

EFFECTS OF ACCELERATED TEST CONDITIONS ON ASR EXPANSION OF CONCRETE CORE

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Abstract

The kinds of solution for immersion of the specimens (NaOH solution and NaCl solution), the solution concentration, and the storage temperature were selected as experimental parameters to examine their effects on ASR expansion of concrete.

The following results were obtained from experiments:

(1) ASR expansion became small when the concentration of the solution rose excessively at low storage temperature, but it increased with rising concentration of the solution at high storage temperature. (2) ASR expansion became small when the storage temperature rose excessively in low concentration of the solution, but it increased with rising storage temperature in high concentration of the solution. (3) The specimen immersed in the NaOH solution generated larger expansion at the early stage than the specimen in the NaCl solution. The specimen immersed in a NaOH solution of 1 mol/l at 60°C generated the largest expansion at the early stage.

Keywords: ASR expansion, accelerated curing, storage temperature, solution concentration

1 INTRODUCTION

When such appropriate remedial measures as repair and strengthening are conducted for concrete structures that have deteriorated due to alkali-silica reaction (ASR), their deterioration situation must be understood and future deterioration must be accurately predicted. The standard of the Japan Concrete Institute (JCI-DD2) [1] is generally conducted as a test to judge whether a concrete structure, which has deteriorated due to ASR, will suffer deleterious expansion (residual expansion) in the future. JCI-DD2 might underestimate the residual expansion of a concrete structure under an environment where the alkali is supplied from the outside because JCI-DD2 does not correspond to environments where seawater, air-borne chlorides, deicing salts, etc. penetrate concrete and promote ASR. Therefore, recently under such an environment, attempts have applied an accelerated test condition of ASTM C 1260 [2] (immersing the specimen in a NaOH solution of 1 mol/l at 80°C) or a saturated NaCl bath method [3] (immersing the specimen in a saturated NaCl solution at 50°C) to a test method to judge the residual expansibility of the concrete core obtained from the structures [4]. In such tests, ASR is accelerated because NaOH or NaCl permeate the specimens from the NaOH or NaCl solutions, increasing the storage temperature. When such an accelerated test is conducted, it is important to set the accelerated test conditions after clarifying their effects on ASR expansion.

In the present study, the kinds of solution for immersion of the specimens (NaOH solution and NaCl solution), the concentration of the solution, and the specimen storage temperature were selected as experimental parameters. Their effects on the ASR expansion of concrete were examined. The present paper reports the results of examining the effects of those experimental parameters on the ASR expansion of concrete.

2 OUTLINE OF EXPERIMENT

2.1 Materials

The following materials were used in the present experiment: ordinary portland cement (0.62% Na₂O_{eq}, ratio K₂O/Na₂O=1.5); non-reactive fine aggregate (saturated surface-dry particle density 2.64 g/cm³); non-reactive coarse aggregate (saturated surface-dry particle density 2.73 g/cm³); and

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reactive coarse aggregate (saturated surface-dry particle density 2.60g/cm³). The reactive coarse aggregate was andesite judged deleteriously reactive by chemical method (JIS A 1145) and mortar bar method (JIS A 1146). NaCl was used to adjust the alkali content of the concrete. NaOH and NaCl immersion solutions were prepared from reagent grade materials.

2.2 Mixture proportions of concrete

The mixture proportions of the concretes are shown in Table 1. Its water-to-cement ratio (W/C) was 0.65, and its alkali content was 8kg/m³, which was adjusted by adding NaCl to the water mixture on the assumption that sea water or deicing salt had penetrated it. The W/C of 0.65 is the upper limit of the W/C of general concrete structures in the standard specifications for concrete structures of the Japan Society of Civil Engineers. On the other hand, the upper limit of the W/C of marine concrete is in the range from 0.45 to 0.50. In consequence, we also are examining a concrete specimen of W/C=0.45 now. Additionally, in the standard specifications for concrete structures of the Japan Society of Civil Engineers, the lower limit of the Cl⁻ concentration in the rebar corrosion is 1.2kg per 1m³ of concrete. Therefore, it is considered that the rebar corrodes in the concrete with an alkali content of 8kg/m³ Na₂O_{eq}. (In this instance, the Cl⁻ concentration is about 7 kg per 1m³ of concrete.). The coarse aggregate used was a mixture of 60 mass% reactive and 40 mass% non-reactive aggregates. The air content of the concrete was adjusted 4.5±1.5% by adding an air-entraining agent to the water mixture.

