IMPORTANCE OF ALKALI-WRAPPING IN CONCRETE PRISM TESTS

Kazuo Yamada[1][*], Yasutaka Sagawa[2], Takahiro Nagase[3], Shoichi Ogawa[4],Yuichiro Kawabata[5,6], Akihiro Tanaka[2]

[1]National Institute for Environmental Studies, Research Center for Material Cycles and Waste Management, Tsukuba, JAPAN

[2]Kyushu University, Department of Civil and Structural Engineering, Fukuoka, JAPAN

[3]Taiheiyo Consultant, Analytical Technology Division, Sakura, JAPAN

[4] Taiheiyo Consultant, Sales & Marketing Division, Tokyo, JAPAN

[5]Université Paris-Est, IFSTTAR, Materials and Structures Department, Marne-la-Vallée Cedex 2, FRANCE

[6]Port and Airport Research Institute, Structural Engineering Division, Yokosuka, JAPAN

Abstract

Concrete prism tests (CPT) for alkali aggregate reaction (ASR) are considered as a relatively reliable method covering the limitations of various aggregate tests. However, CPT has two problems—alkali leaching and drying. As an aggregate test, the CPT is a valuable because the alkali threshold for expansion can be determined by comparison with existing damages. However, as a performance test, these unintended effects need to be prevented and, wrapping concrete prisms with wet cloth containing an alkaline solution with the same pH as that of pore solution of concrete named as "alkali wrapping (AW)-CPT" is proposed in this study. This avoids the movement of alkalis between the cloth and the prisms and makes the acceleration conditions are clear and stable. The analysis of the cloth used for AW-CPT at various acceleration conditions indicates the presence of significant amount of silica leaching depending on the conditions and the mechanisms discussed.

Keywords: concrete prism test, alkali wrapping, performance test, alkali leaching, drying

1 INTRODUCTION

Correlation among various reactivity/expansion tests of aggregate and concrete has been previously discussed [1]. As discussed in [2], existing aggregate testing methods for checking alkali reactivity have limitations such as compositional, size, and temperature pessimum effects. In order to obtain results in a reasonably short time, in these aggregate tests, the reaction is accelerated by alkali boosting and temperature increase. Recently, to address these limitations of aggregate tests, procedures for performance tests are under discussion in RILEM TC 258-AAA, chaired by Prof. B. Wigum. These performance tests are based on concrete prism tests (CPT) such as RILEM AAR-3, AAR-4, ASTM C1293, and CSA A23.2 14A. Figure 1 [3] shows examples of CPT as a performance test, indicating the effect of adding supplementary cementing materials (SCMs) on the expansion of various mixtures composed of highly reactive andesite. It is, however, important to control alkali leaching, which is the loss of alkalis in the concrete prism during curing [4]. One possible solution is wrapping the concrete prism in wet cloth dipped in an alkaline solution.

Alkali leaching is reported to be limited at 40 °C but significant at 60 °C [5].One easy way to suppress alkali leaching may be to control the accelerating temperature to less than 40 °C. However, in case of nuclear power plants, it is indispensable to examine the behaviour at higher temperature owing to their characteristics. Another alternative is to use a larger specimen for testing. RILEM, CAS, and ASTM use a 7.5 cm × 7.5 cm × 25 cm (7.5-7.5-25 cm) prism. However, when a 10 cm × 10 cm × 40 cm (10-10-40 cm) prism wrapped with pure water-wet cloth is used according to the Japanese standard, for example, alkali leaching can be avoided significantly, as shown in Figure 2 [3]. According to other studies [6, 7], even in the case of 38 ºC, significant alkali leaching has been observed and no effective solutions have been established. Alkali leaching may be one of the reasons for poor

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[*] Correspondence to: yamada.kazuo@nies.go.jp

reproducibility of CPT [7]. In addition, the weights of the two abovementioned prisms differ greatly (~3.2 kg for the 7.5-7.5-25 cm prism and ~9.2 kg for the 10-10-40 cm prism). This would make handling and space-saving in the case of the large specimen difficult, which is critical in the investigation of alkali–silica reaction (ASR) expansion under various conditions, as discussed in [8]. Therefore, a more feasible solution would be to apply a smaller size specimen with some improvement in the wrapping.

If simple pure water-wet cloth is applied for the concrete prism, some amount of alkali moves from the prism to the cloth. In contrast, if wet cloth with concentrated alkali solution is applied, some amount of alkali moves from the cloth to the prism. Therefore, there should be a balance in the alkali concentration in the cloth such that no alkali transfer occurs. This study is based on this concept.

First, the effects of alkali wrapping (AW) on ASR expansion are introduced. Then, the mechanisms of less expansion without wrapping are estimated, and leaching control by AW is shown. Finally, the details of element exchanges between the concrete prism and wrapping cloth are discussed.

2   COMPARISON OF EXPANSION BETWEEN CPT AND AW-CPT
2.1   General
In this chapter, the effect of AW on ASR expansion in CPT is explained by comparing results of previous studies and experiments in this study. First, various aggregate mixtures prepared by varying factors of aggregate type (rapid or slow expansive), aggregate size, and SCM type are compared to understand the general trends. Further, for two types of aggregate, expansion and mass changes are explained in more details.

