BOND STRENGTH BETWEEN STEEL BAR AND CONCRETE USING ACCELARATED EXPANSION TEST METHOD OF ASR IMITATED WITH GLASS

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Abstract

In Japan, many concrete structures damaged by ASR have been found since 1950s. Damage such as fracturing of stirrups has an effect on the durability of structures. To clarify ASR mechanism in concrete and propose test methods for large-scale structures, expansion test and bonding tests were conducted using specimens containing expansive aggregates. The parameters were expansive aggregate, addition of Alkalis, and curing. The tests were conducted on the expansion rate, compressive strength, Youngs Modulus, and the bonding between steel bars and concrete.

Specimens containing Glass Cullet and alkalis and cured at normal and high temperatures showed a larger expansion rate than that of normal ASR specimens. Their compressive strength and Youngs Modulus were similar to those of normal ASR specimens. Therefore, it can be said that Glass Cullet is suitable as the expansive material, and it was clarified that the bond strength didn't decrease even though the concrete expanded.

Keywords: imitation material, Glass Cullet, expansion rate, curing method, bond strength

1 INTRODUCTION

In Japan, almost all alkali aggregate reactions (AAR) are alkali silica reactions (ASR). A huge number of concrete structures with cracks due to ASR have been found at many places since the 1950s. Those cracks were caused by unusual expansion of reactive aggregate. Furthermore, cracking and fracturing of stirrups in the concrete structures began to be found after 1996 [1]. To prevent deteriorates of those structures, it is important to investigate the mechanism of ASR. But, its experiment is difficult to conduct because ASR needs a long reaction time, which is the reason why an accelerated expansion test is required.

To investigate the effect of ASR, it is necessary to evaluate the compressive strength and the expansion of concrete structures damaged by cracking. But, many of those structures do not have cracking data due to lack of periodical inspection. So, we cannot evaluate changes in material property after the structures are damaged by ASR. It also causes some trouble in the maintenance and management of those structures. This is also the reason an accelerated expansion test using expansive aggregate is needed.

In this paper, the correlation between the expansion rate and the strength of concrete was investigated by using expansive materials as the aggregate. In accordance with Goda's earlier study, expansive materials containing CaO, which expand faster than AAR but whose compressive strength is different from that of ASR, were used [2]. Such difference is caused by a difference in expansion mechanism. As the parameters for the study, expansive materials as well as the addition of alkalis to the concrete and curing method of specimens were adopted. In Japan, Yamato and Torii [3] have also studied these glasses as the aggregate.

Next, on the basis of the above test results, RC specimens were tested by an accelerated expansion test and the bond strength between steel bars and concrete was evaluated. Normally, the expansion amount of RC specimens is smaller than that of plain specimens because the expansion is confined by steel bars in the former specimens. So, the difference in the expansion amount of those specimens is considered as the amount of confinement. This concept is usable for the prediction of bond strength of concrete expanded by ASR in relation to the fracturing of steel bars. It is also usable for the evaluation of functional characteristics of RC structures analyzed by FEM.

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2 MATERIALS AND METHODS

2.1 General

The purpose of this study is to propose an accelerated expansion test method that shows a similar expansion characteristic with ASR but has a faster expansion rate than ASR, and to grasp a change in bond strength between concrete and steel bars in RC structures when they are expanded.

Generally, ASR concrete expands slower than ASR mortar. From the research on the expansion rate of ASR [2], it was found that ASR mortar expands more than 0.01 vol% [100micronsns] in a day. "Microns" means a unit of strain. 1,000,000microns is the whole length of a specimen. On the other hand, the expansion rate of ASR concrete is half the rate of ASR mortar. This slow speed is caused by the difference in gravel, size effect, and confinement conditions. To obtain the test results quicker, it is necessary to conduct an accelerated expansion test using an alternative aggregate material having an expansion mechanism similar to that of reactive aggregate and containing a lot of reactive minerals. The alternative materials used should expand largely and show a strength change similar to that of reactive aggregate as expansion proceeds. The parameters were the adding method of alkalis and curing temperature and moisture, because they are important factors to the expansion reaction of SiO_2. The expansive materials used were reactive aggregate, Industrial Pyrex Glass, and Glass Cullet. Alkalis were added by dissolving NaOH into mixing water and curing water, which was done to keep pH at 13.5 or above. NaCl was not used because its Cl^- is highly likely to cause corrosion in the case of experiment using concrete containing reinforcing bars. Curing consisted of the first curing period to increase compressive stress and the second curing period to expand concrete. Two curing periods were adopted to avoid a decrease in concrete strength different from that of actual ASR concrete which would occur if expansion begins during the development of strength. ASR aggregate and expansive materials were compared on such items as the total expansion amount, expansion rate, compressive strength, and Youngs Modulus.