2.3 Experimental conditions

Table 2 shows the experiment conditions. The NaOH and NaCl immersion solutions were used at concentrations of 0.5, 1, and 2 mol/l. The concrete specimens immersed in the NaOH and NaCl solutions were stored at 40, 60, and 80°C. The dimension of each concrete specimen (cylinder) was Ø75×150 mm.

2.4 Experimental method

Figure 1 shows a flow chart for the process of the experiment carried out in the present study. After demoulding, the concrete specimens were covered with damp cloths and plastic wrap and cured at 20° for 35 days. After curing, the specimens were tightened in stainless bands which attached gauge plugs to measure their length changes. The distance of the two gauge plugs was 100 mm. Figure 2 shows an outline of the specimen. After measuring their initial length (a distance of two gauge plugs), the specimens were immersed in NaOH or NaCl solutions with given concentrations (0.5, 1, and 2 mol/l) and stored in a thermostatic chamber (40, 60, and 80°C). Then the length changes of the specimens were measured in the given storage period. The length changes were measured after the specimens were removed from the thermostatic chamber and put in a constant temperature room of 20°C for 24 hours, where the temperature of each specimen was decreased to 20°C. In this case, the specimens remained immersed in the NaOH or NaCl solutions.

In addition, accelerated curing tests of the concrete specimens covered with damp cloths and plastic wrap and cured at 20°C for 35 days after demoulding were performed under two accelerated curing conditions of JCI-DD2 (40°C, RH 100%) and the saturated NaCl bath method (immersing the specimens in a saturated NaCl solution at 50°C). In the JCI-DD2, the specimens were covered with damp cloths, sealed in a plastic bag and stored in a thermostatic chamber at 40°C. In the JCI-DD2 and the saturated NaCl bath method, the length changes of the specimens were measured after the specimens were removed from the thermostatic chamber and put in a constant temperature room of 20°C for 24 hours. In this case, the specimens in JCI-DD2 remained covered with damp cloths and sealed in the plastic bag. On the other hand, the specimens in the saturated NaCl bath method remained immersed in the saturated NaCl solution.

3 RESULTS

3.1 JCI-DD2 and saturated NaCl bath method

Figure 3 shows the expansion over time of the specimens on which the JCI-DD2 and the saturated NaCl bath method were performed. Specimen expansion was 0.50% and 0.64% at a 26-week storage period, respectively. Specimen expansion in both methods was almost identical until the 16th week. Specimen expansion in the saturated NaCl bath method became larger than the specimen in the JCI-DD2 over 16 weeks due to higher temperature and the larger alkali content of the specimen that had penetrated the NaCl solution.

3.2 ASR expansion behavior of specimens immersed in the NaOH solution

Figures 4 to 7 show the relationship between the expansion of specimens immersed in the NaOH solutions, the concentration of the NaOH solutions, and storage temperature at 4, 8, 13, and 26 weeks. The expansion of specimens stored at 40°C decreased with the rising concentration of the NaOH solutions in every storage period. When the storage temperature was 60°C, the expansion of the specimen immersed in the 1 mol/l NaOH solution was maximum, whereas the specimen immersed in the 2 mol/l NaOH solution was minimum in every storage period. The expansion of specimens stored at 80°C increased with rising NaOH concentrations in every storage period.

For specimens immersed in NaOH solutions of 0.5 mol/l and 1 mol/l, expansions were maximum when stored at 60°C. When the specimens were immersed in a NaOH solution of 2 mol/l, their expansion increased with rising storage temperature: the expansion of specimens stored at 80°C was the largest.

Within the bounds of the present experiment, the combination of the accelerated curing condition with the largest expansion of the specimen at the early stage (4 weeks) was the combination of the 1mol/l NaOH solution and the storage temperature of 60°C. On the other hand, after a long term (26 weeks) passed, the combination of the accelerated curing conditions with the largest expansion of the specimen was the combination of the 2mol/l NaOH solution and the storage temperature of 80°C.

