 20         | 5.50            | 637.0 | 87.9 | 3.8 | 0.6 | 640.8 | 88.5 | 6.3 | 14.6 |

Table 4 Chemical compositions of solutions extracted from wrapping cloth after 45 weeks of AW-CPT. (Type N, 3.00 kg/m³ alkali)

| Temp. (°C) | Extraction | Chemical composition (mmol) |
|------------|------------|-----------------------------|
|            | Na         | K  | Si   | Ca   | OH  | Na+K |
| 60°C       | hot water  | 13.99 | 0.68 | 7.36 | 0.14 | 14.57 | 14.67 |
|            | HCl        | 0.63 | 3.81 | 2    | 11.04 | - |
|            | HF         | -   | -   | 27.55 | - |
|            | Total      | 14.62 | 4.49 | 36.91 | 120.5 | 25.18 |
| 40°C       | hot water  | 23.72 | 2.7 | 14.93 | 1.3 | 22.77 | 26.42 |
|            | HCl        | -   | -   | 0.46 | 11.04 | - |
|            | HF         | -   | -   | 9.54 | - |
|            | Total      | 23.72 | 2.7 | 24.93 | 12.34 | - |
| 20°C       | hot water  | 16.95 | 2.12 | 7.63 | 0.08 | 19.13 | 19.07 |
|            | HCl        | 0.32 | 0.1 | 6.62 | 9.48 | - |
|            | HF         | -   | -   | 0.44 | - |
|            | Total      | 17.27 | 2.22 | 14.69 | 9.56 | - |
temperature. Most Ca was recovered by HCl extraction (> 89%). At 60°C, the recovery of Si by hot water extraction was below 20%, despite the extraction recovering over 50% in the cases of lower temperature tests. Also, X-ray diffraction (XRD) analysis showed a peak of calcite; these results suggest that different phases existed in the wrapping cloth at different temperatures. The measured hydroxide ion was consistent with total alkalis. Judging from the data obtained, expected mineral phases include portlandite, calcite after carbonation of portlandite, alkali silica gel with a wide chemical composition and its crystalized phase, and decomposed silica.

4.4 Field exposure test

The expansion behaviors of field-exposed concrete blocks are shown in Fig. 16. Concrete with 3.25 kg/m³ alkali showed slow expansion up to approximately 0.04% for the first year, and then the rate of expansion increased drastically. After reaching 0.10% expansion, the horizontal expansion was larger than the vertical expansion. In contrast, for the case of 2.60 kg/m³ alkali vertical expansion was larger. The concrete block with 1.95 kg/m³ alkali showed no expansion until 4.5 years. There was no observed trend of increased expansion during the summer season, although the expansion of concrete with 3.25 kg/m³ alkali progresses from the first until the second summer season.

According to the relationship between initial total alkali content and expansion after 4.5 years of exposure, illustrated in Fig. 17, a quasi-linear relationship was found. By calculating the total alkali content when reaching 0.04% expansion, the threshold total alkali content was estimated. The threshold total alkali content was calculated as 2.05 kg/m³ for the vertical direction and 2.15 kg/m³ for the horizontal direction, respectively.

5 Discussions

5.1 Alkali threshold

Currently, controversy exists on the method to evaluate the reactivity or the potential for expansion to avoid a risk of ASR expansion of job-mix concrete. Many test methods exist to judge the reactivity of aggregates throughout the world. In the case of ASTM C 1293 (38°C), 0.04% at 52 weeks (or 104 weeks for SCMs) is set as the acceptance limit. According to Nixon and Sims (2016), the acceptance limit of AAR-4.1 for a non-reactive aggregate combination is 0.03% at 15 weeks. The relationship between initial total alkali content and expansion of Type N concrete after 15 weeks of testing is illustrated in Fig. 18. Note that for the concrete having 5.50 kg/m³ tested by AW-CPT, the expansion at 13 weeks was used since the measurement at 15 weeks was not carried out; this was expected to be a reasonable substitution because the expansion had almost reached a plateau by this time. The threshold alkali content to reach 0.03% expansion was calculated to be 1.87 kg/m³ for AW-CPT and 2.54 kg/m³ for the conventional CPT. The results of the field-exposure test showed approximately 2.05 - 2.15 kg/m³ as the threshold for ASR expansion. By comparing these values, the threshold alkali content found using AW-CPT is underestimated (89%), while it is overestimated by conventional CPT (121%); this suggests that AW-CPT gives a more conservative estimation of the threshold alkali content.

