EXACT EFFECTS OF TEMPERATURE INCREASE AND ALKALI BOOSTING IN CONCRETE PRISM TESTS WITH ALKALI WRAPPING

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Abstract

In a concrete prism test (CPT), expansion is accelerated by increasing temperature and alkali contents. Alkali leaching and drying are two problems with the CPT. Strict evaluation of their effects independently has been difficult. Therefore, to solve these problems, concrete prisms are wrapped in cloth wetted with a solution of alkali having the same concentration as the pore solution in the concrete. In this study, various Japanese reactive aggregates such as andesite containing opal and/or cristobalite, chert containing chalcedony, and several types of slow expansive aggregate containing cryptocrystalline quartz are examined. The results indicate that, depending on the aggregate type, expansion and mass gain differed on the basis of temperature and alkali content variation. Some of the alkali–silica gel was lost from the prisms without causing expansion. A performance test result showed that accelerated test conditions of the CPT were modified depending on the reactivity of the aggregate.

KEYWORDS: alkali wrapping, temperature, alkali content, expansion, mass gain, concrete prism test.

1   INTRODUCTION

A concrete prism test (CPT) is a candidate for a performance test to quantitatively estimate alkali–silica reaction (ASR) expansion of concrete under various conditions. Several difficulties with the CPT have been reported such as alkali leaching, drying or unstable moisture supply, and dimension effects [1]. In particular, several studies have reported alkali leaching [2,3,4] but an effective solution has not been developed. The CPT as a performance test enables determination of the alkali threshold level for ASR expansion or evaluation of future expansion behavior. However, alkali leaching depends on the acceleration temperature and moisture supply, while drying depends on alkali content [5]. Therefore, if a CPT is conducted for various alkali contents, it is not easy to judge whether the results are affected by alkali content, drying, or alkali leaching.

Recently, a new method known as "alkali wrapping" (AW) of concrete prisms has been proposed to avoid alkali leaching and drying [6]. AW involves wrapping concrete prisms by cloth wetted with alkaline solution having the same pH as the pore solution in the concrete. Although the alkalinity of the wrapping cloth solution is equivalent to that of the pore solution of the concrete, due to the progress of ASR, some amount of alkali is consumed and alkali–silica gel (ASG) is formed, which are exchanged between the wrapping cloth and the prism. However, by AW, the alkali content and the moisture supply can be controlled as sufficient for the experiment. In this paper, in the application of AW in the CPT (AW-CPT), exact dependencies of ASR expansion on temperature and alkali content free from alkali leaching and drying are reported for various aggregate types. Further, the possibility of using the CPT to determine an alkali threshold for ASR expansion is discussed by comparing mass gains during the curing process.

2   MATERIALS AND METHODS
2.1   Aggregates

Eight types of Japanese reactive aggregates having caused damages in real structures and one type of non-reactive pure limestone were used as aggregates. Petrographic characteristics and alkali–

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silica reactivity, evaluated by various methods, are summarized in Table 1. Three aggregate types (labelled NT, OT, and IS) are rapidly expansive andesite of the Neogene that show a compositional pessimum effect of approximately 30%. These aggregates are popular in Japan. Four aggregates (labelled IW, EH, KG, and OD) are slow-expansive aggregate containing cryptocrystalline quartz such as sandstone, hornfels, and green schist. These do not show compositional pessimum effect. Another reactive aggregate, labelled TY, is chert containing chalcedony and cryptocrystalline quartz. The pessimum behavior has not been observed but the reactivity of this chert cannot be detected by the accelerated mortar bar test (e.g., ASTM C1260 or RILEM AAR-2) because of the size pessimum effect. By the RILEM AAR-5 method, this chert is judged as reactive.

The reactivity of rapid expansive andesite can be detected by all test methods. However, for slow reactive aggregates, there are discrepancies among test methods. As is known, the classic mortar bar test cannot detect reactivity. For these, RILEM AAR-4 accelerated 60 °C seems suitable.

2.2   Materials and mix designs

An ordinary Portland cement (OPC) mixture conforming to JIS A5211 was used. Its density was 3.16 g/cm³, alkali content was 0.61 mass% and the Blaine specific surface area was 3110 cm²/g. Regarding mix designs, the unit water content was 160 kg/m³ and the water to cement ratio was 0.50. The target air content was 4.5 ± 1.5%. Reagent NaOH was dissolved in water to achieve an alkali solution of a certain concentration, required to boost the total alkali contents from 2.0 to 5.5 kg/m³.

2.3   Measurements

According to the procedure of RILEM AAR-3, three 7.5 cm × 7.5 cm × 25 cm concrete prisms were cast. After 24 h, the prisms were demolded and the base length and mass were measured. The concrete prisms were then immersed in water for 30 min and the masses were measured again.

As AW, 50 g of alkaline solution having the same alkali concentration (depending on the alkali contents from 2.0 to 5.5 kg/m³) was added to a piece of unwoven cloth, and each prism was wrapped with this cloth, which was then wrapped with thin plastic film to avoid material movement. Then, the three prisms in each level were contained in a sealed stainless steel box containing water in the bottom. The container was maintained in a humid chamber with a target temperature of 20, 38/40, and 60 °C. In ASTM and CSA, a storage temperature of 38 °C is used, but in Japan, 40 °C is historically used. In this study, a difference of 2 °C is considered small and is ignored in the discussions.