Next, the boundary conditions between concrete and steel bars were investigated by an accelerated bond strength test. The principal of this test is to estimate the difference in the expansion amount of RC and plain specimens as the amount due to confine effect. Beam specimens were used for this test. Expansive materials used were reactive aggregate and Glass Cullet. For RC specimens, steel bars were arranged at 0.8 % by area rate.

2.2 Materials and mix designs

In this study, normal Portland cement was used for specimen produciton. The chemical composition of cement is shown in Table 1. Reactive coarse aggregate is andesite and reactive fine sand is crushed andesite which is crushed using a Jaw crusher. Non-reactive coarse aggregate is sandstone and non-reactive fine sand is sea sand from Genkai Bay. Industrial Pyrex Glass is the type of glass used for industrial vessels like a beaker and a flask. To imitate reactive aggregate, it is crushed by a Jaw crusher. Glass Cullet contains Na^+ and K^+ more than those in Industrial Pyrex Glass. Glass Cullet was chosen as the recycle material. The material properties of these glasses are shown in Table 2. Alkali added to the mixing water was NaOH, and it was also added to curing water.

ASR expansion is caused by an absorptive silica gel formed by the chemical reaction between reactive silica mineral in the aggregate and hydraten alkalis in concrete. Silica mineral was contained in all expansive materials used in this study, and addition of alkali ion was needed to cause a reaction with silica in the water for the accelerated expansion test. Mix proportion of concrete is shown in Table 3. The volume of expansive material was defined as 60 vol% of coarse and fine aggregates. This percentage was determined based on the basic research on the relationship between mix proportion and expansion of concrete. To control flowability, air-entraining water-reducing agent was added to the reactive aggregate concrete, and high performance Air-entraining water-reducing agent was added to glass aggregate concrete. NaOH was added to the concrete by dissolving into the mixing water.

Concrete was cast into steel molds. The specimens produced were cured in the 20℃constant temperature room for 24 hours. Then, they were taken out of the room and divided into two groups: specimens for the expansion test and specimens for the compressive strength test. To increase compressive strength, specimens of both groups were cured in the 20℃ constant temperature room for 2 weeks. This is the first curing period. Silica has a property to produce an alkali silica gel and expand at a temperature of 40℃. So, the specimens were cured at this high temperature to accelerate expansion. This is the second curing period. Such two-period curing was adopted to control unexpected expansion during the period of compressive strength increase. According to other research in the past [1], the compressive strength of concrete becomes rather small compared to that of ordinary ASR concrete if the concrete expands during the period of compressive strength increase.

The parameters of specimens are shown in Table 4. The specimens had a cylindrical shape, 100mm in diameter and 200 mm in length. For expansion measurement, five specimens were made for each parameter, and acrylic plates were applied to both rest surfaces of the specimen. Compressive strength was measured at intervals of 500microns during the expansion.

The parameters of the bond strength test are shown in Table 5. Beam specimens, each 100mm ×100mm×400 mm, were used for this test, as shown in Fig 1. Steel bars were 10mm in diameter. Material property of steel bar is shown in Table 6. Three specimens were tested for each parameter. An acrylic acid resin plate was applied to both edges of the specimen.