2.2   RILEM AAR-4 and modified JASS5N T603 with wet wrapping [3]
Experiments

Two different types of CPT were considered: RILEM AAR-4 and modified JASS5N T603 (AAR-L). The specimen size for AAR-4 was 7.5-7.5-25 cm and that for AAR-L was 10-10-40 cm. Japanese normal Portland cement and fly ash of siliceous type II of JIS were used. Fly ash used replaced 25 mass% of normal Portland cement. Three types of aggregate were used: 30 mass% of coarse or fine aggregate composed of highly reactive andesite of rapid expansive type including opal and cristobalite, 100 mass% of coarse aggregate composed of hornfels of slow expansive type including cryptocrystalline quartz, and remaining coarse and fine aggregates composed of non-reactive pure limestone. Andesite and hornfels used in this study caused ASR damages in field. Water to cement ratio was 0.50 and unit water content was 160 kg/m³. The total alkali content was 5.5 kg/m³ Na_2O_{eq} prepared by adding NaOH dissolved in mixing water. For AAR-4, specimens were placed in sealed SUS containers containing water at the bottom and the containers were kept in a humid chamber at 60 °C. For AAR-L, the alkali content was adjusted from the original values to 5.5 kg/m³ and curing temperature was at 40 °C and 60 °C. Concrete prisms of AAR-L were wrapped with two pieces of wet cloth (nonwoven polypropylene fabric cloth (Kimtex, pop-up-type, white), Nippon Paper Crecia, Co., Ltd.). Each cloth piece contained 50 g of water without alkalis. During length measurement, the reduced amount of water was added to maintain the initial level.

Results

Expansion behaviours for the two types of CPT are shown in Figure 3. Data from 4 to 26 weeks are plotted. In a wider range of expansion, both methods exhibit similar tendency (Figure 3 (a)). Significant differences are observed in smaller range of expansion (Figure 3 (b)). AAR-4 gave considerably smaller expansion than AAR-L. With the threshold value judging alkali reactivity harmful assumed to be 0.04%, hornfels is judged to be harmful in case of AAR-L, while not in case of AAR-4. AAR-4 failed to detect the reactivity of this hornfels but AAR-L detected. Besides, regarding adding effect of fly ash, the different results were obtained; non-reactive by AAR-4 but reactive by AAR-L.

2.3   RILEM AAR-4 without and with AW
Experiments

To directly compare the effects of AW, same size prisms (7.5-7.5-25 cm) were prepared and their expansion and mass change of the same specimens but without and with AW at 60 °C were compared. pH condition of the solution for AW will be described in the following section. Aggregates used were rapid expansive-type andesite that includes tridymite (OT) and slow expansive-type hard sandstone (IW) that includes cryptocrystalline quartz. 30 mass% coarse aggregate of OT and 100 mass% coarse aggregate of IW were used. The remained coarse aggregate and sand were non-reactive pure limestone, the alkali content was 5.5 kg/m³, and the cement used was normal Portland cement.

Water to cement ratio was 0.50 and unit water content was 160 kg/m³. Before measurement, specimens were cooled in sealed containers to 20 ºC. Mass of specimens with AW was measured after removing wrapping paper.

Results

Expansion and mass gain are shown in Figures 4 (a) and (b), respectively. In the case of OT, AW and no-AW showed similar expansion at 26 weeks but the expansion behaviours were different. AW showed continuous but no-AW showed saturated expansions at 52 weeks. Regarding IW, both methods gave completely different results. AW showed continuous expansion until 52 weeks but no-AW showed saturated expansion only in 5 weeks. With the threshold value judging alkali reactivity harmful set as 0.04% at 20 weeks, the same judgment can be obtained for OT as harmful but it will be different for IW as harmless and harmful by without AW and with AW, respectively. As discussed in [8], the difference of wrapping provides considerably different results for expansion estimation in future. Moisture control is very important for expansion testing.

Apart from alkali leaching, drying may also affect the expansion. The mass of the prisms increased during curing, as shown in Figure 4 (b), after demolding and dipping in water for 30 minutes, followed by curing in a sealed humid chamber. After that, there are significant differences in mass gain behaviours. IW with no AW showed continuous loss of mass. OT with no AW lost mass for 2 weeks but gained slowly and reached the same level as in the case of AW at 26 weeks but lost mass again in further curing. IW showed more mass gain although the expansion was limited compared to OT. One of the reasons of greater expansion by AW is not clear but moisture might have affected.

3 BEHAVIOURS OF CPT WITHOUT AW UNDER VARIOUS CONDITIONS
3.1 General

To understand what happens in CPT without wrapping, a series of experiments was carried out by varying alkali content and curing temperature by using two kinds of typical reactive aggregates found in Japan—rapid expansive-type andesite at pessimum composition of 30 mass% and as 100 mass% coarse aggregate and chert as 100 mass% coarse aggregate. Along with expansion, mass gain and alkali leaching were measured. The effect of AW is also compared for loss of alkali for reference.