Containers were moved to a room of 20 ± 2.0 °C 24 h before each measurement. Once the wrapping cloth was removed, the length and the mass were measured. The mass of the cloth was measured and pure water was added up to the original mass. Then, the prisms were wrapped again with this mass-controlled cloth and thin plastic film and placed in containers.

3   RESULTS
3.1   General trend of expansion

Temperature and alkali content dependences of ASR expansion were examined in detail for aggregates NT and TY, and their expansion and mass gain behaviors are shown in Figure 1. For aggregates NT and TY, the expansion behaviors had characteristic similarity. At higher temperature, the expansion was initiated from early ages and tended to saturate rapidly, and there were strong alkali content dependences. At lower temperatures, the initiation of expansion was delayed and the expansion rate decreased, but expansion continued for a long time and exceeded the expansion rate at higher temperature at certain ages. At lower temperatures, the dependence on alkali content reduced considerably. There was almost no effect of alkali content at 40 °C. At 20 °C, several or tens of weeks were required for the onset of expansion. Less alkali content induced a longer time to initiate expansion, but the expansion continued for a longer term. The behavior of mass gain was very different from that of the expansion. Mass gains were greater at lower temperatures and alkali contents. The alkali dependence on mass gain was significant for every temperature, which is completely different from the behavior of expansion.

In Figure 2, behaviors of expansion and mass gain for other aggregates, OT, IS, IW, EH, and KG, are shown. Basic behavior of rapid expansive aggregates OT and IS was similar to that of aggregates NT and TY. Higher temperatures and alkali contents result in a more rapid expansion and lower mass gain. However, for slow reactive aggregates IW, EH, and KG, although expansion behaviors were similar to those of rapid expansive aggregates showing dependences on temperature and alkali content, mass gain behaviors were not so different compared to rapid expansive aggregates.

3.2   Effects of alkali content

Alkali content effects on expansion and mass gain for aggregates NT and TY at each age are shown in Figure 3, and those for aggregates OT, IW, and EH are shown in Figure 4. For NT, the alkali threshold for expansion at 60 °C can be determined as 1.0–1.5 kg/m³. However, at lower temperatures, lower alkali contents resulted in higher expansion at later ages and no alkali threshold was observed in the range of this study. For aggregates TY, OT, and EH, the situation was similar to that of aggregate NT. Only for IW, the alkali threshold can be determined as 2.5 kg/m³, but this is the value only at 60 °C and it is not clear if the value can be applied at lower temperatures. Although the CPT is expected as a performance test, using it for the determination of an alkali threshold value for ASR expansion does not seem so straightforward.

The alkali content dependences on mass gains can be classified into three types: less mass gain at a higher alkali content for NT, TY, and OT; higher mass gain at a higher alkali content for EH at 38 °C; and the mixture of the first and the second types for IW and EH at 60 °C. In earlier ages, positive correlations were found such as for the second type but at later ages, the correlations changed to negative, for example, in the first type. In general, mass gains are caused by cement hydration and ASR. Although ASR is expected to be accelerated at a higher temperature and elevated alkali content, the results were different. Therefore, some other mechanisms may have contributed.

3.3   Effects of temperature

Temperature dependences of expansion and mass gain for aggregates NT and TY are shown in Figure 5, and those for aggregates OT, IW, and EH are shown in Figure 6. The temperature pessimum effects have been reported [7]. The ASR expansion became highest at 40 °C. Such behaviors were observed for aggregate NT with alkali contents 3.0 kg/m³ and, to some extent, 2.5 kg/m³ and for aggregate TY with alkali contents 5.5 kg/m³ and possibly 4.0 kg/m³ and 4.75 kg/m³. For aggregate NT, with alkali contents 5.5 kg/m³ and 4.25 kg/m³, temperature pessimum behaviors were not observed. For other aggregates, OT, IS, IW, EH, and KG, temperature pessimum behaviors were not detected. Regarding mass gain, for aggregates NT, TY, and OT, simple negative correlations between temperature and mass gain were observed, especially at later ages. Aggregate IS showed less sensitive but negative correlation. For late expansive aggregates IW, EH, and KG, temperature dependences on mass gain were not as strong at early ages. However, in the case of higher alkali content of 5.5 kg/m³, the correlations were slightly negative. In lower alkali content of 4.25 kg/m³, the correlations were slightly positive.