2.3 Methods for assessment and analysis

Assessment of expansion amount, expansion rate, and bond strength between steel bar and concrete

Cylindrical specimens, 100mm in diameter and 200 mm in length, were used for the expansion test. Beam specimens, 100mm × 100mm × 400mm, were used for the bond strength test. Measurements were made using a stainless steel comparator and a digital automatic indicator. The expansion was measured at intervals of 3 days.

Compressive strength

Cylindrical specimens, 100mm in diameter and 200 mm in length, were used for this test. The compressive strength test was conducted in accordance with Japanese Industrial Standard (JIS) A1108 [4]. This test was conducted when the expansion became 400, 800, 1200, 1600, 2000, 2500, 3000, 3500, 4000, 4500, 5000microns.

Youngs Modulus

Youngs Modulus test was conducted in accordance with JIS A 1149-2001 [4].

3 RESULTS

Figures 2, 3, 4 and 5 show the relation between the expansion characteristic and the strength characteristic. The main parameter of these figures is the expansive material. The three expansive materials are reactive aggregates of the andesite, Industrial Pyrex Glass, and Glass Cullet. Fig 2 shows the expansion during the second curing period. Figure 3 shows the expansion rate during the expansion period. Figure 4 shows the relation between the expansion and compressive strength. Figure 5 shows the relation between the expansion and Youngs Modulus.

Figures 6, 7, 8, 9and 10 show the results from the specimens using Industrial Pyrex Glass as the expansive material. They show the relation between the expansion characteristic and the strength characteristic when Na_2Oeq is added to the concrete. The amount of Na_2Oeq in concrete was set at 0.5%, 0.8%, 1.0%, 1.5%, and 2.0% of cement by weight. The NaOH concentration in the mixing water was 0.5mol/l. Figure 6 shows the expansion during the second curing period. Figure 7 shows the relation between Na_2Oeq and the expansion at 30 days, 90 days, and 150 days. Figure 8 shows the expansion rate during the expansion period. 30 days were made to one unit. Figure 9 shows the relation between the expansion amount and compressive strength. Figure 10 shows the relation between the expansion amount and Youngs Modulus.

Figures 11, 12 and 13 show the results from specimens using Glass Cullet as the expansive material. They show the relation between the expansion characteristic and the strength characteristic when the parameter is Na_2Oeq in concrete. Na_2Oeq in concrete was 0.5% and 1.5% by weight rate. The NaOH concentration in the curing water was 0mol/l. Figure 11 shows the expansion amount during the second curing period. Figure 12 shows the expansion rate during the second expansion period. 30 days were made to one unit. Figure 13 shows the relation between the expansion amount and Youngs Modulus.

Figures 14, 15 and 16 show the results from specimens using reactive aggregate and Glass Cullet as the expansive material. Figure 14 shows the expansion amount during the second curing period. Figure 15 shows the expansion rate between RC specimens and plain specimens during the second curing period. Figure 16 compares the expansion amount of RC specimens obtained by experiments and calculation. The calculated amount was obtained by substituting the experimentally-obtained Youngs Modulus value into Equation 1 for expansion calculation which focuses on the sectional force based on the fundamental theory of elastic dynamics.

$$\varepsilon_{f'c}=\varepsilon_c/\left(1+\left(E_s/E_c\right)/\left(A_s/A_c\right)\right) \quad (1)$$

$\varepsilon_{f'c}$: Expansion of reinforced concrete by calculation [microns]

$\varepsilon_{f'c}$: Expansion of no reinforced concrete by experiment [microns]

Es : Youngs Modulus of steel bar [N/mm²] Ec : Youngs Modulus of concrete [N/mm²]

As : Sectional area of steel bar [mm²] Ac : Sectional area of concrete [mm²]

4 DISCUSSION

From Figure 2, it is seen that the expansion of 2 types of glass (Industrial Pyrex Glass, Glass Cullet) is considerably larger than that of the reactive aggregate. These glasses showed a similar expansion characteristic up to 5000microns [0.5%]. But, after 5000microns, they showed a different expansion characteristic. The Glass Cullet continued to expand. According to Yamato's research [3], it is caused by the fact that Glass Cullet contains larger amount of alkalis than that in Industrial Pyrex Glass. From Figure 3, it is seen that concrete containing Industrial Pyrex Glass expanded quickly until the 60th day at a rate of 100microns/day. In contrast, Glass Cullet expanded at 50microns/day from 0-30days to 150-180days. This means that Glass Cullet can exhibit large expansion steadily.