3.2 Experiments

A popular mixture in Japan, Japanese normal Portland cement with a water to cement ratio of 0.50 and unit water content of 160 kg/m³, was used. The size of prisms was 7.5-7.5-25 cm. Twenty-four hours after mixing, the specimens were demolded, and the base mass and length were recorded. Then, the prisms were immersed in water for 30 minutes and the mass and length were recorded again. After measurement, some of the prisms were wrapped with wet cloth containing an alkaline solution corresponding to alkali content of 1.95–3.63 kg/m³ alkali content.

The pH of pore solution of concrete having different alkali contents was calculated according to [9]. In this calculation, the following were assumed as basic factors. In the paste, C–S–H content is 790 kg/m³, Ca/Si ratio of C–S–H is 2.0, and free water content is 270 L/m³. For example, equivalent alkali concentrations are 0.48, 0.89, 1.35 M for alkali content of 1.95, 3.63, 5.50 kg/m³, respectively. 50 g of alkali solution corresponding to each level of total alkali content was added to one cloth piece, whose details were mentioned in Section 2.2. A prism was wrapped with this cloth piece and covered with a thin plastic film for isolating it from the environment. At every measurement time, pure water was added to maintain the same mass of the wet cloth as in the beginning.

Three prisms, one each for each alkali mixture, were maintained at 40 and 60 ºC in sealed humid containers. The humid containers were stored in a larger humid chamber under a temperature-controlled condition.

3.3 Results

Expansion and mass gain

The results of expansion and mass changes of the prisms without AW are shown in Figure 5. Most of the andesite showed expansion and chert showed shrinkage. More than half of the prisms showed mass loss, which implies that some prisms expanded but dried to some degree.

Figure 6 shows the correlation between alkali content and expansion or mass gain. For each mixture and curing temperature, linear positive correlations are obtained, indicating that higher alkali content increased expansion, because of the formation of alkali silica gel (ASG), as suggested by more mass gain. This correlation suggests simultaneous competitive length change phenomena, i.e., expansion by ASR with the formation of ASG accompanying mass gain and shrinkage by drying.

Differences in equilibrium relative humidity between 0.48 and 0.89 M of alkali concentration, corresponding to 1.95 and 3.63 kg/m³ of alkali contents, are almost the same as in the range of relative humidity 98.3–96.8 % [10]. However, this limited difference can affect the moisture supply for concrete. As seen here, without wrapping, the expansion suffers drying, the degree of which depends on alkali content even in controlled conditions such as in a laboratory. Moreover, it is difficult to distinguish several factors such as alkali content, temperature, aggregate type, mix proportions, or moisture supply. For these reasons, simple CPT cannot be an efficient performance test.

Alkali leaching

Loss of alkali was evaluated by measuring alkali concentration in the water in the containers. A small amount of water was sampled and alkali concentration was measured by neutralization titration using HCl. With the volume of water in each container and measured alkali concentration, the leached alkali amounts for the three prisms were calculated. The measurement results are shown in Figure 7.

Figure 7 (a) shows that alkali leached continuously with aging. The data can be fitted logarithmically, and it seems to be controlled by diffusion. Figure 7 (b) shows the correlations between initial alkali content and loss of alkali. Positive linear correlations depending on the mixture are observed. At 40 °C, alkali leaching was negligible, but at 60 °C, significant amounts were lost. The leaching amounts were less in the case of 100% andesite but four times more in the case of 30% andesite. The mechanism underlying this difference is not clear; however, if the ASG production amount of is more in the case of 100% andesite and if alkali from ASG is expected not to leach out easily, it will be possible to explain the alkali leaching as affected by the progress of ASR as well as temperature accelerating alkali movement. Therefore, the amount of alkali leaching varies depending on the type of mixture and different ASG formation amount. The regression lines of two mixtures at 60 °C intersect the x-axis at similar points, i.e., 1.0–1.5 kg/m³ of initial alkali. This value may correspond to the insoluble alkali in unhydrated clinker minerals.

For comparison, alkali leaching of AW-CPT evaluated by the alkali content in the bottom of containers is shown in Figure 7 (c). Even in the case of 30% andesite at 60 °C, alkali leaching was considerably less (one-sixth) than that in case of CPT without wrapping. At lower temperatures also, alkali leaching was negligible.

4 ANALYSIS OF AW CLOTH
4.1 General

From the discussions above, it is clear that AW can control alkali leaching and drying. In this chapter, alkali balance between wrapping cloth and concrete prism is discussed based on the experimental of another series of AW-CPT for two kinds of aggregate at various alkali contents and temperatures. By AW, if the effects of alkali leaching and drying are eliminated, intrinsic effects of them can be detected and their effects on expansion are discussed elsewhere [11]. Here, so far, alkali balance between the concrete prism and wrapping cloth will be discussed here.