3.4   Combined effects of alkali content and temperature

Correlations of alkali content and temperature with expansion at 52 weeks for aggregates NT and TY are shown in Figure 7, and those for aggregates OT, IS, IW, EH, and KG are shown in Figure 8. From Figure 7, several characteristics are observed:
- For both aggregates NT and TY, as shown in Figure 7 (left), positive expansion dependencies on alkali content were observed only at 40 °C but not at 20 °C and 60 °C. Aggregate OT showed a similar behavior as shown in Figure 8 (right upper).
- For both aggregates NT and TY, as shown in Figure 7 (middle left), negative mass gain dependences on alkali content were observed at every temperature. For aggregate OT, as shown in Figure 8 middle left upper, a similar behavior was observed. However, for slow expansive aggregates IW and EH, shown in Figure 8 (middle left lower), almost no dependencies of mass gain on alkali content were observed.
- Temperature pessimum effects of expansion were observed for aggregate TY at all alkali contents, as shown in Figure 7 (middle right lower). However, for aggregate NT, as shown in Figure 7 (middle right upper), a temperature pessimum effect was observed at alkali contents less than 3.00 kg/m³. At higher alkali contents, the higher temperature resulted in higher expansion. There were no temperature pessimum behaviors for slow expansive aggregates IW and EH, as shown in Figure 8 (middle right lower). Simply, the higher temperatures resulted in the higher expansion.
- For both aggregates NT and TY, as shown in Figure 7 (right), and for aggregate OT, as shown in Figure 8 (right upper), negative dependences of mass gain on temperature were observed at all alkali contents. For slow expansive aggregates IW and EH, as shown Figure 8 (right lower), there was almost no dependence of mass gain on temperature.

3.5   Correlations between mass gain and expansion

Time variations in the correlations of mass gain and expansion are shown for aggregates NT and TY in Figure 9 (left and right, respectively); for aggregates OT and IS in Figure 10 (left); and for late expansive aggregates IW, EH, and KG in Figure 10 (right). In each combination of aggregate type,

temperature, and alkali content, there were positive correlations, although the degree of correlation and scattering positions differed greatly depending on combinations.

In Figure 9, there are two trends for aggregates NT and TY. One is a positive correlation shown as blue dashed line circles for less accelerating conditions. Mass gain resulted in expansion, although the position of the circle of TY is located in the lower mass gain position. This may be because AW-CPT, at mild acceleration conditions, was not carried out for aggregate TY. Another trend is a negative correlation shown as red line circles for the results at 60 °C. Although in each alkali content level, positive correlations were observed, as a whole, higher expansions were shown in lower mass gain. In Figure 10, correlations between mass gain and expansion for other aggregate types are shown. For rapid expansive aggregates OT and IS, trends similar to those of aggregate NT were observed. In relatively lower accelerated conditions, the correlation existed in the higher mass gain and in the lower expansion, shown as the blue dashed line area. For slow expansive aggregates, many of the data were located in the same blue dashed circles area, except the cases of acceleration at 60 °C.

4   DISCUSSION

The mass gain during accelerated curing with alkali wrapping is expected to be caused mainly by two reasons: cement hydration and ASG formation by absorbing water from the wrapped cloth. Both reactions consume water, and water is supplied continuously in the AW-CPT condition, which simulates the worst case for ASR. When a concrete prism was made using nonreactive pure limestone aggregate, containing an alkali content of only 5.5 kg/m³ and cured at 60 °, the mass gain was 0.45% mass at 26 weeks. Assuming the same cement hydration, obviously most of prisms recorded significantly higher mass increases, except aggregates OT, TY, and OT with relatively higher temperature and alkali contents as shown in Figures 1 and 2. In these prisms, significant amounts of ASG are considered to have issued from the samples, as suggested by the silica content measured in the wrapping cloth [6].

ASR expansion is expected to be caused by the formation of ASG in the aggregate. However, as shown in Figure 9, the results obtained in this study showed that the higher expansions are obtained with lower mass gains, for relatively higher reaction conditions, although the formation amount of ASG is expected to be greater in such conditions. There should be some mechanisms, and the ASG loss is expected to be the reason.

According to Ichikawa [8], one mechanism of ASR expansion is the expansive pressure accumulated in aggregate by forming an impermeable layer of C-S-H surrounding the aggregate by the exchange reaction between alkalis in ASG and Ca in cement paste. The amount of ASG itself is not directly correlated with ASR expansion, but the constrained ASG in the aggregate is important. When the reaction occurs in an aggregate with a higher rate of reaction, the amount of ASG is more but the ion exchange between alkali in ASG and Ca in cement paste will be less and the formation of an impermeable layer will be difficult. Even in this case, if the formation rate is sufficient, concrete will expand without forming an impermeable layer by generating expansive pressure of the viscous ASG to penetrate quickly in cement paste.

If ASR is caused by the two mechanisms—(1) sufficiently rapid ASG formation and (2) accumulation of ASG to generate expansive pressure in aggregate by the formation of an impermeable layer—then the results obtained in this study can be explained. For rapidly reactive aggregates, the rate of ASG formation is rapid at a higher temperature or alkali content and a significant part of ASG is expelled without causing expansion. On the other hand, for slow reactive aggregates and relatively mild acceleration conditions, there is sufficient time to form impermeable layers around the aggregate, and the correlation between mass gain and expansion is similar for various kinds of aggregate. These are the qualitative explanations of ASR expansion/mass gain dependences on temperature and alkali content dependence.

