AW-CPT as an ideal laboratory potential expansion test for ASR with constant alkali content and maximized water supply and the design of an alkali solution for wrapping

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Abstract

Quantitative estimation of the expansion from alkali-silica reaction (ASR) is required for performance-verification based design. For this, reliable results of the acceleration test for ASR are indispensable. Although concrete prism tests (CPT) such as RILEM AAR-3 [1] and 4 [2] or CAN/CSA-A23.2-14A-14 [3] are promising for the assessment of the potential expansion of aggregate by ASR, when thinking as performance tests, several challenges have arisen such as alkali loss from the concrete test prisms (alkali leaching) and insufficient water supply compared to water immersion. RILEM AAR-10 is designed to reduce these adverse effects by increasing specimen size and providing quick measurement without cooling the specimens. This procedure can reduce alkali leaching during the test and may give reasonable results in assessing the suppression ability of SCMs or the alkali threshold level of the alkali content. However, it will be difficult to maintain the alkali content constant under varying testing temperatures and ages. Furthermore, the authors think that the water supply from the humid condition is limited compared to immersion in liquid water. For quantitative testing, it is important to maintain the testing condition constant. For this purpose, alkali-wrapped CPT (AW-CPT) has been proposed. Concrete prisms are wrapped by a water-holding material containing an alkali solution mimicking the pore solution composition. In addition, it is well known that many kinds of aggregate show so-called pessimum effects on the mix proportion of the aggregate and other factors such as alkali content, temperature, age of evaluation, and size. In the present study, the AW-CPT procedure is explained briefly along with the background of determination of the alkali concentration for wrapping. Test results for various types and combination of aggregate are introduced.

Keywords: alkali leaching; alkali-wrapping; concrete prism test; pore solution composition; quantitative expansion estimation

1. INTRODUCTION

Alkali-silica reaction (ASR) is a concrete deterioration phenomenon, different from other deterioration mechanisms due to the methods used to estimate deterioration. Chloride- or neutralization-induced steel corrosion has been modeled in various types of concrete, and performance-based design is possible with quantitative evaluation of the corrosion phenomenon. However, the quantitative modeling of ASR and the resultant expansion of concrete is challenging. Therefore, countermeasures to prevent or reduce damage from ASR are specified based on experience for each region where concrete is used. RILEM technical committee 258 Avoiding harmful Alkali-Aggregate reaction (TC258-AAA) provides a mandate to establish a "performance-based specification" [4] by developing new methods separated from the former RILEM AAR-3 (concrete prism test, CPT at 38 ºC) [1] and AAR-4 (accelerated CPT at 60 ºC) [2] as aggregate tests. Although those new test methods can supply the required amounts of supplemental cementitious materials (SCMs) or the total alkali threshold to avoid ASR, the evaluation is safe or not and there remains no long-term quantitative evaluation. Quantitative estimates are critical for performance-verification based design for long-term use in various environmental conditions, such as for long-life infrastructure, buildings, nuclear power plants used in high temperature, and radioactive waste disposal facilities.

To estimate the long-term expansion resulting from ASR in the field, several models have been established based on the reaction mechanism, with appropriate parameters obtained experimentally or determined from field experience. For this, a reliable experimental procedure is indispensable to determine the important modeling parameters. Further, it is necessary to understand the factors that affect ASR expansion in the field. Many studies have compared in-field and CPT expansions [5, 6]. In the majority, direct correlation is discussed; however, the affecting factors have not been clarified. The authors have indicated the importance of precipitation [7] and sunlight [7] in addition to environmental temperature, anyone can estimate the importance. For this method of comparison and analysis, controlled conditions for the CPT are critical as it is challenging to quantitatively determine the critical factors without reliable results.

RILEM AAR-3 and AAR-4 are reliable test procedures for aggregate used to evaluate the potential expansion of aggregate by ASR. However, alkali leaching (loss of alkalis from a concrete prism during the test) during the test procedures have been suggested as disadvantages when these methods are intended to use as performance tests. The new AAR-10 (CPT at 38 °C) and AAR-11 (CPT at 60 °C) procedures that are under preparation avoid the disadvantage and thus significant improvement will be achieved. However, there remain uncertainties in regards to constant experimental conditions. To detect critical factors, the total alkali content must be kept constant and sufficient moisture supply must be assured in all CPT testing conditions, regardless of temperature, specimen age, prism size, aggregate type, and mixture proportion of the concrete. The authors think that moisture supply is more in immersion condition than in moist atmosphere. All these factors affect alkali leaching and moisture supply [9].