3.3 ASR expansion behavior of specimens immersed in NaCl solution

For the specimen immersed in the NaCl solution, Figures 8 to 11 show the relationship between the expansion, the concentration of the NaCl solution, and storage temperature at 4, 8, 13, and 26 weeks. This relationship is not clear at 4 weeks because the specimen expansion is too small. In storage periods of 8, 13 and 26 weeks for the specimen stored at 40°C, the expansion of the specimen immersed in 1 mol/l NaOH solution is maximum. For the specimens of 60°C and 80°C, the expansion increased with greater concentration of NaCl solution.

The expansion of the specimens immersed in the 0.5 mol/l and 1 mol/l NaCl solutions decreased with rising storage temperature. On the other hand, for the specimen immersed in the 2 mol/l NaCl solution, expansion increased with storage temperature.

For the specimen immersed in the NaCl solution, the combination of the accelerated curing condition with the largest expansion of the specimen at the early stage (4 and 8 weeks) was the 2 mol/l NaCl solution and the storage temperature of 60°C. On the other hand, after a long term (26 weeks) passed, the combination of the accelerated curing condition with the largest expansion was the 2 mol/l NaCl solution and the storage temperature of 80°C.

3.4 Comparison of expansions of specimens immersed in NaOH and NaCl solutions

Figures 12 to 14 show the expansion of the specimen immersed in NaOH and NaCl solutions at 40°C over time. When the solution concentration was 0.5 mol/l, for the specimen immersed in the NaOH solution, the expansion began to generate quickly and was larger than the specimen immersed in the NaCl solution. When the solution concentrations were 1 mol/l and 2 mol/l, the expansion of the specimen immersed in the NaOH solution began to generate quicker than the specimen immersed in the NaCl solution. The expansion of the specimen immersed in NaOH solution was larger than the specimen immersed in the NaCl solution until 14 weeks, and subsequently the specimen immersed in the NaCl solution became larger. For the specimens stored at 60°C and 80°C shown in Figures 15 to 20, the expansion of the specimen immersed in the NaOH solution began to generate quicker than the specimen immersed in the NaCl solution. When the solution concentrations were 0.5 mol/l and 1 mol/l, the expansion of the specimen immersed in the NaOH solution was greater than the specimen immersed in the NaCl solution. On the other hand, for the 2 mol/l solution, the expansion of the specimen immersed in NaOH solution was larger than the specimen immersed in the NaCl solution when stored at 60°C until 12 weeks and when stored at 80°C until 13 weeks. However, the expansion of the specimen immersed in the NaOH solution was smaller than the specimen immersed in the NaCl solution on and after those storage periods.

4 DISCUSSION

As shown in Section 3.2, for specimens immersed in NaOH solution, ASR expansion became small when the solution concentration rose excessively at low storage temperature (40°C). At high storage temperature (80°C), ASR expansion increased with rising solution concentration. As above, the relationship between ASR expansion and the concentration of the NaOH solution reflected storage temperature differences. When a highly concentrated NaOH solution permeates a specimen,

its expansion increases because ASR is promoted, and consequently a large quantity of alkali-silica gel (ASR gel) is produced that depends on the increase of the specimen's alkali content. On the other hand, when there is a large amount of alkali, the expansion pressure of the ASR gel decreases because the $\text{Na}_2\text{O}/\text{SiO}_2$ ratio in the ASR gel increases, and consequently the viscosity and stiffness of the ASR gel decrease [5]. It is for this reason that ASR expansion became small when the specimen's alkali content increases excessively. As above, the rising concentration of the NaOH solution had two contradictory influences on the ASR expansion of the specimen.

In addition, ASR expansion became small when the storage temperature rose excessively in low concentration of solution. In high solution concentration, ASR expansion increased with rising storage temperature. The relationship between ASR expansion and storage temperature reflected the difference of the concentration of the NaOH solution for the following reason. ASR expansion increases with rising storage temperature when there is significant alkali content to continue ASR. This is because the reactive rate of ASR quickens, and a large amount of ASR gel is produced at the early stage as the storage temperature rises. On the other hand, without a significant alkali content to continue ASR, higher storage temperature decreases ASR expansion because the ASR gel takes in Na^+ at an early stage, and the viscosity of the ASR gel decreases due to an increase in its $\text{Na}_2\text{O}/\text{SiO}_2$ ratio. As above, the rising of the storage temperature had two contradictory influences on the ASR expansion of the specimen.