Figure 4 shows that the compressive strength of all specimens decreased to 90% of the strength before the start of expansion when the expansion amount reached 2000microns. As is seen from Figure 3, the difference in expansion rate has no effect on the decrease in compressive strength. This means that even if those two kinds of glass expand by accelerated curing, their strength characteristics as the same with that of reactive aggregate. Figure 5 shows that Youngs Modulus of the reactive aggregate decreased to 50% at 500microns. On the other hand, Youngs Modulus of the two glasses decreased gradually compared with that of the reactive aggregate. After 2000microns, all of Youngs Modulus decreased to about 50% compared with the initial state. This implies that the two glasses can be used as the alternative aggregate in the experiment needing a large expansion.

Figure 6 shows that alkalis mixed into concrete have a large effect on concrete expansion. In this experiment, two kinds of alkalis exist in the concrete. One is the original alkalis contained in the cement and aggregate, the other is intentionally added NaOH. The alkalis originally contained in cement accounts for 0.5 wt% of cement. Then, 0-1.5% of alkali was intentionally added to each specimen. Case 2 has no intentional alkali addition by NaOH. Case 2 has an expansion characteristic clearly different from the remaining cases. One cause is that pH approached around 14 because of an increase in OH^- in mixing water by the intentional addition of NaOH. Figure 7 shows the relation between Na_2O (alkali) added artificially and the amount of expansion. The expansion amount of 4 specimens at 30 days was rather identical regardless of the amount of Na_2O. On the other hand, the relation between Na_2O and the expansion amount at 90-150 days was proportional. This indicates that the alkali added intentionally has an effect on the amount of long-term expansion.

Figure 8 shows that Industrial Pyrex Glass expanded at 100microns/day at 0-30days, when the concrete contained more than 0.8 wt% alkali (by weight rate to cement). In addition, the expansion rate of all specimens decreased as time passed. The expansion rate at 150-180 days was about 10% of the expansion rate at 0-30days. Figure 9 shows that the compressive strength of Case 2 was increased, but that of the remaining specimens decreased. This is because the expansion rate of Case 2 was very small and a strength increase by the long-term water-cement reaction was larger than the strength decrease by expansion. According to Figure 10, Youngs Modulus of all specimens decreased to about 50% at the time of 2000microns or more. This indicates that the alkali amount added by NaOH has no effect on the compressive strength characteristic.

According to Figure 11, Glass Cullet expanded more than 10000microns regardless of the alkali amount added into concrete. This is because the alkalis contained in the glass dissolve by the reaction of silica and then participated in the alkali-cilica reaction, according to Yamato et al [3]. Figure 12 shows that the compressive strength of all specimens containing Glass Cullet decreased by 10% just like the specimens containing Industrial Pyrex Glass. Youngs Modulus in Figure 13 began to decrease with expansion and decreased to about 50% before reaching 2000microns. This indicates that Glass Cullet can expand greatly in a short time even without an intentional addition of alkalis into concrete. It was also confirmed that the difference in alkali amount does not have effect on the compressive strength.

From these results, it was found that Glass Cullet is the material having the largest expansion among the three materials tested. An accelerated expansion test using Glass Cullet is very safe because addition of NaOH into curing water is not needed.