To overcome these difficulties, several unique testing procedures have been proposed [10, 11, 12]. The authors proposed a test protocol called alkali wrapping (AW). Concrete prisms are covered by water-holding materials containing an alkali solution mimicking the pH of the pore water [13]. AW is discussed in RILEM TC-258 AAA as the new testing method RILEM AAR-13, "Application of alkali-wrapping for concrete prism testing to assess the expansion potential of alkali-silica reaction." AW was originally proposed in a research committee at the Japan Concrete Institute as a potential test of expansion from ASR for real concrete mixtures. Through discussion in RILEM TC-258 AAA, only the wrapping process is planned to be standardized.

In this review paper primarily based on published data, the outline and background of AW is explained. First, the AW procedure is introduced. Second, the calculation method of the alkalinity for wrapping is explained. Third, a comparison is presented of alkali leaching in various CPTs based on RILEM AAR-3, 4, 10, and others with/without AW. Fourth, expansions and mass change during testing are shown. Finally, some areas for improvement are mentioned. Of course, RILEM AAR-10 and AAR-13 are in the final stage to establish and details have not been disclosed. Therefore, from the strict style of paper preparation, this review paper might not be sufficient to describe the details of the experimental procedures. However, it is worth reporting preliminary results in this ICAAR, which is held every four years.

2. AW PROCEDURE

2.1 Basic concept of AW

Concrete being directly cured in a humid chamber always has some risk of alkali leaching, even if some of the countermeasures from RILEM AAR-10 are used. The problem lies not with the amounts of alkali leaching; it is instead the dependence of the amount of alkali leaching on various factors. Through the employment of effective countermeasure, the effect can be decreased; however, the amount of leaching can vary at higher temperatures, with longer testing time, or with specimen size [14]. By stopping the material transfer of concrete prism to and from the surrounding environments under sealed storage condition, it can be possible to prevent alkali leaching. However, additional moisture supply, which is indispensable for ASR, would become difficult. Therefore, a concrete prism may be wrapped by a material impregnated with a water-based solution containing sufficient amounts of alkali solution with a pH equal to that of the pore solution to realize both requirements. As the alkalinities are balanced between the concrete and wrapping materials, there would be no exchange of alkalis yet water can be supplied from the wrapping material to the concrete.

The pH of the pore water in concrete is not simply determined by alkalis from the cement; it varies due to several parameters, such as alkali absorption by/release from the aggregate, hydration of SCMs, temperature, and due to ASR itself. As a nature of experimental testing, simplification is inevitable. Except for the alkali release from the aggregate, every process is an alkali consumption reaction.