The concentration of the NaOH solution and the storage temperature influence the ASR expansion intricately, as described above.

For specimens immersed in NaCl solution, ASR expansion became small when the solution concentration rose excessively at low storage temperature (40°C) after the storage period of about 4 weeks. On the other hand, at high storage temperatures (60°C and 80°C), ASR expansion increased with rising solution concentration. Furthermore, ASR expansion became small when the storage temperature rose excessively in low concentration of solution. In high solution concentration, ASR expansion increased with rising storage temperature. ASR expansion demonstrated this tendency due to the difference in the concentration of the NaCl solution and the storage temperature. This is because ASR expansion came under two conflicting influences concerning the concentration of the NaCl solution and the storage temperature, as with the specimens immersed in the NaOH solution mentioned above. The concentration of the NaCl solution and the storage temperature influence the ASR expansion intricately, as described above.

The specimens immersed in the NaOH solution began to expand quicker than those immersed in the NaCl solution, as shown in Section 3.4, for the following reasons. NaCl indirectly acts on ASR while NaOH acts directly on ASR. That is, the OH^- ion, which is generated by a reaction with NaCl and the aluminates, acts on ASR [6]. This explains why the start of the ASR of the specimens immersed in the NaCl solution lagged behind the specimens immersed in the NaOH solution because it took time until the OH^- ion was generated by the above reaction and until it reached a concentration that caused ASR.

From the results shown in Figures 4 to 11, two conditions were selected as accelerated curing conditions that comparatively caused the largest expansion at the early stage: specimens immersed in a NaOH solution of 1 mol/l at 60°C and in a NaCl solution of 2 mol/l at 60°C . In addition, two conditions were selected as the accelerated curing conditions that caused the largest long-term expansion (26 weeks): specimens immersed in a NaOH solution of 2 mol/l at 80°C and in a NaCl solution of 2 mol/l at 80°C . Figure 21 shows expansion with time of the specimen cured under these accelerated curing conditions. The specimen immersed in the NaOH solution caused larger expansion at the early stage compared with the specimen immersed in the NaCl solution. In addition, the accelerated curing condition of immersion in the 1 mol/l NaOH solution and storage at 60°C is the most appropriate for accelerated tests to judge the residual expansibility of the concrete core due to ASR at the early stage because the expansion was greatest at the early stage.

5 CONCLUSIONS

In the present study, we examined the effects of the kinds of solution, the concentration, and storage temperature on the ASR expansion of concrete specimens immersed in NaOH and NaCl solutions. The following results were obtained.

- (1) For specimens immersed in the NaOH and NaCl solutions, the relationship between ASR expansion and solution concentration reflected the storage temperature. ASR expansion became small when the solution concentration rose excessively at low storage temperature. At high storage temperature, ASR expansion increased with rising solution concentration.

- (2) For specimens immersed in the NaOH and NaCl solutions, the relationship between ASR expansion and storage temperature was different when the solution concentration was different. ASR expansion became small when the storage temperature rose excessively in low concentration of solution. In high solution concentration, ASR expansion increased with rising storage temperature.
- (3) The specimen immersed in the NaOH solution generated larger expansion at the early stage compared with the specimen immersed in the NaCl solution. The accelerated curing condition that generated the largest expansion at the early stage was where the specimen was immersed in a NaOH solution of 1 mol/l and stored at 60°C.

6 ACKNOWLEDGMENTS

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Table 1: Mixture proportions of concrete.

W/C (%)	s/a (%)	Unit content (kg/m ³)			
		Water	Cement	Sand	Gravel
65	45	180	277	816	1002

Table 2: Experimental conditions

Kinds of immersion solution	NaOH solution, NaCl solution
Concentration of solution (mol/l)	0.5, 1, 2
Storage temperature (°C)	40, 60, 80
Dimension of specimen (mm)	φ 75×150