To obtain the results in shorter periods of time, higher temperature and more alkali boosting are required. However, for relatively higher reactive aggregates, such as Japanese reactive andesite of the Neogene and chert containing chalcedony of the Jurassic age, an acceleration temperature of 60 °C or alkali content of 5.5 kg/m³ is excessive, because the expansion mechanism becomes different from that observed in actual structures, in normal environmental conditions, except concrete members at high temperature. This excessive acceleration may provide one reason for the discrepancy between the CPTs in laboratory and field exposure conditions, at relatively low temperatures and without alkali boosting. Therefore, the acceleration condition has to be selected according to the reactivity of aggregate. At this moment, it is difficult to recommend suitable conditions, but several conditions such as 60 °C and 5.5 kg/m³, 38 °C and 5.5 kg/m³, 38 °C and 3.0 kg/m³ are recommended to be further examined and compared. With the combination of petrographic evaluations, for

aggregates containing highly reactive opal, chalcedony, cristobalite, and tridymite, less aggressive acceleration conditions should be selected, while for aggregates containing crypto-/micro-crystalline quartz, more severe acceleration conditions should be selected. The suitable acceleration condition may be those that generate 0.1 % expansion at one year.

To use the CPT as a performance test, several requirements, as given below, are extracted from the discussions in this study:

- Alkali wrapping is effective for preventing alkali leaching and drying.
- Determination of an alkali threshold content is not easy in every case.
- Temperature pessimum effects are limited, depending on aggregate reactivity, acceleration conditions, and evaluation age.
- Universal conditions for the CPT may be difficult to determine for every aggregate. For highly reactive aggregates, 60 °C and 5.5 kg/m^3 of alkali content is excessive but for slow expansive aggregate, these conditions may be suitable.

There is one possible solution utilizing the results of the AW-CPT for expansion estimation in the future, in various environmental conditions. Assuming an expansion curve, temperature and alkali content interdependencies of parameters describing the curve can be obtained by adapting the results of AW-CPT provided as in this study. Then, by calibrating the parameters to the conditions of interest, it is possible to estimate the expansion in future [9].

5 CONCLUSIONS

By applying alkali wrapping for concrete prism tests of ASR expansion, alkali leaching and drying during curing were avoided and the specific effects of temperature and alkali content on ASR expansion were investigated. Comparing expansion and mass gain behaviours, the mechanism of expansion were discussed.

Depending on aggregate types, the effects of temperature and alkali content are different. For rapidly expansive aggregate such as Neogene andesite and chert that includes chalcedony, there were negative correlations between mass gain and expansion suggesting extrusion of ASG. Test conditions of 60°C and 5.5 kg/m^3 may be too severe for this kind of highly reactive aggregate because this condition makes the expansion mechanism different from what is observed in field exposure. However, for slowly reactive aggregates, acceleration conditions of 60°C and 5.5 kg/m^3 may be suited to detect reactivity.

One important conclusion is the necessity to modify acceleration conditions in order to reproduce the same expansion mechanism in target structures.

6 ACKNOWLEDGEMENT

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TABLE 1: Characteristics of aggregates. [10,11,except NT,TY,LS]

Test methods	Aggregate type								
	Rapid expansive			Slow reactive				Unclear	No reactive
	TO	SI	NT	WI	HE	GK	DO	TY	LS
Origin	Hokkaido	Hokuriku	Tohoku	Kanto	Shikoku	Kyushu	Chubu	Chubu	Kyushu
Rock type	Andesite	Andesite	Andesite	Sandstone	Hornfels	Green schist	Hornfels	Chert	Limestone
Reactive minerals	trid, v-glass	crist., v-glass	opal, crist., v-glass	crypt-qz	crypt-qz	crypt-qz	crypt-qz	chalcedony, crypt-qz	no
Damage example	Yes	Yes	Yes	Unknown	Yes	Yes	Yes	Yes	No
Density (g/cm³)	2.69	2.62	2.52	2.64	2.7	2.73	2.66	2.6	2.71
Absorption (%)	1.52	1.59	2.33	0.82	0.52	0.81	0.71	1.07	2.7
Chemical Sc/Rc	Harmful 637/100	Harmful 447/170	Harmful 672/207	Harmful 29/24	Harmless 32/36	Harmless 17/50	Harmless 16/109	Harmful 158/2	Harmless 1/8
JIS mortar bar	Harmful 0.415%	Harmful 0.216%	Harmful 0.189%	Harmless 0.038%	Harmless 0.069%	Harmless 0.022%	Harmless -0.004%	Harmful 0.100%	Harmless 0.004%
RILEM AAR-2	Harmful 0.54%	Harmful 0.40%	Harmful 0.50%	Harmful 0.23%	Harmful 0.30%	Harmful 0.23%	Unclear 0.12%	Harmless 0.04%	Harmless 0.08%
RILEM AAR-3 AW	Harmful* 0.242%	Harmful* 0.205%	Harmful* 0.140%	Harmful 0.051%/26w	Harmful 0.055%/26w	Harmless 0.046%	—	Harmful 0.070%	—
RILEM AAR-4 AW	Harmful* 0.207%	Harmful* 0.196%	Harmful 0.170%	Harmful 0.093%	Harmful 0.112%	Harmful 0.086%	Harmful 0.057%	Harmful 0.061%	Harmless 0.013%
RILEM AAR-4	Harmful* 0.219%	—	Harmful 0.06%	Harmful 0.038%	—	—	Harmless 0.013%	—	—