Therefore, setting the pH only based on cement including SCMs is considered a conservative way of testing. When the reaction proceeds, water is also consumed. Therefore, at each measurement interval, water is added to the water-holding material. Through this AW, it is possible to minimize alkali leaching and realize sufficient water supply to the test specimen.
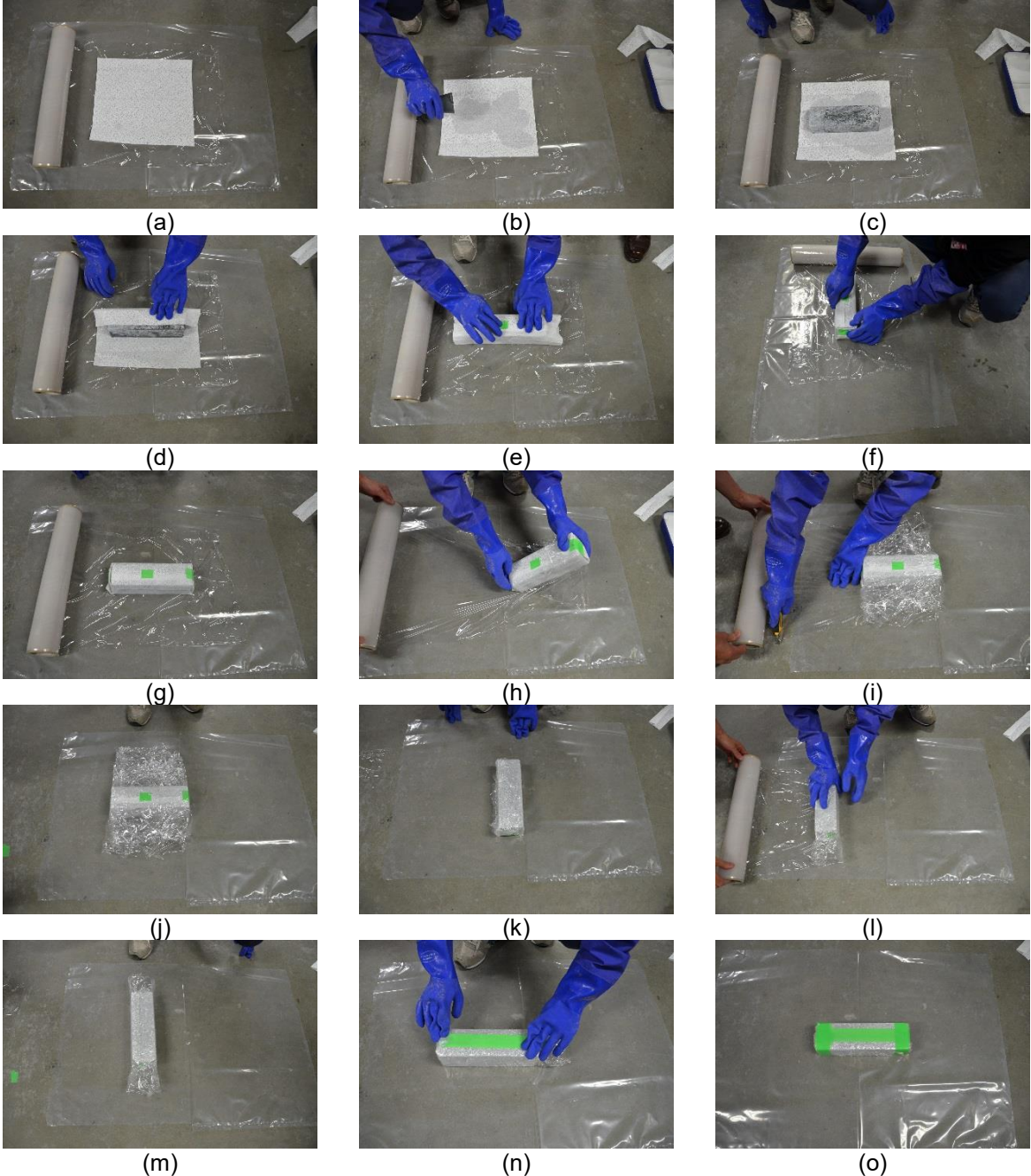

Figure 2.1: Wrapping procedures for 75×75×250 mm concrete specimen (prepared by the authors and planned to be used in RILEM AAR-13)

Another characteristic of AW is that it can be applied to all kinds of CPT such as RILEM AAR-3, 4, CSA, ASTM for aggregate testing, RILEM AAR-10 and 11 for alkali threshold testing or determining the required amount of SCMs, JASS5N-T603 for job mixture tests, and even for ASTM C 117-10 (withdrawn in 2018) and others. Therefore, AW is planned to be standardized as RILEM AAR-13.

2.2   Wrapping procedure

In Figure 2.1, the wrapping procedure is shown. The water-holding material, sized appropriately to wrap the test prism, is placed on a thin plastic film. Here, the non-woven cloth KimTeX© Pop-up White wipers (355 mm × 425 mm) made from polypropylene fiber (product ID 60701, Nippon Paper Crecia Co., Ltd.) was used for a 75 mm × 75 mm × 250 mm prism. On the water-holding material and appropriate amount of alkali solution is poured. Here, 50 g is the maximum amount able to be held by the cloth. The alkalinity is adjusted by adding NaOH to the solution depending on the total alkali content. Then, the prism is wrapped by the cloth and overwrapped by plastic film and stapled by adhesive tape.