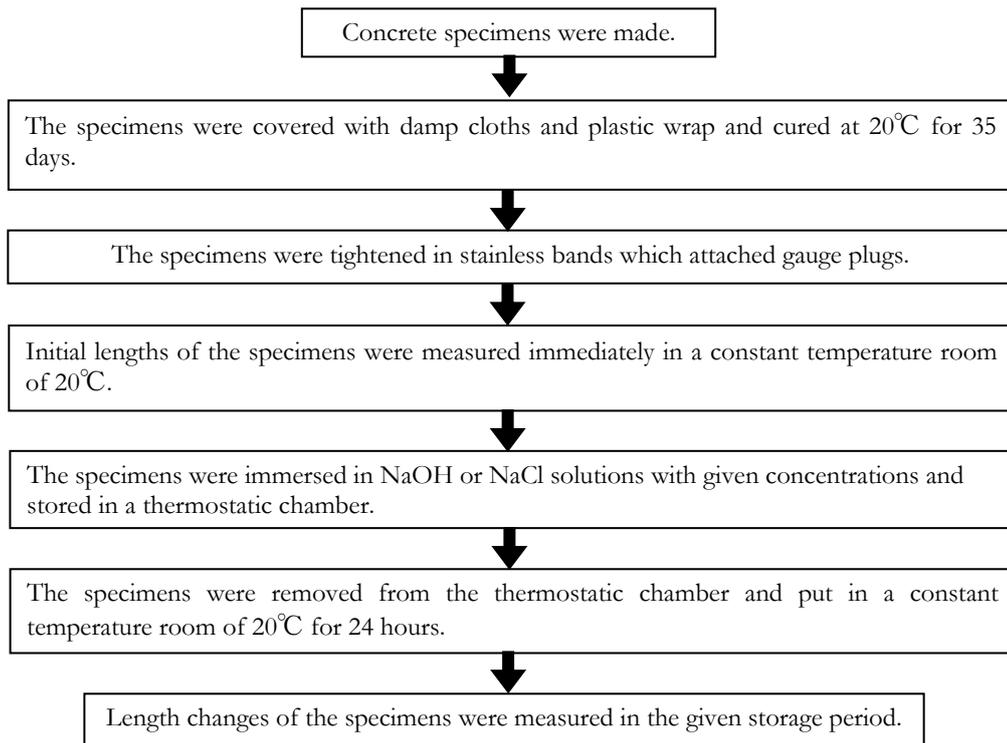


Figure 1: Flow chart of experimental method.

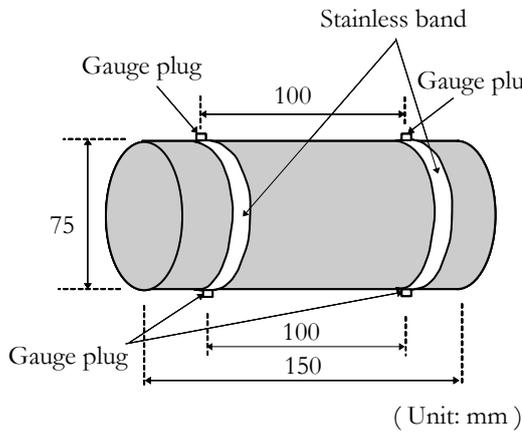


Figure 2: Outline of specimen.

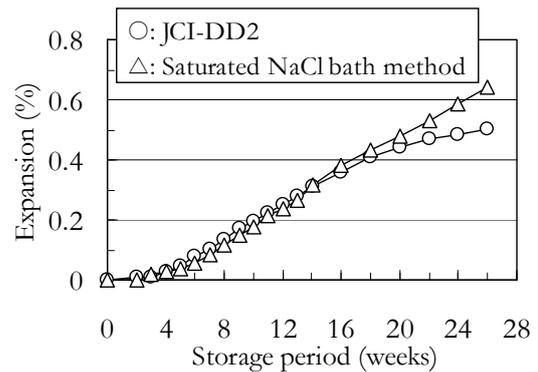


Figure 3: Expansion of specimens over time.

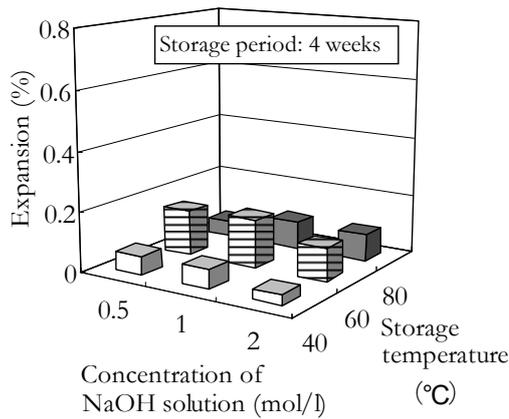


Figure 4: Relationship between expansion of specimens, concentration of NaOH solution and storage temperature.