4.2 Experiments

In the experiment, the following aggregates were used: 30 mass% coarse aggregate composed of highly reactive andesite N containing opal and crystobalite, 100 mass% coarse aggregate of reactive chert T were used, and non-reactive pure limestone for the remaining aggregate. Other mix proportion and the expansion test procedure are the same with Section 3.2. The prisms were kept at 20, 40, and 60 °C. The wrapping cloth, which is a nonwoven synthetic fiber, was removed from the prism at 45 weeks and used for chemical analysis. The cloth pieces were dried at 105 °C, which were then immersed in hot water two times, followed by immersing in 1N HCl. Then, dissolved Na and K were quantified by an atomic absorption method. After these extractions, the cloth pieces were again dried at 105 °C. The weight of one piece of cloth is 12.2 g; 26.7 mg of silica was found to be included according to HF dissolution and the silica was found to be in mineral phase as quartz or crystobalite, as characterized by X-ray diffraction. By a blank test for one piece of this cloth, 1.7 mg of Na and 0.2 mg of Ca was extracted by hot water treatment. Following HCl extraction, 0.02 mg of Si, 0.25 mg of Ca, and 0.76 g of Al were detected and these amounts were considered in the results. From alkali amounts in initial prisms, wrapping cloths, and leached alkalis in containers, increased alkali amounts in prisms were calculated.

4.3   Results

Alkali balance between wrapping cloth and prism

The experimental results are shown in Table 1 listing the extracted Na and K by hot water and HCl, total alkali amount as Na_2O_{eq}, increased contents of alkalis in concrete prisms and its ratio to original content, estimated silica content in the cloth after CPT, and expansion ratio at 45 weeks.

Figure 8 shows correlations based on Table 1. Figure 8 (a) shows the correlation between the initial alkali content and the final alkali content in the cloth pieces. Although in a limited amount, alkali leaching to the water at the bottom of the container was considered. Furthermore, the decrease in the alkali content in the wrapping cloth pieces is assumed to have moved into the prisms. Depending on the aggregate type, alkali contents in the prisms are changed in different ways but the effect of temperature may be limited. For aggregate N, the variation in alkali content was limited in relatively higher alkali content as shown in near positions near the 100% line but was around 120% in relatively higher content of 2.0–3.0 kg/m³. However, in the case of aggregate T, the alkali content increased by 20% in concrete prisms all over the range. In the case of aggregate N with 15 or 30 mass% fly ash, the alkali content increased about 20%. The some part of increase in alkali content in concrete prisms may be caused by ASR in the prisms. In the beginning, the alkali concentration in the wrapping cloth had been the same with that in the pore solution. However, with the progress of ASR, ASG consumes alkali and alkali concentration in the pore solution decreases and alkali has moved from the cloth piece to the concrete prism. Therefore, even if the alkali concentration in the wrapping cloth is equivalent to that in the pore solution without ASR, with the increase in ASG, some parts of the alkali in the wrapping cloth are absorbed in ASG. This mechanism will be happened the case of fly ash concrete regardless of the effects of ASR. To verify the mechanism, by using pure limestone having low ability of alkali binding and by varying the alkali concentration in the wrapping cloth, alkali balance has to be checked, as will be discussed in the next step. Simultaneously, by changing the alkali concentration in the wrapping cloth, similar experiments are under preparation for limited levels.

In Figure 8 (b), correlations between Na and K content in the cloth are shown for different mixtures and temperature conditions. Excepting aggregate N at 60 °C, there is a general positive trend between them. This trend is unusual. If alkalis are in simple equilibrium between solutions in concrete pore solution and the solution in wrapping cloth, K content in the cloth will become constant because K and Na can diffuse independently. However, K content in cloth is higher when Na content is higher although the content level is 10 times more in the case of Na. Figure 8 (c) shows correlations between the initial alkali content and estimated silica content in the cloth. For each combination of aggregate type and temperature, positive correlations are obtained. Higher alkali content results in higher silica content in the cloth. Higher temperature also increases the silica content in the cloth. Aggregate N generates more silica than aggregate T.

In some cases, negative values are obtained; there can be two possible causes. One is dissolution of silica from the cloth. However, since the effect should be limited in 0.027 g, this does not seem to be the reason. Another reason is the loss of the cloth. In some conditions of experiments, the cloth was adhered to the prisms stiffly. In such a case, it is not easy to peel off all the cloth from the prism. In general, the higher the expansion ratio, the more difficult it is to remove the cloth. Some examples of cloth pieces are shown in Figure 9. In the worst case, recovering the cloth was difficult.

Correlations among estimated (not initial) alkali content at 45 weeks, estimated silica content in cloth, and expansion ratio are shown in Figure 10. The details of the correlation between expansion and temperature or alkali content will be discussed in [11]. As shown in Figure 10 (c), in some cases such as N30-60 and T100, there are positive correlations between alkali content at 45 weeks and expansion ratio. However, in others, there is no clear dependence on alkali content. Regarding estimated silica content in the cloth, as shown in Figure 10 (b), there is better correlation between alkali content at 45 weeks depending only on the aggregate type. From Figure 10 (a), we see that for estimated silica content and expansion ratio, aggregate N shows a unique positive correlation but not aggregate T. The ASR expansion mechanism may not be simple and exact explanation has not been obtained yet.

Detailed analysis of wrapping cloth

There are many unclear points in the chemical compositions of elements in wrapping cloth pieces. Therefore, more detailed chemical analysis was carried out for selected samples. The cloth pieces of aggregate N with 3.0 kg/m³ of alkali content after 45 weeks were selected. In this analysis, besides Na and K, other major elements such as Si, Ca, and Al were evaluated. Measured data are summarized in Table 2.