2.3   Calculation of alkalinity for wrapping

It is necessary to determine the alkali concentration of the solution used for wrapping. Based on an extensive overview from [15] and as explained in the former section covering the testing method, a conservative approach was chosen using both Portland cement and SCMs.

To calculate the total Na_2O_{eq} of the binder, Eq. (1) can be used, which is a conservative approach:

$$Na_2O_{eq,binder} = Na_2O_{eq,cem} \times C/B + Na_2O_{eq,SCM1} \times S1/B +$$
$$+ Na_2O_{eq,SCM2} \times S2/B + 61.98/(39.997 \times 2) \times NaOH/B \times 100 \quad (1)$$

where $Na_2O_{eq,binder}$ is the equivalent alkali content of the total binder (%), $Na_2O_{eq,cem}$ is the equivalent alkali content of the Portland cement (%), $Na_2O_{eq,scm1}$ is the equivalent alkali content of supplementary cementitious material 1 (SCM1, %), and $Na_2O_{eq,scm2}$ is the equivalent alkali content of supplementary cementitious material 2 (SCM2, %). B is the total unit content of the binder (kg/m^3), C is the unit content (kg/m^3) of the Portland cement, S1 is the unit content of SCM1 (kg/m^3), S2 is the unit content of SCM2 (kg/m^3), and NaOH is the unit content of added NaOH (kg/m^3) for alkali boosting. The factor $61.98/(39.997 \times 2)$ converts the unit of added NaOH (kg/m^3) to Na_2O_{eq} (kg/m^3).

Next, the alkali concentration (mol/L) of the solution mimicking the pore solution of the concrete can be calculated by Eq. (2)

$$[OH^-] = 0.386 \times Na_2O_{eq,binder} \times B/W \quad (2)$$

where W is the unit content of water (kg/m^3). When no SCMs are present in the concrete, this equation reduces to

$$[OH^-] = 0.386 \times Na_2O_{eq,cem} \times C/W \quad (3)$$

As an example, a Portland cement is assumed with a Na_2O_{eq} = 0.60%. The concrete is made with 320 kg of cement and a water-to-cement ratio of 0.50 (i.e., the water amount is 160 kg/m^3 of concrete) without alkali boosting. Following Eq. (3) the alkali concentration is then $[OH^-]$ = (0.386 × 0.60 × 320)/160 = 0.46 mol/L. The concentration of 0.46 mol/L corresponds to the alkali concentration of the relatively low alkali Portland cement paste.

If instead fly ash is used for example, a Portland cement with Na_2O_{eq} = 0.60% and fly ash with Na_2O_{eq} = 1.00% are assumed. The concrete is made with 280 kg/m^3 cement, 40 kg/m^3 fly ash, and a water-to-binder ratio of 0.50 (i.e., water amount is 160 kg/m^3 of concrete). Following Eq. (2), the alkali concentration is then $[OH^-]$ = {0.386 × (0.60 × 280 + 1.00 × 40)}/160 = 0.50 mol/L.

When the total alkali content is boosted by adding NaOH solution, the equivalent alkali content of the total binder is also calculated according to Eq. (2). For an example of alkali boosting, a Portland cement is assumed with Na_2O_{eq} = 0.60%. The concrete is prepared with 320 kg/m^3 cement and a water-to-cement ratio of 0.50 (i.e., water amount is 160 kg/m^3 of concrete). The total alkali content of concrete is boosted to 5.5 kg/m^3 by adding 4.62 kg/m^3 NaOH, resulting in an equivalent alkali content of the total binder ($Na_2O_{eq,binder}$) of (5.5 / 320) × 100 = 1.72%. Following Eq. (2), the alkali concentration is then $[OH^-]$ = (0.386 × 1.72 × 320)/160 = 1.33 mol/L.

2.4 Measurement

At each measurement interval, the water-holding material is removed and its mass reduction from the initial mass of the water-holding material and alkali solution is measured. The reduction is recovered with pure water but not with alkali solution. If alkali solution is used, the total alkali content increases and this is different from to the intent of maintaining the total alkali content constant during the test period.