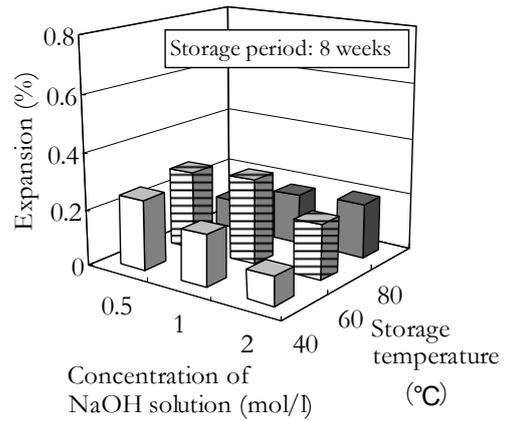


Figure 5: Relationship between expansion of specimens, concentration of NaOH solution and storage temperature.

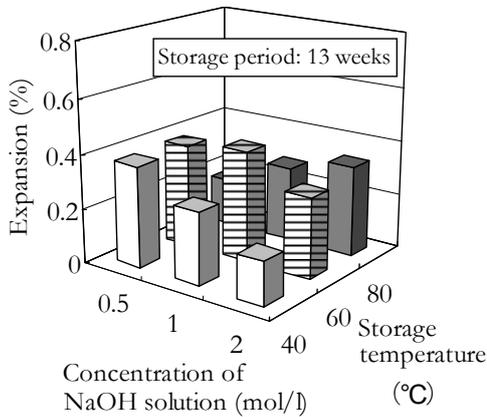


Figure 6: Relationship between expansion of specimens, concentration of NaOH solution and storage temperature.

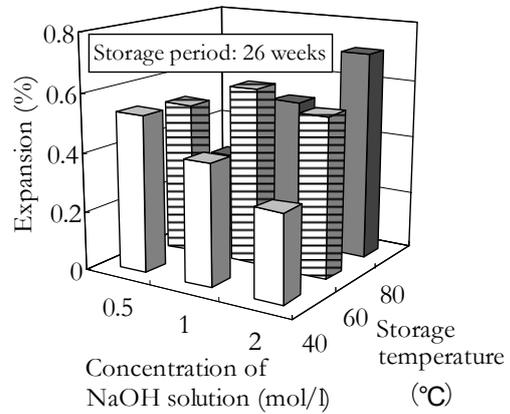


Figure 7: Relationship between expansion of specimens, concentration of NaOH solution and storage temperature.

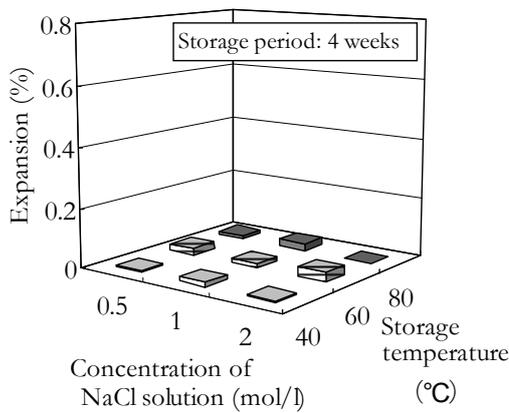


Figure 8: Relationship between expansion of specimens, concentration of NaCl solution and storage temperature.

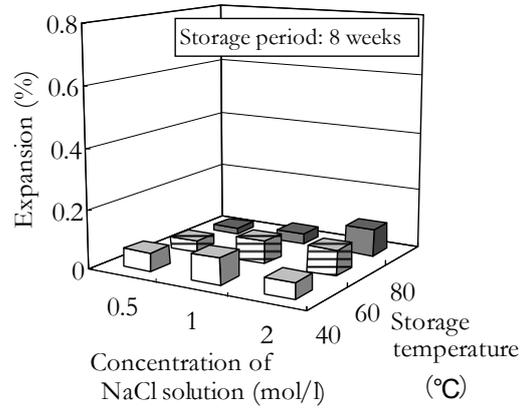


Figure 9: Relationship between expansion of specimens, concentration of NaCl solution and storage temperature.