In the beginning, hot water extraction was applied five times. In the case of cloth at 40 ℃, the majority of Na (~98%), 90% of K (which is less than Na), 50% of Si, and 1% of Ca were extracted with the first two extractions. Later in the third to fifth extractions, limited but similar amounts of Si and Ca were obtained, suggesting continuous dissolution of a less soluble phase such as C–S–H. The cloth was subsequently subjected to extraction by HCl. By this treatment, 18% of Si and 89% of Ca were extracted. In the last step, the cloth was burned out when subjected to extraction by HF, and the dissolved amount was assumed to be silica. In this step, 38% of Si was extracted. By X-ray diffraction measurement of the cloth, in the beginning, calcite and unknown crystal phase were found to be contained. Hydroxide ion concentration determined by neutralization titration coincided with alkali concentration, which indicates that the pH of the solution in the wrapping cloth is controlled by the amount of dissolved alkali.

The dissolved amount of each element was complicated and depended on the curing temperature. Na dissolution was highest at 40 ℃, while K, Ca, and Si dissolution was highest at 60 ℃. Judging from the data obtained, mineral phases included in the wrapping cloth are estimated as ASG, C–S–H, K–S–H, and silica. ASG can be dissolved by hot water. In this ASG, Ca was not included so much. By HCl, C–S–H, calcite, and K–S–H were extracted. In addition, by HF, remaining silica was extracted. Al was also extracted by HCl and HF but its amount was very limited and can be omitted from the discussion. Interestingly, major element distribution in each phase was considerably different depending on temperature.

At 60 ℃, calcite was detected, which is thought to be carbonation products. Carbonation seems to be accelerated at higher temperature. The question is how Ca came out from prism. ASG is formed in the aggregate by ASR. The reaction speed is higher at higher temperature and alkali contents. Data of total Si in Table 2 suggests greater generation of ASG at higher temperature. After generation of ASG, it causes expansive pressure if ASG is trapped in the aggregate because of, for example, low viscosity that are expected to extrude out easily but constrained by the formation of rigid shell around the aggregate by ion exchange between the alkalis in ASG and Ca in cement paste. However, generation speed of ASG high enough to penetrate in cement paste without ion exchange. Once ASG come out of the prism, at the surface, ion exchange takes place gradually to form C–S–H. Another possible explanation is the segregation of Ca bearing ASG into two phases; C–S–H and Ca-free ASG. Simultaneously, at higher temperature, carbonation of C–S–H after ASG occurs and the final products calcite and polymerized water insoluble amorphous silica are formed. By this reaction, Na becomes excessive and may diffuse back into the prism.

5   DISCUSSION

AW can avoid drying and humidity control may be very important. In many standards, more than 95%RH is regulated. However, even beyond 95%, slight change in humidity can modify ASR expansion significantly, as shown in the block expansion test of [2]. Since different drying behaviours occur depending on the alkali content can be avoided by AW, the problem of determining the threshold alkali content for ASR expansion can be resolved. Therefore, AW is an excellent way to control moisture supply in maximum condition of moisture supply.

Alkali leaching also can be effectively countered by AW. However, some alkali uptake accompanying ASR may be inevitable even if the pH of the wrapping cloth is the same as that of the pore solution of concrete without ASR. However, it is possible to know how much alkali content exists in the prism at the end of the test by measuring alkali content in the water at the bottom of the chamber and in the wrapping cloth but by reducing the amount of alkali solution in wrapping cloth, the amount of alkali uptake by concrete prisms may be decreased. This is a significant difference from the traditional CPT without AW. Thus, with AW-CPT, it is possible to discuss the effects of various factors such as temperature, alkali amount, and others affecting ASR.

6   CONCLUSIONS

To control alkali leaching and drying during CPT, alkali wrapping (AW) is applied. The effects of AW on ASR expansion, mass change, alkali leaching are shown. AW can avoid drying of prisms and provide greater expansion. Different drying degrees depending on the difference in alkali content were shown clearly; this difference also can be avoided by AW. AW can reduce alkali leaching to a very low level. However, alkali uptake by prisms from the cloth appears inevitable. Even in this case, the final alkali content can be determined by the analysis of alkali content in the cloth by hot water extraction. AW-CPT is a reasonable method as a performance test for ASR expansion estimation.

7 ACKNOWLEDGEMENT

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TABLE 1: Analysis results of wrapping cloth.