Figures 14 and 15 show that, in the case of reactive aggregate, the expansion amount differed between RC and plain specimens after 500μ, and that the expansion amount of RC specimens was restrained to 60% by the confinement by steel bars. On the other hand, in the case of Glass Cullet, the expansion amount between RC and plain specimens became different after 2000μ, indicating that the confinement effect appears rather gradually. Before 2000μ, no difference attributable to the presence/absence of steel bars was seen in the expansion amount. This is not because bonding was lost, but because Youngs Modulus of concrete was so large and the sectional force of steel bars was small relatively. Therefore, steel bars were unable to restrain the expansion of concrete sufficiently. As to the range where an expansion difference was seen, it is considered that Youngs Modulus decreased due to the expansion and the sectional force also decreased, which led to a relative increase in the sectional force of steel bars. Figure 16 shows that the calculated expansion amount under confinement which was obtained by Equation 1 is roughly identical to the experimental amount. This indicates the sectional force derived as the product of Youngs Modulus and sectional area of each material has a correlation with the expansion characteristic, and that the expansion amount under confinement can be estimated from the expansion amount under no confinement by using Equation 1.

Plain specimens with no confinement expanded more than that of confined specimens after the confinement effect was confirmed in both cases of reactive aggregate and Glass Cullet. If the bond strength had been lost, the expansion amount of them would have been equal to the expansion under no confinement by steel bars. Therefore, obtained results suggest that the bond strength between steel bars and concrete remains even though those aggregates expanded largely.

5 CONCLUSIONS

In this study, the expansion characteristic of two kinds of glasses (Industrial Pyrex Glass, Glass Cullet) was compared with that of reactive aggregate to propose an accelerated expansion test for large RC structures. The bond strength characteristic between steel bars and concrete was also clarified. From this study, the following conclusions were drawn:

- Suitable curing method for accelerated expansion test is the combination in the first curing of 20℃ in air with the second curing of 40℃ in water.
- Industrial Pyrex Glass is the suitable material for accelerated expansion test of Reactive Aggregate when the concrete contains more than 0.8 wt% alkali and cured in NaOH water.
- Glass Cullet is the suitable material for accelerated expansion test of Reactive Aggregate even if the concrete doesn't contain enough alkali and doesn't cure in NaOH water.
- Accelerated expansion test method using Glasses can reproduce ASR's expansion and strength characteristics.
- The bond strength remains to exist in RC specimens expanded by ASR even if the expansion increases.
- The expansion of concrete under confinement can be calculated by Equation 1 which considers the sectional force of the specimen.

6 REFERENCES

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[3] Yamato, H. and Torii, K. (2005): Chemical compositions of crushed waste glass and alkali silica reactivity. Proceeding of the Japan Concrete Institute. vol.27. No.1. pp.1429-1434.

[4] Japanese Industrial Standards (2002):JIS HB Ready mixed Concrete.

7 ACKNOWLEDGEMENT

Thanks to Professor Kosa and Mrs.Kosa's assistance to translate from Japanese into English, I could make this paper. I'm deeply grateful to them for their support.

TABLE 1: Properties of Normal Portland Cement.

Density	Blaine Fineness	Ignition Loss	SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3	Na_2O Equiv.
kg/m^3	cm^2/g	%	%	%	%	%	%	%	%
3.16	3260	2.23	21.9	5.2	63.6	1.2	2.2	3.0	0.49

TABLE 2: Properties of Aggregates and Expansive Materials.

Materials	Density	Water Absorp.	FM
	kg/m^3	%	
Reactive Coarse Agrregate	2740	0.54	6.9
Non-Reactive Coarse Agrregate	2710	0.33	6.7
ReactiveFine Aggre.	2740	0.54	3.0
Non-Reactive Sand	2580	1.38	2.7
Industrial Pyrex Glass	2210	-	2.4
Glass Cullet	2510	-	3.8

TABLE 3: Mixture Proportions of Concrete.

Expansion Materials	G max	Slump	Air	W/C	s/a	W	C	Non-Reactive		Reactive		Glass	AE WRA	SP
								S	G	S	G			
	mm	cm	%	%	%	kg/m^3								
Ractive Aggre.	20	10±2	5.0	50	44	170	340	300	406	478	609	0	3.40	0.00
Industrial Pyrex	20	10±2	5.0	35	45	170	486	286	371	0	0	815	0.00	7.29
Glass Cullet	20	10±2	5.0	35	45	170	486	286	371	0	0	926	0.00	7.29

TABLE 4: Specimen Types of Expansion Test.