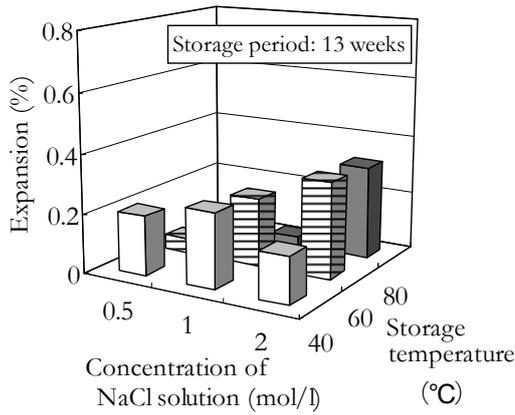


Figure 10: Relationship between expansion of specimens, concentration of NaCl solution and storage temperature.

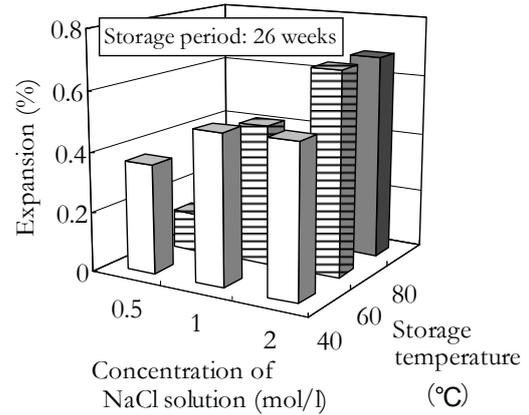


Figure 11: Relationship between expansion of specimens, concentration of NaCl solution and storage temperature.

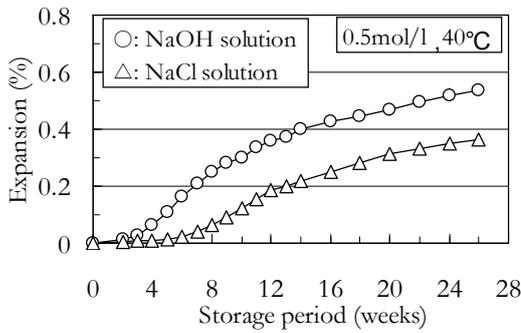


Figure 12: Comparison of expansion of specimens immersed in NaOH and NaCl solutions.

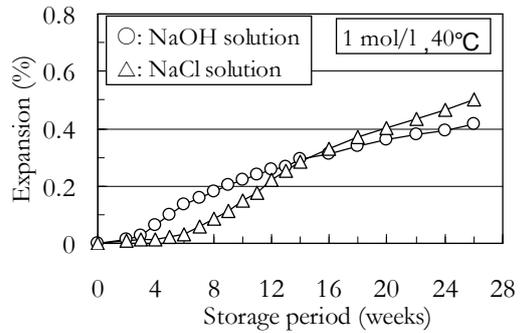


Figure 13: Comparison of expansion of specimens immersed in NaOH and NaCl solutions.

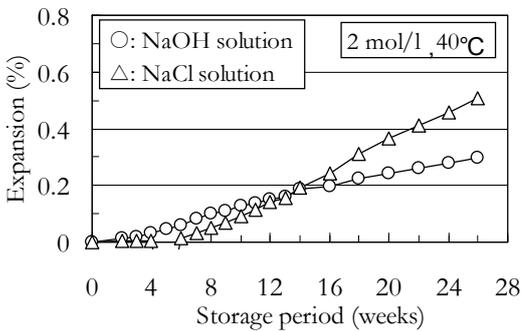


Figure 14: Comparison of expansion of specimens immersed in NaOH and NaCl solutions.

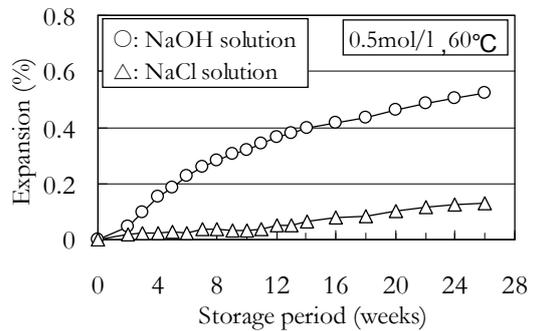


Figure 15: Comparison of expansion of specimens immersed in NaOH and NaCl solutions.