Aggregate comp.-FA-Temp/ °C	Initial alkali content/ kg/m³	Alkali in cloth by hot water extraction/ mg		Alkali in cloth by HCl extraction/ mg		Total alkali in cloth/ mg		Alkali content at 45 weeks/ kg/m³	Increase in alkali		Estimated silica content* in cloth/ g	Expansion at 45 weeks/ %
		Na	K	Na	K	Na	K		kg/m³	Ratio		
N30-60	3.00	321.8	26.4	14.6	148.7	336	175	3.38	0.38	0.13	0.772	0.110
N30-60	2.50	212.9	28.8	6.4	62.0	219	90.8	2.91	0.41	0.16	1.11	0.088
N30-60	2.00	98.5	23.1	2.5	18.1	101	41.2	2.41	0.41	0.21	-0.09	0.061
N30-60	4.25	620.9	26.4	64.7	116.5	686	143	6.81	1.21	0.22	3	0.162
N30-60	5.50	801.1	34.5	172.9	44.0	974	78.5	6.58	1.08	0.20	4.37	0.173
N30-40	5.50	1546.4	114.7	61.4	30.1	1608	145	4.58	0.33	0.08	1.33	0.131
N30-40	4.25	1068.7	106.4	24.4	17.6	1093	124	6.12	0.62	0.11	1.35	0.123
N30-40	3.00	545.5	105.2	-	-	546	105	5.48	-0.02	0.00	0.267	0.143
N30-20	5.50	1281.0	138.6	13.3	6.8	1294	145	3.95	-0.30	-0.07	0.46	0.097
N30-20	4.25	784.0	105.4	11.4	5.2	795	111	3.22	0.22	0.07	0.44	0.095
N30-20	3.00	389.8	82.6	7.3	3.9	397	87	5.78	0.28	0.05	0.012	0.096
N30-20	2.50	270.8	63.8	6.3	3.7	277	67.4	4.49	0.24	0.06	0.19	0.102
N30-FA15-60	5.50	618.7	38.8	11.2	45.3	630	84.0	3.37	0.37	0.12	0.84	0.094
N30-FA30-60	5.60	375.6	34.0	5.9	6.8	381	40.8	2.86	0.36	0.15	0.4	0.006
N30-FA30-60	5.50	506.4	45.1	3.6	8.1	510	53.2	6.45	0.95	0.17	0.22	0.004
T-fine	5.50	369.7	40.2	7.2	44.2	377	84.4	6.69	1.19	0.22	1.21	0.071
T100-60	5.50	801.6	30.8	87.1	89.7	889	120	6.18	0.68	0.12	2.84	0.067
T100-60	4.75	393.7	20.8	8.0	47.2	402	68.1	5.66	0.91	0.19	1.44	0.037
T100-60	4.00	243.9	22.1	5.6	14.0	249	36.1	4.81	0.81	0.20	0.83	0.028
T100-60	3.00	160.8	19.5	3.0	3.6	164	23.0	3.63	0.63	0.21	-0.75	0.020
T100-40	5.50	1061.5	77.5	65.0	39.3	1127	117	5.95	0.45	0.08	1.66	0.069
T100-40	4.75	553.5	55.0	9.0	20.9	563	75.9	5.50	0.75	0.16	0.79	0.066
T100-40	4.00	426.5	65.7	7.9	5.9	434	71.6	4.61	0.61	0.15	0.25	0.064
T100-20	5.50	637.0	87.9	3.8	0.6	641	88.5	6.44	0.94	0.17	-0.11	0.008

*Increase in cloth weight after hot water and HCl extraction was assumed to be silica. When C-S-H or K-S-H that are extracted by HCl is included, silica in these phases are ignored.

TABLE 2: Detailed analysis of wrapping cloth of aggregate N with 3.0 kg/m³ of alkali content.

Temp. (°C)	Treatment	Na (mmol)	K (mmol)	Si (mmol)	Ca (mmol)	Al (mmol)	OH- (mmol)	Na + K (mmol)
60	Hot water extraction	13.99	0.68	7.36	0.14	-	14.57	14.67
	HCl extraction	0.63	3.81	2.00	25.04	0.21		
	HF dissolution	-	-	27.55	-	0.06		
	Total	14.55	4.49	35.95	25.17	0.24		
40	Hot water extraction	23.72	2.70	14.93	1.30	0.00	22.77	26.41
	HCl extraction	-	-	0.46	11.04	0.25		
	HF dissolution	-	-	9.54	-	-		
	Total	23.64	2.70	23.97	12.32	0.23		
20	Hot water extraction	16.95	2.12	7.63	0.08	-	19.13	19.06
	HCl extraction	0.32	0.10	6.62	9.48	0.19		
	HF dissolution	-	-	0.44	-	0.08		
	Total	17.19	2.22	13.74	9.55	0.24		

TABLE 3: Distribution of three major elements in each phase based on the results in Table 2.

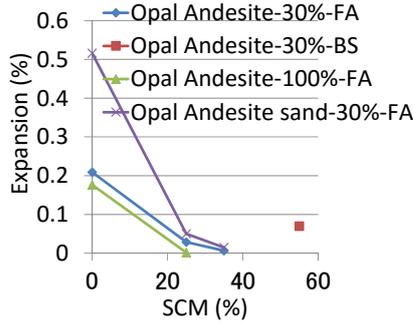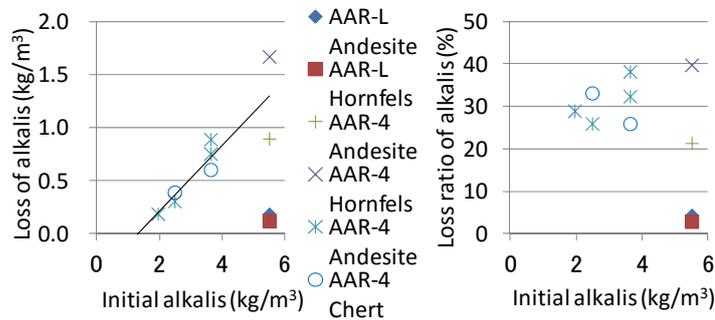| Temp. (°C)	Si (mmol)			Ca (mmol)		Na (mmol)	K (mmol)	
	ASG	C-S-H	Silica	C-S-H	Calcite	ASG	ASG	K-S-H
60	7	2	28	0	25	14	1	4
40	15	0.5	10	0	11	24	3	0
20	8	7	0.4	9	0	17	2	0