Crist: cristobalite, tri: tridymite, v-glass: volcanic glass, crypt-qz: cryptocrystalline quartz.
RILEM AAR-2: harmless <0.20%, unclear <0.10% at 14 days.
RILEM AAR-3 AW: harmless <0.05% at 1 year.
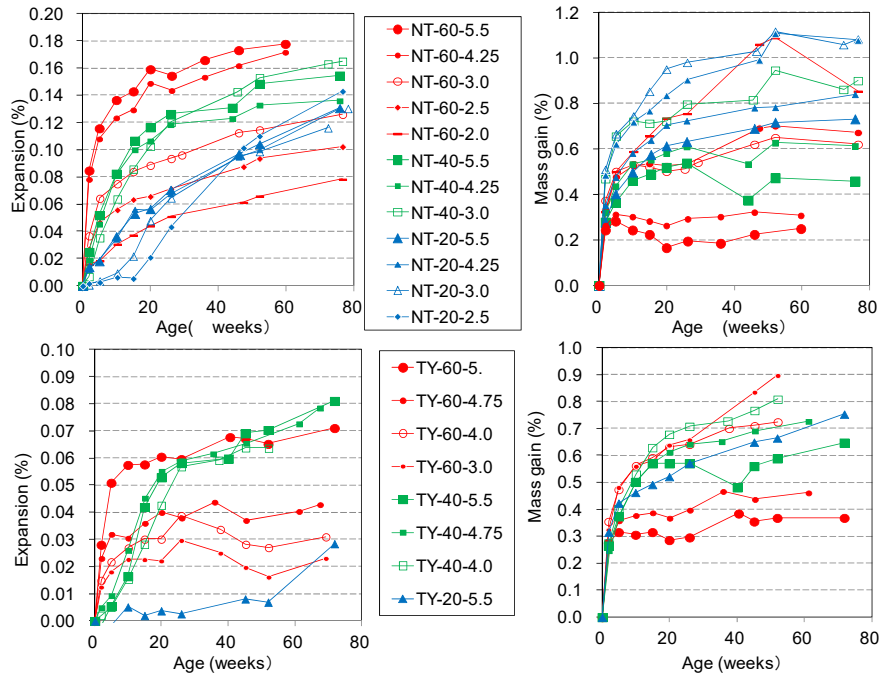RILEM AAR-4, AAR-4 AW: harmless <0.03% at 20 weeks

FIGURE 1: Expansion and mass gain of aggregates NT and TY.
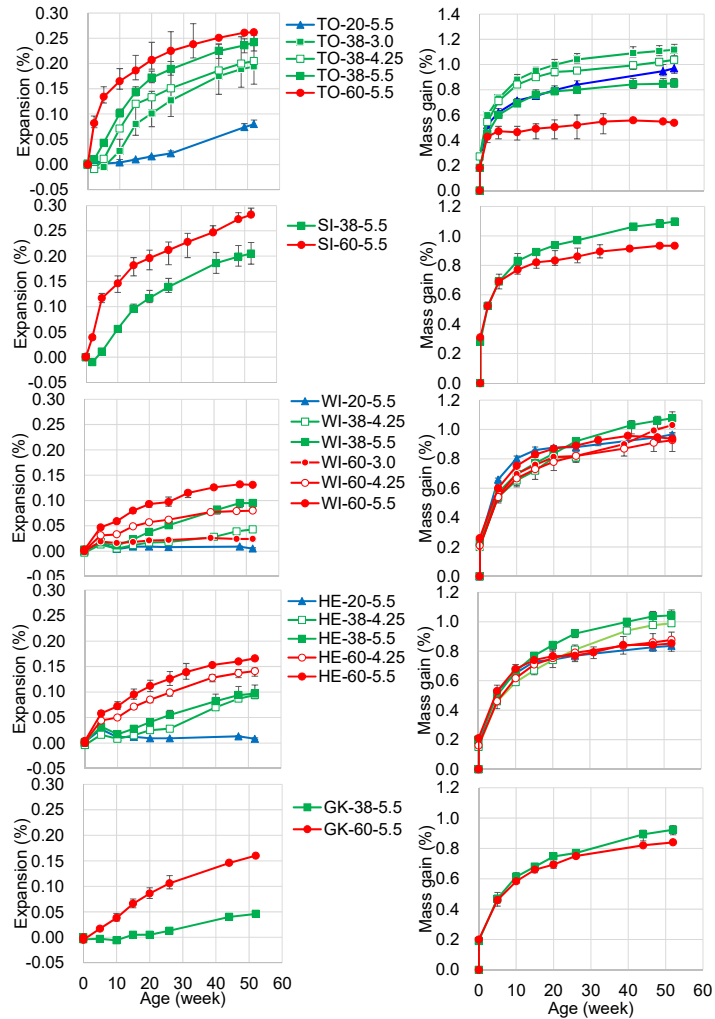