It should be noted that for the test results using AW-
CPT for Type N concrete at 20 and 40°C, the threshold content could not be calculated because of their complex expansion behaviors. However, all cases tested by AW-CPT at 20 and 40°C showed expansion since the initial alkali contents were above the threshold value. For test results with the conventional CPT at 40°C, although the test duration was 26 weeks, the expansion was completely suppressed below 3.10 kg/m³ alkali which led to overestimation of the threshold. Figure 14 shows negligible alkali leaching for concrete having less than 3.10 kg/m³, but mass gain was also limited in comparison to AW-CPT (see Figs. 5 and 9). This tendency is distinctive for Type N concrete having less than 2.48 kg/m³ total alkali content after 45 weeks. Therefore, it was reasonable to consider that expansion was suppressed in the cases of concrete with lower total alkali content because less moisture was available.

5.2 Alkali mass balance

The test results clearly showed that approximately 20% of alkali was transferred from the wrapping cloth into the concrete when using AW-CPT, while significant alkali leaching was observed with the use of conventional CPT. The mechanism of alkali transfer from the wrapping cloth was considered. Due to cement being hydrated, water uptake by the concrete specimen occurred. This water uptake was accompanied by alkalis from the wrapping cloth. After the test started, water was added to the wrapping cloth and thus the alkali concentration in the wrapping cloth decreased. Alkalis were supplied to the concrete specimen by this mechanism during this measurement cycle. Assuming that ions in the concrete specimen did not move to the wrapping cloth, the change in alkali concentration in the wrapping cloth can be calculated from the initial concentration of alkali hydroxide in the cloth and the amount of water added to the wrapping cloth during the test. Although this assumption is quite different from reality (Tables 3 and 4), it is a first-step approach to consider the effect of water uptake on the migration of alkali. The calculated results are shown in Fig. 19, with a comparison to measured total alkali content after 45 weeks. The calculated results were within a 10% range of the measurements. Therefore, almost 10% of transferred alkali may be attributed to the water uptake by concrete. This water uptake with alkali transference occurred from an early stage of testing.

However, a detailed chemical analysis indicated complex behavior of ions. The amount of alkali metal ions (Na⁺ and K⁺) extracted by hot water was consistent with OH⁻. Most of the alkali metal ion existed as water-soluble alkali hydroxide in the wrapping cloth. However, a considerable amount of additional K was detected in the samples produced by HCl extraction, suggesting the existence of different precipitated phases in the wrapping cloth. In fact, Si and Ca were detected by HCl and HF extractions. Using the results of the chemical analysis and XRD, water-soluble alkali silicate (ASR gel), calcite, C-S-H gel, portlandite (CH), and crystallized ASR gel can be estimated. Total Si content in the wrapping cloth indicates a greater amount of ASR gel was formed in concrete and then extruded to the cloth. At 60°C, amorphous silica was estimated to exist since Ca was extracted by HCl. On the other hand, at 20°C almost all of the Si was recovered by hot water and HCl, suggestive of ASR gel, CH, and C-S-H gel. The result at 40°C showed the co-existence of amorphous silica, ASR gel, CH, and C-S-H gel.

The important point is that ASR gel could be extruded to the wrapping cloth without Ca exchange. It is commonly known that the ion exchange of ASR gel with Ca occurs, forming precipitated C-S-H gel in the concrete. After this reaction, ASR gel is solidified as C-S-H gel and fills voids and cracks in the concrete. This reaction is fast relative to the formation of ASR gel. In accelerated conditions, however, this reaction is likely to be slowed. Previous studies showed that the higher temperature reduces the viscosity of sodium silicate (Vail 1952). When a large amount of fluid ASR gel is formed at high temperature, fluid ASR gel flows out from the specimen through voids and cracks with less Ca-exchange (Vayghan et al. 2016). Additionally, Ca was also leached out of the concrete specimen. Therefore, a part of extruded ASR gel may react with Ca leached from the specimen to form C-S-H gel in the wrapping cloth. Then, decomposition of C-S-H gel due to carbonation could lead to formation of calcite and amorphous silica. The detailed analysis of wrapping cloths (Table 4) indicated that specimens tested at higher temperatures were likely to be subjected to more severe carbonation, leading to formation of a larger amount of HF-soluble Si. At 20°C, most of the Si was water/acid-soluble, suggestive of formation of ASR gel and C-S-H gel.