FIGURE 1: Examples of CPT (10 × 10 × 40 cm and wrapped with wet cloth) with alkali content of 5.5 kg/m³ and at 60 ºC. Modified from [3].


(a) Loss amount of alkalis

(b) Loss ratio of alkalis

FIGURE 2: Alkali leaching estimated by alkali content in cloths and the bottom water in containers during CPT at 60 ºC. AAR-4: 7.5-7.5-25 cm prism without wrapping. AAR-L: 10-10-40 cm prism wrapped with wet cloth [5].
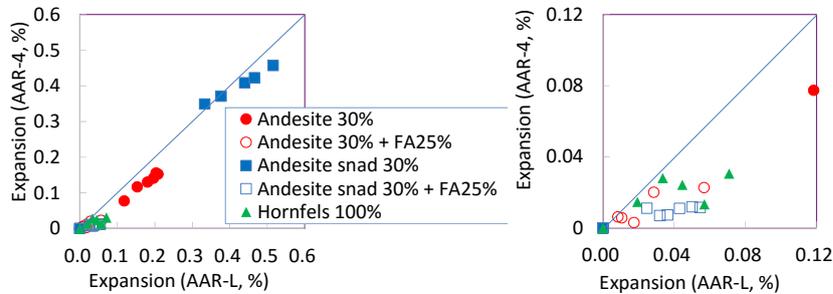
(a) Overall correlation

(b) Magnified correlation

FIGURE 3: Comparison of CPT results without wrapping (AAR-4) and with wet wrapping (AAR-L) from 10 to 26 weeks [3].
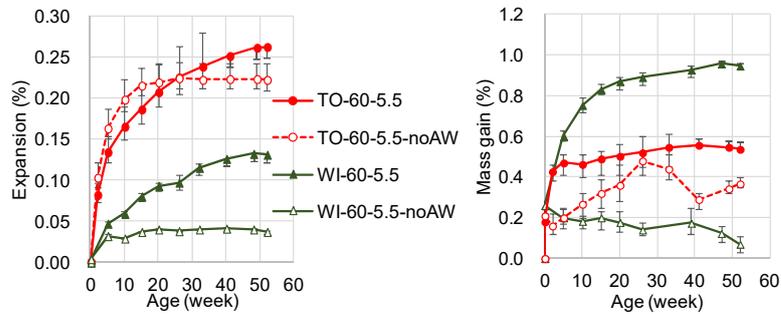
(a) Expansion

(b) Mass gain

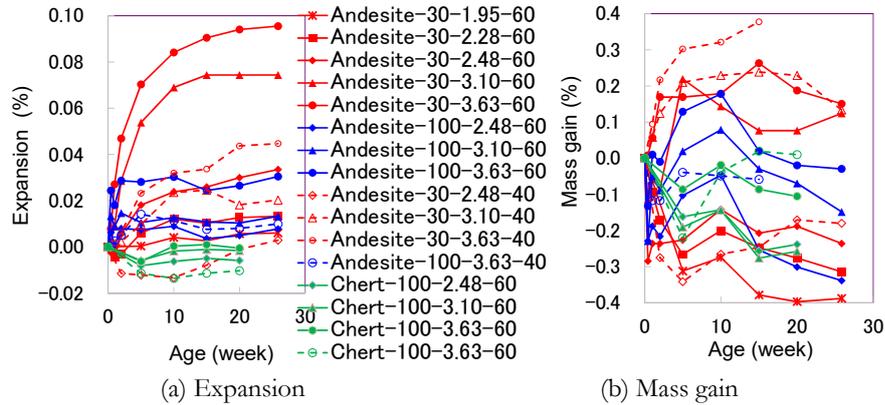FIGURE 4: Comparison of CPT with and without AW[12].

(a) Expansion

(b) Mass gain

FIGURE 5: Expansion and mass changes in CPT without AW.
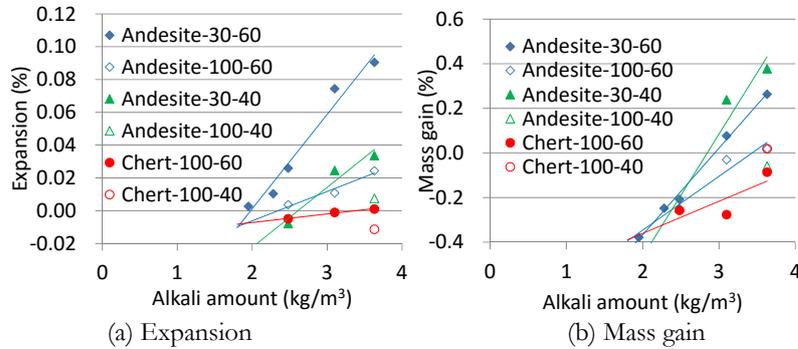Legend: aggregate type, aggregate content (%), alkali content (kg/m³), curing temperature (°C)

(a) Expansion

(b) Mass gain

FIGURE 6: Correlations between alkali content and expansion or mass gain at 26 weeks.