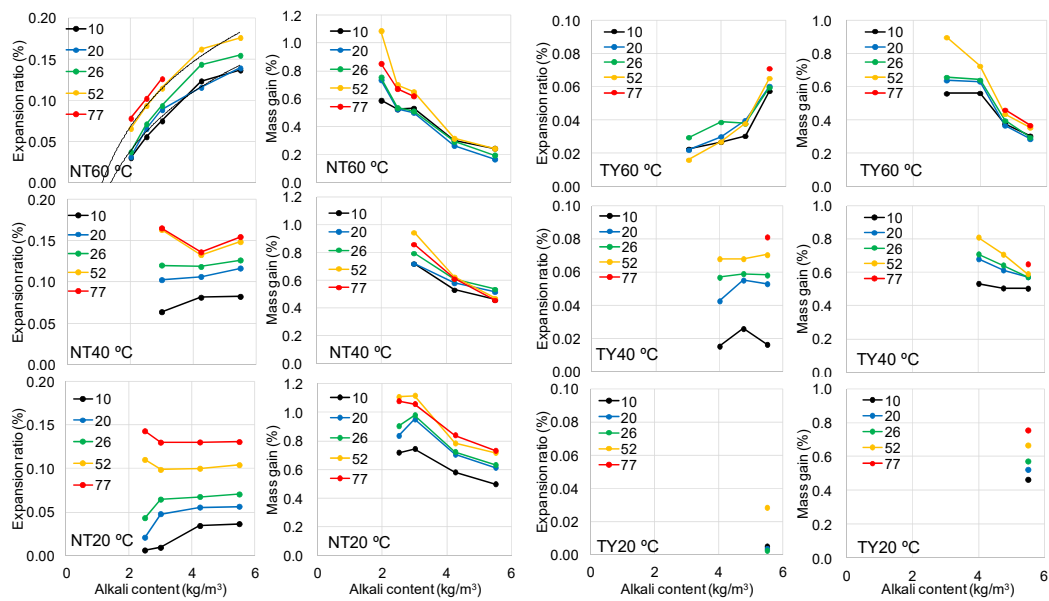FIGURE 2: Expansion and mass gain of aggregates OT, IS, IW, EH, and KG. [11]

FIGURE 3: Alkali content dependence on expansion and mass gain of aggregates NT and TY. Legend: Age (days).
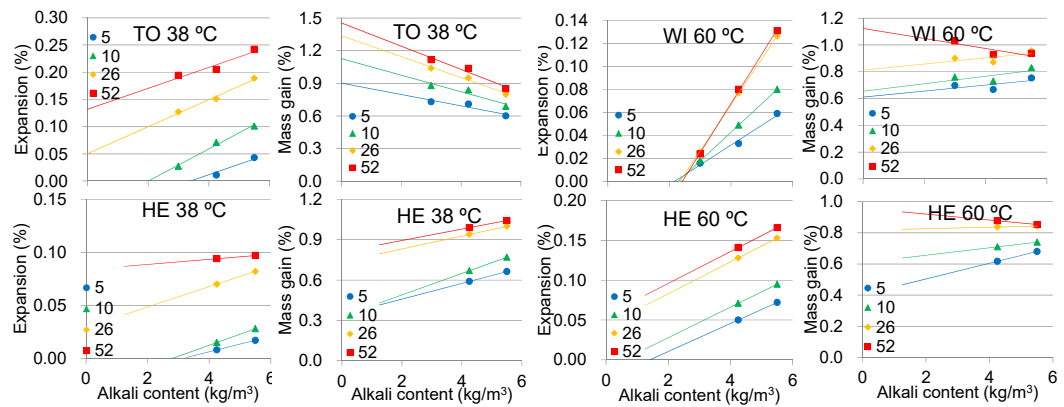