Case Number	Expansion Material	Mixing	1st Curing		2nd Curing
		Na_2O_{eq} (×C%)	Environment	Period (day)	Environment
No.1	Reactive Aggregate	1.5	40℃Water	14	40℃ NaOH Water (1mol/l)
No.2	Indestrial Pyrex Glass	0.5	20℃ Air (70%RH)		
No.3		0.8			
No.4		1.0			
No.5		1.5			
No.6		2.0			
No.7	Glass Cullet	0.5			40℃ Water
No.8		1.5			

TABLE 5: Specimen Types of Bonding Test.

Case Number	Expansion Material	Mixing	1st Curing		2nd Curing	Steel bar
		Na_2O_{eq} (×C%)	Environment	Period (day)	Environment	Diameter 10mm
No.9	Reactive Aggregate	2.0	40℃Water	14	40℃ NaOH Water (1mol/l)	1
No.10						0
No.11	Glass Cullet	1.5	20℃ Air(70%RH)		40℃ Water	1
No.12						0

TABLE 6: Material Property of Steel Bar.

Diameter	Area	Yield Stress	Tensile Stress	Young Modulus
mm	mm^2	N/mm^2	N/mm^2	N/mm^2
9.53	71.3	297	437	18900

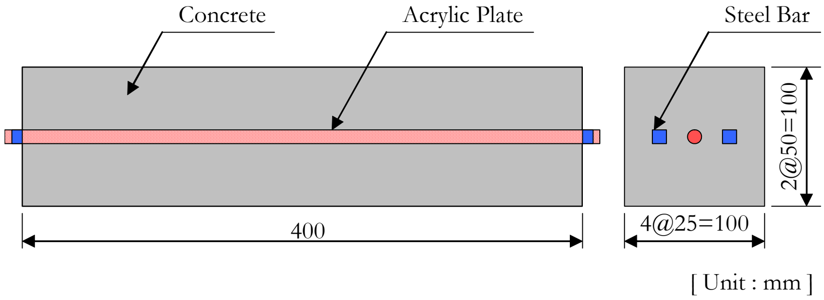

Figure 1: Specimen for Bond Strength Test.

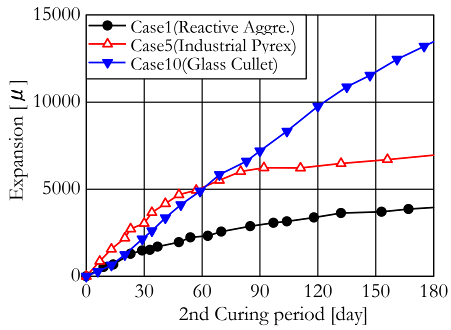

Figure 2: Expansion vs second curing period.

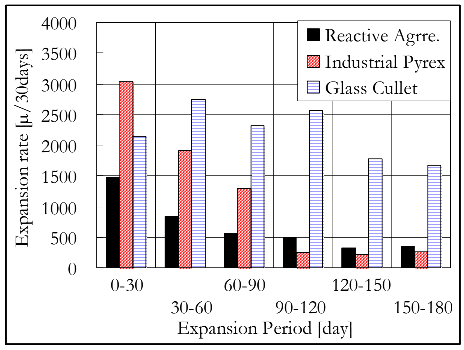

Figure 3: Expansion rate at 30days as unit.

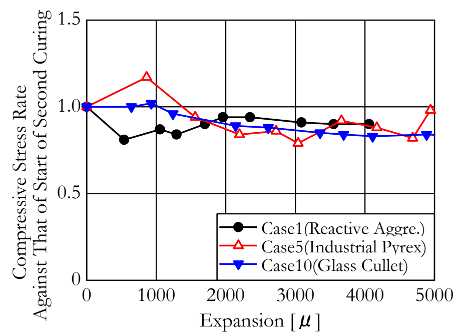

Figure 4: Comparison Compressive stress rate for three expansive materials.