(a) Change by age (5.5kg/m³, 60°C) (b) Without AW (26 weeks) (c) AW-CPT(26 weeks)
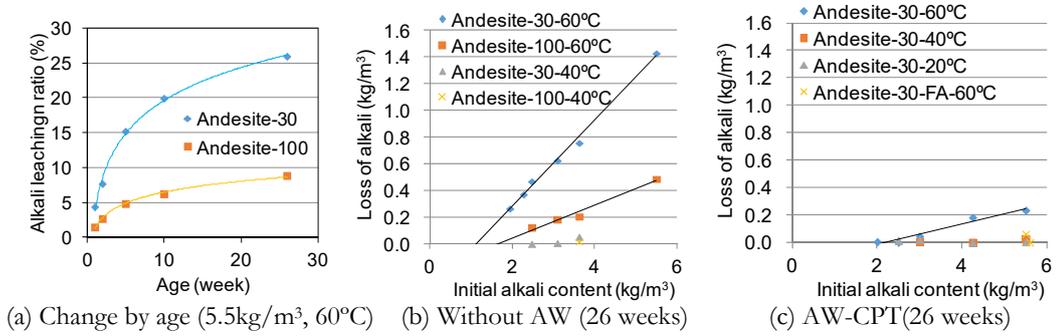
FIGURE 7: Alkali leaching from concrete prisms measured by alkalis leached in containers.

(a) Initial and final alkali content (b) Na and K content in cloth (c) Initial alkali and dissolved silica
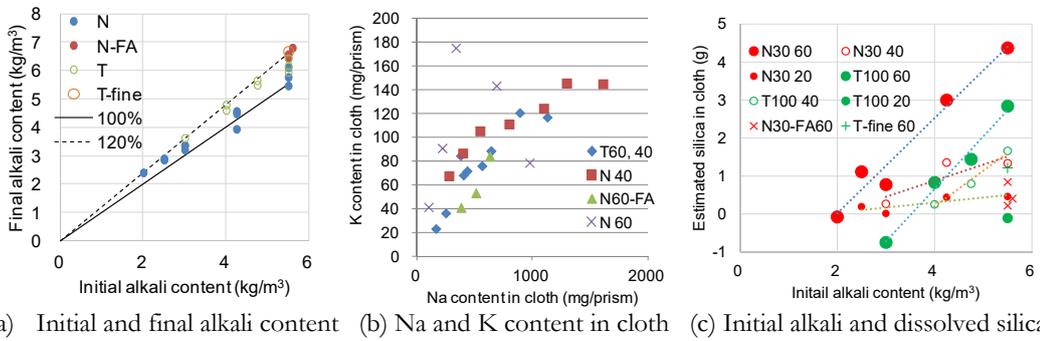
FIGURE 8: Analysis results of wrapping cloth.

(a) Aggregate T, alkali = 3.00 kg/m³, 60 °C   (b) Aggregate N, alkali = 2.00 kg/m³, 60 °C.

FIGURE 9: Wrapping cloth adhered to prisms.

(a) Silica content and expansion (b) Alkali and silica contents (c) Alkali content and expansion
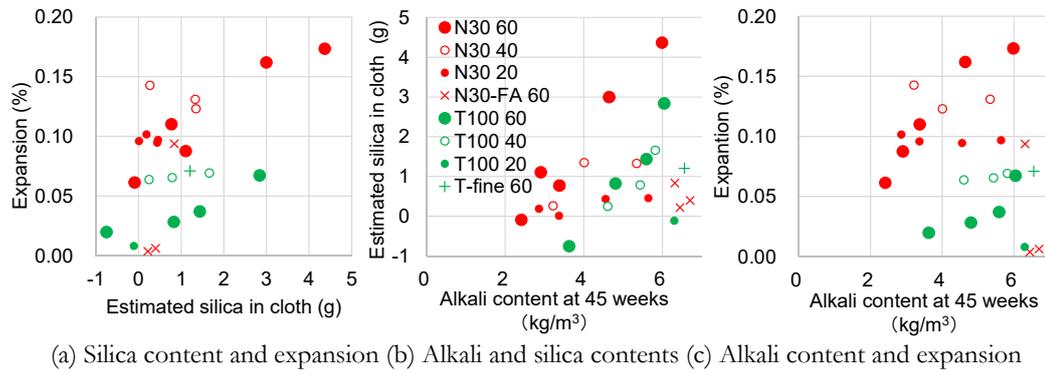
FIGURE 10: Correlations among chemical composition of wrapping cloth, estimated alkali content in prisms and expansions at 45 weeks.

Legend: aggregate type, aggregate composition (%), fly ash addition, temperature (°C)