3. VERIFICATION OF THE EFFECT OF AW

3.1 Outline of experiments

To verify the effectiveness of AW, several kinds of aggregate have been examined in various test methods. One type of aggregate is highly reactive Japanese andesite containing opal and cristobalite/tridymite and volcanic glass. This andesite was used in railway bridges and caused significant damage in Northeastern Japan. A second aggregate tested is another reactive Japanese andesite containing cristobalite/tridymite, which is considered a reactive aggregate and caused some damage in Hokkaido. In addition, hornfels from large Tokyo area were used; however, the existence of damage is not clear. Chert containing chalcedony and crypto/microcrystalline quartz from Middle Japan was tested as well. Finally, Norwegian reactive cataclasite was used as a standard reactive aggregate in the region according to Dr. J. Lindgård.

RILEM AAR-3, AAR-4, AAR-10[draft], and JASS 5N T603 were used as base testing methods. However, because of the tradition in Japanese test methods, there are slight differences in testing conditions. The testing temperature is 40 °C instead of 38 °C. The air content of concrete is controlled at 4.5±1.5% by adding AE agent and water reducer was used, resulting in a reduced water content approximately 160 kg/m^3 instead of 220 kg/m^3, which is the standard value in RILEM tests. The grading of aggregate is not specified in Japan as severely as in RILEM tests. AW was applied during curing.

3.2 Experimental results of alkali-leaching

The major purpose of AW is to control the experimental conditions to provide constant alkali content and sufficient moisture supply. In Figure 3.1, the behavior of alkali leaching in CPTs based on RILEM AAR-3 and AAR-4 and the effect of AW [9] and those in CPTs based on RILEM AAR-10 without/with AW [16, 17] are shown. The specimen size was 75 mm × 75 mm × 250 mm for RILEM AAR-3 and AAR-4 and measurements were carried out after cooling the prisms in a humid chamber to 20 °C. For RILEM AAR-10, the specimen size was 100 mm × 100 mm × 400 mm and measurements were carried out without cooling. The amount of alkali leaching was evaluated by measuring the alkali concentration of water in the storage container under the assumption that leached alkali from the specimen are dropped in the water.