FIGURE 4: Alkali content dependence on expansion and mass gain of aggregates OT, IW, and EH. Legend: Age (days). [11]
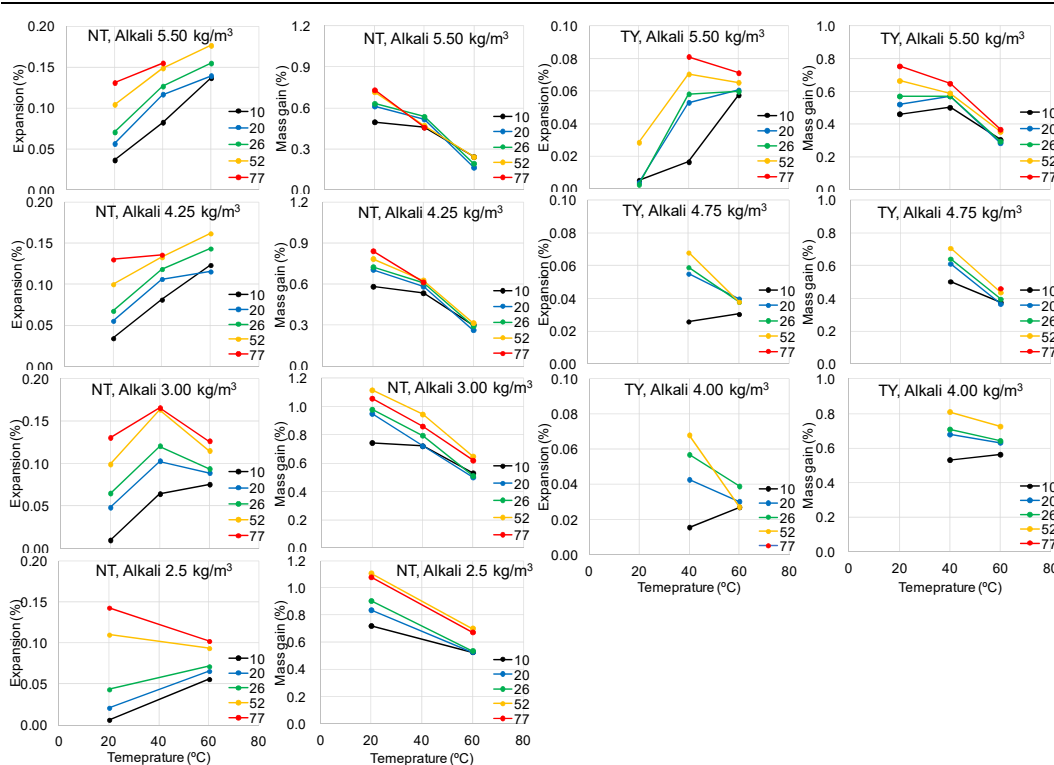
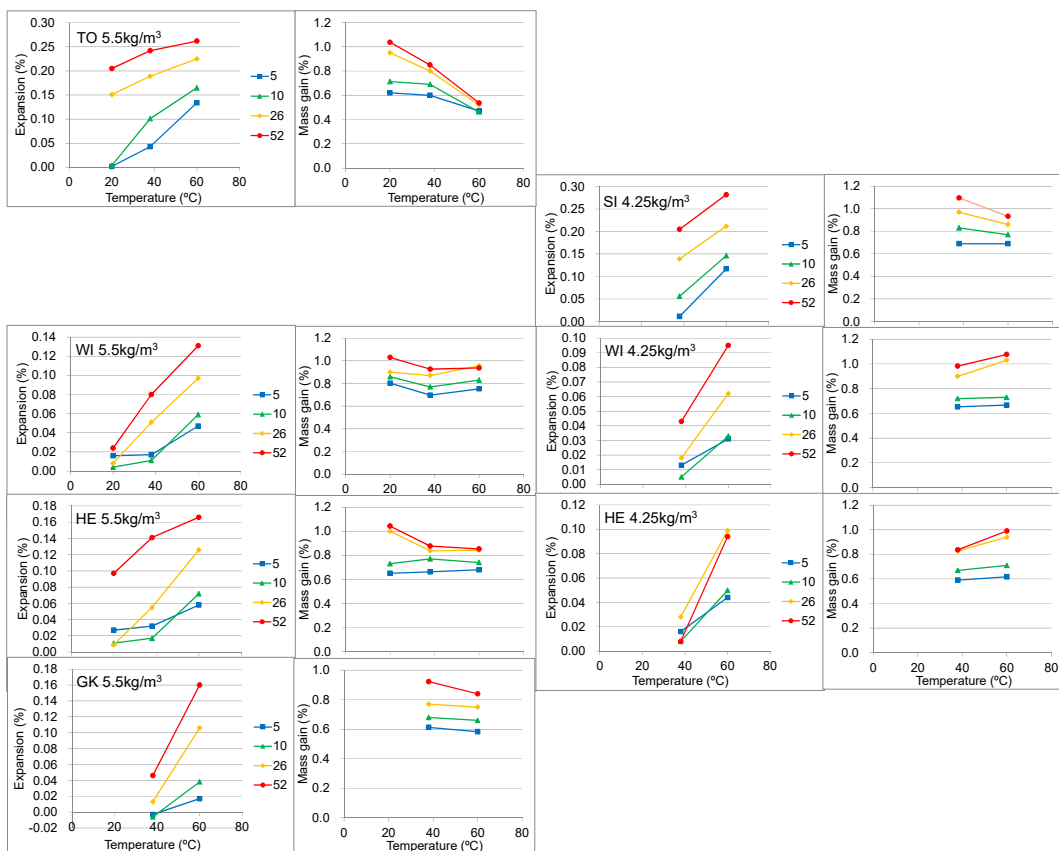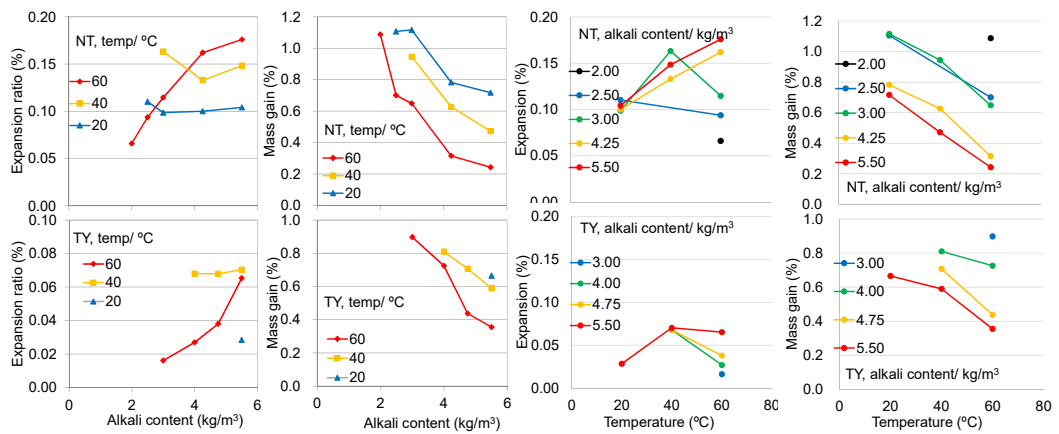FIGURE 5: Temperature dependence on expansion and mass gain of aggregates NT and TY. Legend: Age (days).