After 45 weeks, the wrapping cloths were oven-dried at 105°C, and the mass gain of the cloth was measured. Assuming that the total mass gain was attributed to Si and alkalis, then silica content in the cloth was estimated by subtracting the weight of alkalis from the mass gain of the cloth. The relationship between estimated silica content in the cloth and expansion at 45 -
47 weeks is shown in Fig. 20. The data points are scattered, and no clear trend is observed; this suggests that a portion of ASR gel is not responsible for expansion.

For conventional CPT, higher temperature and a greater total alkali content leads to more alkali leaching. The amount of alkali leaching was consistent with previous study (Lindgård et al. 2013a). It was also clear that the different aggregates give different amounts of alkali leaching. No clear relationship was found for alkali leaching. It was difficult to control alkali leaching since the process was strongly influenced by uncertain parameters such as water droplets from the top of the container, the micro-climate inside the container, the saturated vapor pressure of pore solution, the moisture content of the concrete itself, and the amount of ASR gel. The amount of alkali leaching is thus unpredictable so that it is necessary to consider a safety margin. For AW-CPT, on the other hand, the amount of alkali supplied is controllable, as shown in Fig. 20. Considering that AW-CPT gave an 11% lower initial total alkali content threshold in comparison to the field-exposure test, it is quite reasonable to consider AW-CPT as a more promising performance test method than conventional CPT.

5.3 Temperature and alkali effects on ASR expansion

The results showed that the expansion behavior of concrete tested by AW-CPT was complex. It has been commonly known that total alkali content in concrete accelerates ASR expansion. ASR expansion has a pesimum temperature of approximately 40°C (Lindgård et al. 2012), but the mechanisms remain controversial. Solubility of silica is increased exponentially with increasing temperature (Iler 1979). However, at higher temperature the sulfate ion concentration in pore solution is increased due to higher solubility of ettringite (Lindgård et al. 2012; Fournier et al. 2004). Consequently, hydroxide ion concentration is decreased, resulting in a lower reaction of reactive minerals. This is especially true at temperature above 60°C, where the hydroxide ion concentration drops drastically. Higher temperature also influences the moisture state in pore solution as well as alkali leaching and/or supplying.

It is very interesting that, when tested by AW-CPT, after expansion begins the rate of expansion is higher at higher temperature. This tendency cannot be explained by reduced alkalinity. The initial rate of expansion depends strongly on temperature. However, the rate of expansion later in testing was negligible at higher temperature. The rate of expansion later in testing was pronounced in the case of lower temperature (20 and 40°C). Table 4 shows that the higher temperature accelerates extrusion of ASR gel from concrete specimens. This means that a portion of ASR gel may not contribute to ASR expansion; this point is strongly related to the mechanism of ASR expansion. There may be an optimum condition of temperature and the level of alkali boosting for each reactive aggregate. For N aggregate, which is highly reactive, excessive alkali boosting at 60°C is too severe as ASR gel extrudes out of the system without significant expansion. This behavior leads to very complex expansion behavior depending on the combined effects of temperature, alkali content, and time. Therefore, temperatures below 40°C were better for ASR gel to exert expansive pressure in the case of N aggregate. From this point of view, the criticism by Lindgård et al. (2016), in which low alkali concrete with high pH wrapping did not show expansion at 60°C while showing greater expansion at 38°C, may be explained. Discussions on the temperature effect will be in a future paper.