Highly reactive andesite was used in Figure 3.1 (left) and (middle). The data of alkali leaching at 26 weeks are plotted. Norwegian aggregate was used in Figure 3.1 (right). As shown in Figure 3.1 (left), at a higher temperature, more alkalis were lost while the alkali leaching was limited at lower temperatures. However, the alkali leaching depends on the initial alkali content and on the mixture proportion. Furthermore, temperature variations must be considered when quantitatively estimating expansion for long-term field usage. In particular, for concrete used in high temperature conditions such as for bio-shields in nuclear power plants, 60 °C is not an accelerated condition: it is the operating condition. Therefore, differences in alkali leaching due to temperature should be avoided. When AW is applied, as shown in Figure 3.1 (middle), alkali leaching can be suppressed. RILEM AAR-10 has been developed to reduce the alkali leaching. CPTs based on the draft AAR-10 under preparation in RILEM TC-258 AAA were carried out with and without AW. In these CPTs, the mixture proportion and measurement procedure were in accordance with AAR-10 while the curing temperature was modified to 40 and 60 °C. As shown in Figure 3.1 (right), the total alkali content was kept in a limited range even without AW. AAR-10 is an efficient procedure to avoid alkali leaching. With AW, minimal alkali leaching was observed.
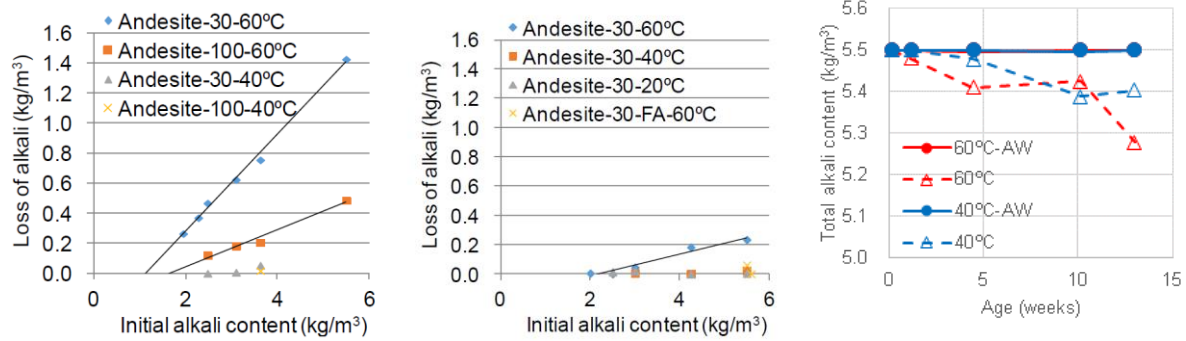
Figure 3.1: Comparison of alkali leaching at 26 weeks in conventional CPT (left) based on RILEM AAR-3 and AAR-4, in AW-CPT (middle) [9], and in CPTs based on RILEM AAR-10 and with AW (right) (modified after [16, 17]). Losses of alkali were calculated from the alkali concentrations in storage containers. Legend (left and middle): Aggregate type-mixing ratio-test temperature. (Right): Test temperature-with/without AW.
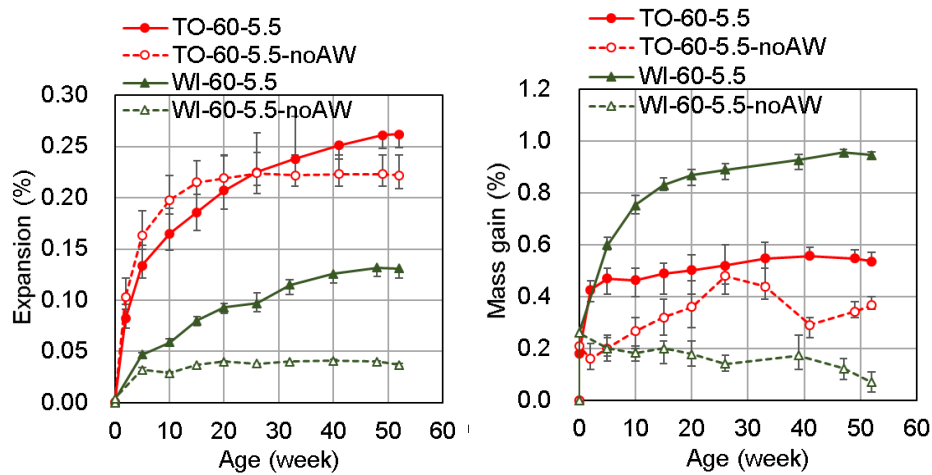

Figure 3.2: Effects of AW on expansion and mass change in CPT based on RILEM AAR-3 and AAR-4 [18, 19]. Legend: aggregate type-test temperature (ºC)-alkali content (kg/m^3)-with/without AW. To is andesite and WI is hornfels as coarse aggregate. Ordinary Portland cement (OPC) was used.
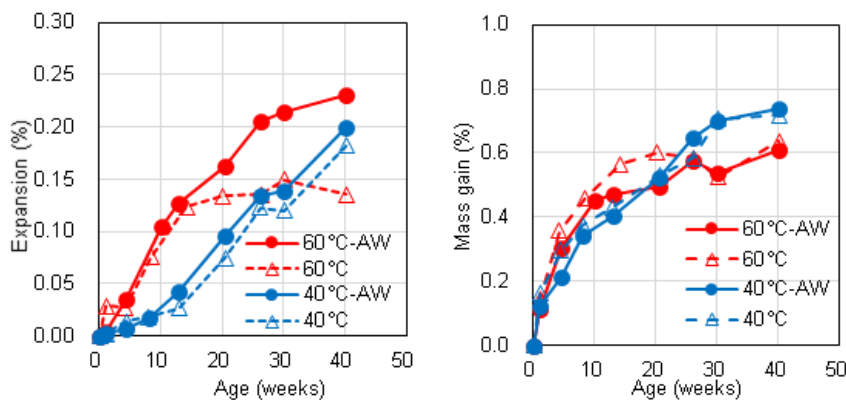

Figure 3.3: Adding effects of AW on the expansion and the mass change in CPT based on RILEM AAR-10 (modified from [16, 17]). Coarse aggregate is mixed of highly reactive andesite for 30 % and no-reactive limestone for 70%. OPC was used. The total alkali content was 5.5 kg/m^3.