FIGURE 6: Temperature dependence on expansion and mass gain of aggregates OT, IW, and EH. Legend: Age (days).

[11]

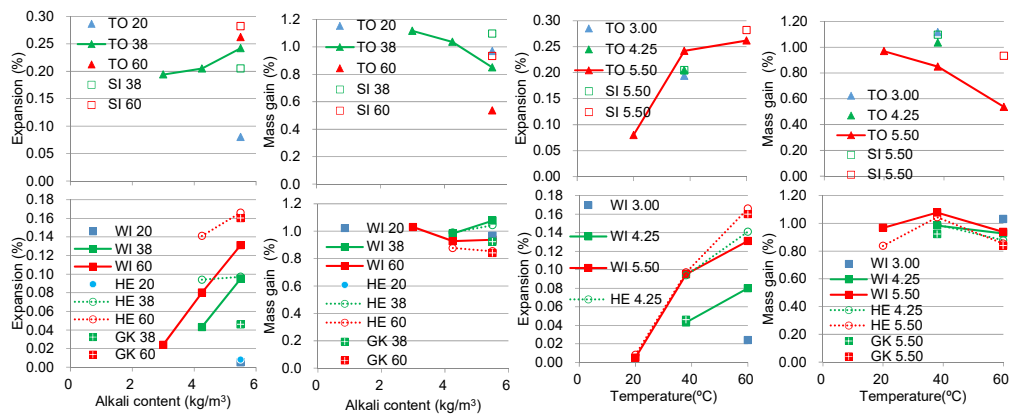FIGURE 7: Correlations of alkali content and temperature with expansion for aggregates NT and TY at 52 weeks.

FIGURE 8: Correlations of alkali content and temperature with expansion for aggregates OT, IS, IW, EH, and KG at 52 weeks. [11]
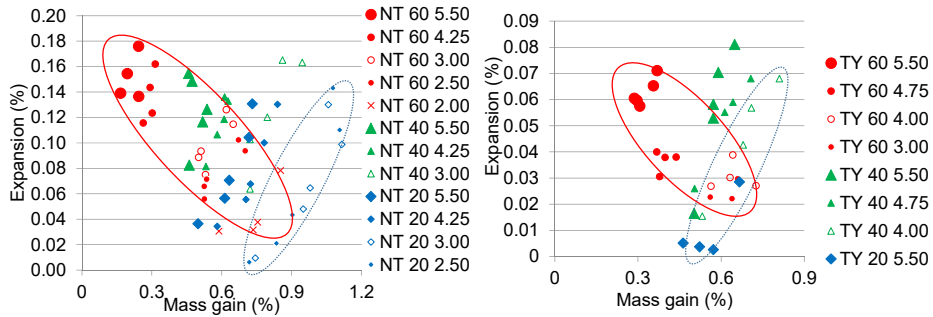

FIGURE 9: Time variations in the correlations of mass gain and expansion for aggregates NT and TY (10–72 weeks).
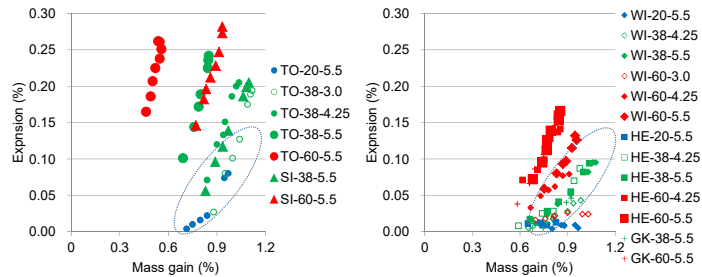Legend: Aggregate type -Temperature (°C) - Alkali content (kg/m³).

FIGURE 10: Time variations in the correlations of mass gain and expansion for aggregates OT, IS, IW, EH, and KG (10–52 weeks). [11]
Legend: Aggregate type -Temperature (°C) - Alkali content (kg/m³).