5.4 Correlation between laboratory and field

To establish a good performance test, the correlation between laboratory and field measurements is important to understand: this will lead to better prediction of ASR expansion in the field with considering service life of the structure. The alkali threshold obtained by AW-CPT at 60°C was consistent with the field data. However, as described above, it was difficult to calculate the threshold content from the results at 20 and 40°C. The expansion behaviors of selected concrete under different con-
conditions are re-plotted in Fig. 21. For field-exposed blocks, horizontal expansions were plotted. The onset of expansion of “2.50-20” sample was almost the same as “3.25-field” sample in spite of different total alkali contents. The reasons may be attributed to three factors. First is alkali supply. According to the simplified calculation (Fig. 19), the total alkali content was increased by 10% within 5 weeks for the concretes with 2.50 kg/m² due to high moisture uptake. Therefore, the total alkali content reached almost 3.00 kg/m² initially and gradually increased over the remaining test period. Second is the effect of temperature. The field concrete block is subjected to temperature variation. Especially for the concrete blocks that were exposed in March, which were subjected to a mean temperature of approximately 10°C. Therefore, the onset of expansion of field concrete blocks was retarded. The last is moisture supply. The mean R.H. of the field is around 70% and rainfall is also limited. Therefore, the concrete was subjected to drying while abundant moisture was available for AW-CPT. The effect of rainfall has an especially large impact on the moisture state of the block (Kawabata et al. 2016). Therefore, it is necessary to consider these factors when correlating laboratory and field measurements. Detailed climate data for the exposure site is indispensable for such analysis.

It should be noted that expansion of similar concretes (3.10 kg/m² alkali) tested by the conventional CPT method reached a plateau at 0.08% even at 60°C, which is unsatisfactory for assessing the swelling potential of the concrete. AW-CPT showed superior results to quantify these effects. In order to minimize the transfer of alkali from the wrapping cloth, the calculation method for alkali concentration is important. Alkali wrapping will be one of the key solutions toward performance testing, although further validation will be necessary.

6. Conclusions

A new testing protocol, Alkali-Wrapped Concrete Prism Test (AW-CPT), is proposed to avoid or minimize alkali leaching and drying. In this protocol, the concrete specimen is wrapped with wet cloth containing alkaline solution mimicking pore solution. A calculation method to estimate the concentration of alkaline solution in concrete was also shown. The tested results were validated in terms of threshold alkali content, alkali mass balance, and drying (mass gain/loss). The conclusions can be summarized as follows:

1) By using AW-CPT, alkali leaching and drying were significantly reduced while the concrete tested by conventional CPT had greater amounts of alkali leaching and drying. However, in AW-CPT, the total alkali content was increased by 1.2 times due to alkali transference from the wrapping cloth. Half of the alkali transfer was attributed to water uptake derived from hydration of cement.

2) The threshold total alkali content determined by AW-CPT at 60°C was slightly lower than one determined by a field-exposure test. This might be attributed to increased alkali content due to alkali supplied from the wrapping cloth. In contrast, conventional CPT overestimated the threshold content since alkali leaching and drying affected the expansion behavior.

3) A considerable amount of ASR gel was extruded to the wrapping cloth without Ca exchange. The amount of ASR gel extrusion was well defined and seemed to be carbonated at higher temperature. At lower temperature, the amount of water/acid-soluble Si, suggestive of ASR gel and C-S-H gel, increased.

4) The combined effect of temperature and alkali content gave different concrete expansion behaviors. However, the initial rate of expansion was pronounced at higher temperature while becoming negligible later in the experiment. This tendency could not be explained by reduced alkalinity at high temperature alone. The evidence of ASR gel extrusion might be one of the reasons for the complex behavior. It was also indicated that there may be an optimum condition of temperature and level of alkali boosting for each reactive aggregate.

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Appendix

Estimation of alkali concentration of pore solution in concrete with SCMs

It should be noted that no perfect indicator has been proposed to estimate alkali concentrations of pore solutions, especially for systems with SCMs. It is well known that the main role of SCMs to inhibit ASR expansion is to reduce the alkalinity of the pore solution (Kawabata and Yamada 2015). This appendix presents an example for estimating the alkalinity of pore solution for a system with SCMs.