3.3 Experimental results of expansion and mass changes

Examples of the effects of AW on expansion and mass change during CPT based on RILEM AAR-4 are shown in Figure 3.2 [18, 19]. The specimen size was 75 mm × 75 mm × 250 mm and the mixture proportion followed the Japanese method, differing from the original RILEM AAR-4 as mentioned above. In this case, reactive andesite (TO) and hornfels (WI) were used. As shown in Figure 3.2 (left), for TO, the effect of AW is limited; however, for WI, without AW, the expansion was limited. These behaviors have been thought to be caused by alkali leaching. However, they may result from an insufficient moisture supply. As shown in Figure 3.2 (right), there are significant discrepancies in mass gain during curing. Without AW, the specimen cannot absorb water or suffered the effects of drying. Moisture supply may be different in a humid chamber and direct contact with liquid water.

In Figure 3.3, another example is shown for RILEM AAR-10 with and without AW for the Norwegian aggregate with the curing temperature modified to 40 and 60 °C. The mass changes were identical for all testing conditions. The procedure introduced by RILEM AAR-10 is considered effective as per design. When this AAR-10 is applied for higher temperature, only in the case of higher temperature, the expansion was saturated; however, with AW, it continues. The characteristic expansion dependence on temperature is successfully obtained by applying AW. At lower temperatures, an initial amount of time is required for the onset of expansion, yet in the long-term, the expansion exceeds that at higher temperatures.

Figure4.1: Procedure of over-wrapping by aluminum bag under vacuum

4. AREAS FOR IMPROVEMENT

Various options of the procedures of AW have been examined although for RILEM AAR-13, the contents of the procedures adopted have been limited to well-confirmed subjects.

AW is originally proposed to facilitate the test. Therefore, smaller samples that have higher possibilities of losing alkalis in conventional CPTs were thought to be preferable. AW can prevent alkali leaching even for small prism sizes such as 75 mm × 75 mm × 250 mm or even 40 mm × 40 mm × 160 mm. However, the aggregate is sometime inhomogeneous and requires a larger specimen. The difference of the reactivity of aggregate particles can be clarified by detailed study [20]. Especially, pessimum effects of highly reactive aggregate in the mixture proportion require a larger volume of concrete to provide greater homogeneity. In some cases, the pessimum proportion of coarse aggregate may only be 5% [21]. In such cases, smaller specimens are beneficial for easy operation; however, this limits the reliability of the test. The mass of the 75 mm × 75 mm × 250 mm specimen of normal weight concrete such as examined in the chapter 3 was 3.2 kg, while that of the 100 mm × 100 mm × 400 mm specimen was 9.2 kg. As a technician, 3.2 kg is very easy to handle yet 9.2 kg requires significant effort. For obviously homogeneous rock type, even smaller sized test prisms can provide a precise result, in contrast to an inhomogeneous rock type that requires a larger size prism.

Wrapping the specimen in a thin plastic film is also a laborious and complicated process, especially for larger size prisms. In such cases, vacuum packing in an aluminum-coated bag is beneficial. In Figure

4.1, the procedure is outlined. After wrapping with the water-holding material, instead of plastic thin film, the wrapped prism is stored in an aluminum bag and the air inside of the bag was extracted to attach the wrapping material firmly on the prism. The expansion and mass change results are comparable with normal AW [16, 17].

5. CONCLUSION

The concept for alkali wrapping is the application of reliable test results for the long-term quantitative estimation of ASR expansion through constant test conditions.

AW is a part of a testing procedure, covering specimens with a water-holding material containing an alkali solution having the same pH as the concrete pore solution. AW can be applied for existing concrete prism testing. AW can avoid alkali leaching and can realize sufficient moisture supply and enhance the reliability of CPTs.

Through several experiments evaluating alkali leaching, expansion, and mass changes, alkali leaching was successfully suppressed and greater expansion and mass gain were observed. Therefore, AW is considered as a promising additional procedure for existing CPTs.

The effect of specimen size and alternative overlapping methods were introduced as possible improvements to the test procedure.

6. ACKNOWLEDGEMENT

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