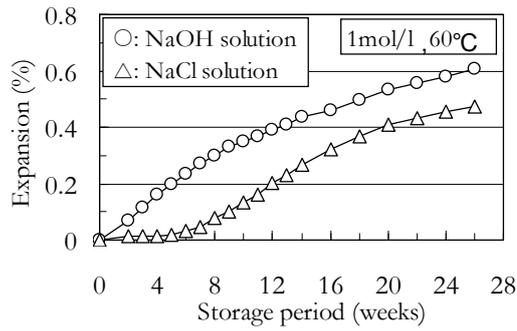


Figure 16: Comparison of expansion of specimens immersed in NaOH and NaCl solutions.

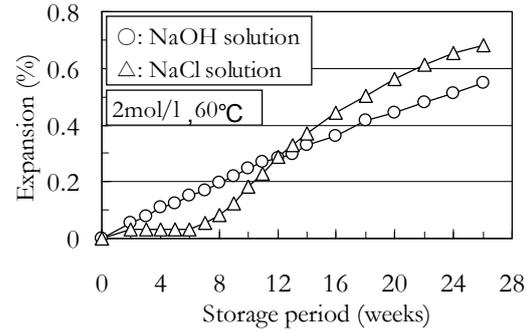


Figure 17: Comparison of expansion of specimens immersed in NaOH and NaCl solutions.

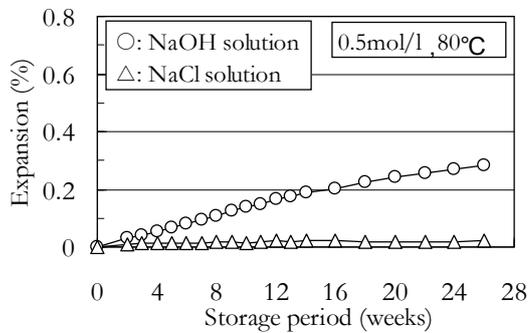


Figure 18: Comparison of expansion of specimens immersed in NaOH and NaCl solutions.

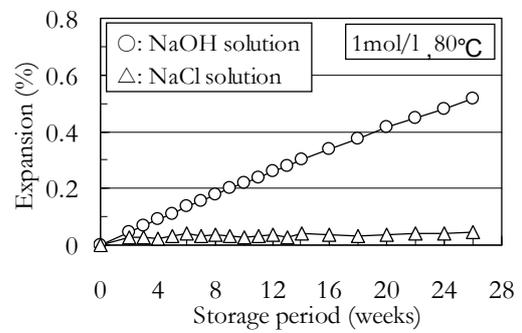


Figure 19: Comparison of expansion of specimens immersed in NaOH and NaCl solutions.

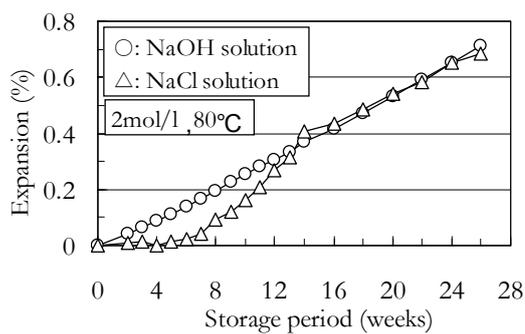


Figure 20: Comparison of expansion of specimens immersed in NaOH and NaCl solutions.

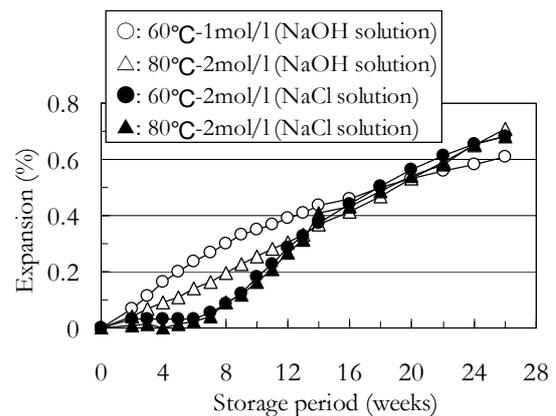


Figure 21: Expansion of specimens over time.