Given the Ca/Si molar ratio, the content of C-S-H gel, free water content, and the total alkali content, the degree of reduction in alkalinity can be calculated using Eqs. (3) - (5). When SCMs replace a part of the cement, aluminum may have an impact on alkali uptake. As explained in the main text, however, the presence of aluminium has a minimal impact on alkali uptake. According to the previous study, the Ca/(Si+Al) molar ratio may be a predictor for alkali uptake of C-A-S-H gel (Yamada et al. 2018). The authors (2015) proposed that the total available alkali content of concrete can be estimated by: (1) calculating the degree of reduction in alkalinity due to alkali uptake by C-S-H gel and (2) diluting the alkali by replacing cement with SCMs. The
available total alkali content can be calculated with the following equation.

\[ T_{\text{SCM}} = T_{\text{OPC}} \times \frac{(100-RL)/100}{} \times \frac{(100-RL \times R_{\text{OH}})/100}{} \]  

(A1)

where \( T_{\text{SCM}} \) is the total alkali content of SCM-replaced concrete (kg/m³), \( T_{\text{OPC}} \) is the total alkali content of the control concrete specimen (kg/m³), \( R_{\text{OH}} \) is the ratio of alkalinity reduction per unit replacement level of SCMs (wt%), and \( RL \) is the replacement level of SCMs (wt%).

The most important parameter in this equation is \( R_{\text{OH}} \), which represents alkali uptake by C-S-H gel. \( R_{\text{OH}} \) of SCM is defined as shown in Table A1, which was determined from experiments on phase composition of systems with SCMs. Therefore, a similar approach may be applied to estimate the alkali concentration of systems with SCMs, leading to Eq. (A2), as shown below.

\[ [\text{OH}^-] = 0.386 \times \frac{\text{Na}_2\text{O}_{eq}}{(W/C)} \times \frac{(100-RL)/100}{} \times \frac{(100-RL \times R_{\text{OH}})/100}{} \]  

(A2)

where \([\text{OH}^-]\) is positive (\( \geq 0 \)).

It should be noted that the alkali supplied from other sources, such as SCMs and chemical admixtures, should be converted to the alkali content of cement (the total alkali content should be divided by the unit content of cement). An example calculation is shown in Fig. A1. For instance, when concrete with 20 wt% low-Ca fly ash and a cement alkali content of 0.6 wt% is tested, the alkali concentration for the wrapping cloth is calculated to be 0.18 - 0.21 mol/l. The calculated results are obtained from limited data, so further investigation is necessary for various SCMs.

| Table A1 R_{\text{OH}} of SCM |
|-----------------------------|
| Low-Ca fly ash | Moderate-Ca fly ash | Slag |
| \( R_{\text{OH}} \) | 2.16-2.49 | 1.47 | 0.89 |

There are a wide variety of available SCMs, and alkali concentrations of pore solutions depend on many factors such as chemical/mineral compositions, reactivity, and fineness. According to previous studies, based on a large set of experiments, a chemical index, \((\text{Na}_2\text{O}_{eq} \times \text{CaO})/(\text{SiO}_2)^2\) of binder, was found to have a good correlation with OH\(^-\) concentration of the pore solution (Lindgård et al. 2012). This approach might be one solution to this issue. Fineness is also an important factor, especially when combined with highly-reactive aggregate: hydration of SCMs and ASR of the reactive aggregate is competitive. The previous study reported that the fineness of fly ash is the most influencing factor to mitigate ASR expansion of mortar tested by ASTM C 1260 (Hayashi et al. 2009). The mechanism of mitigation is mainly attributed to densification of the microstructure. Kawabata et al. (2008) proposed an index, \(\alpha\text{SiO}_2\times \text{Al}_{2}\text{SiO}_5/(\text{Na}_2\text{O}_{eq})\), which is calculated by amorphous silica content of fly ash (\(\alpha\text{SiO}_2\)), fineness measured by laser diffraction (\(\text{Al}_{2}\text{SiO}_5\)) and the total alkali content of the system (\(\text{Na}_2\text{O}_{eq}\)). According to Obla et al. (2003), ultrafine fly ash (< 3 μm) with moderate-Ca content can mitigate ASR expansion effectively. These results indicate that fineness as well as chemical/mineral compositions should be taken into account. Further work should be necessary to evaluate the effect of fineness although it is not taken into account in most of the standards.

In either case, it is currently quite difficult to precisely predict the alkali concentration of systems with SCMs. Therefore, it might provide conservative results for the applied wrapping cloth concentration without considering alkali uptake and dilution.

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