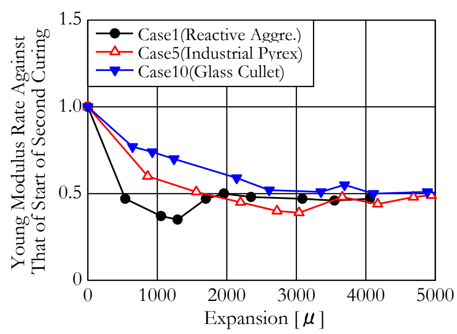

Figure 5: Comparison Youngs Modulus rate for three expansive materials.

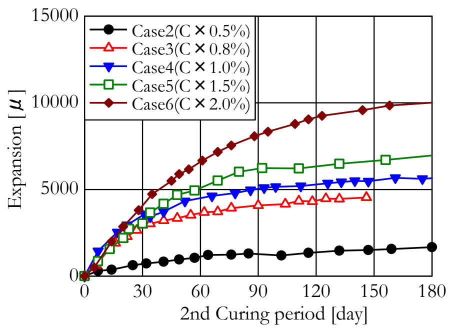

Figure 6: Expansion vs second curing period (Industrial Pyrex Glass).

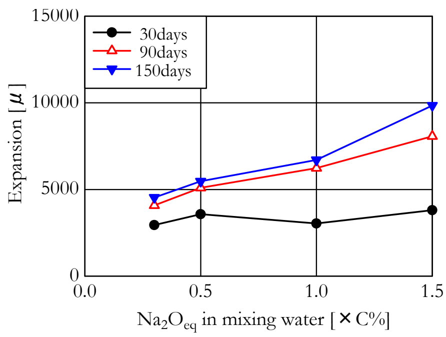

Figure 7: Relation between Na_2Oeq and expansion (Industrial Pyrex Glass).

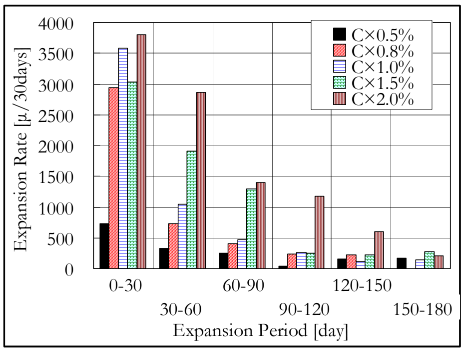

Figure 8: Expansion rate at 30days as unit (Industrial Pyrex Glass).

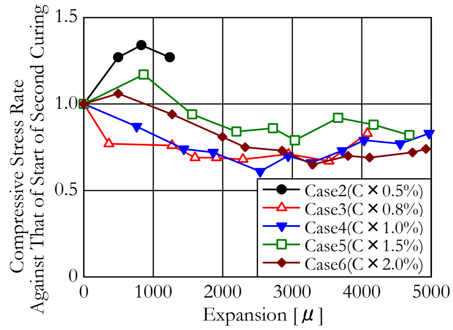

Figure 9: Expansion vs compressive stress rate at varying alkali rate (Industrial Pyrex Glass).

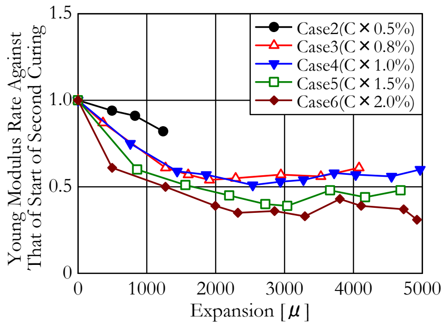

Figure 10: Youngs Modulus rate vs expansion at varying alkali rate (Industrial Pyrex Glass).

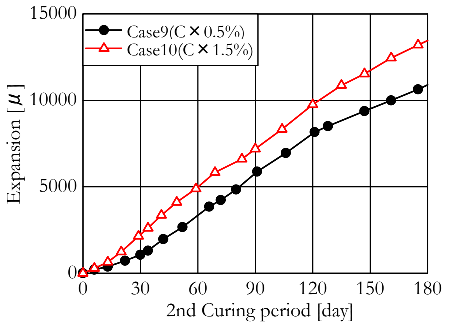

Figure 11: Expansion vs second curing period (Glass Cullet).

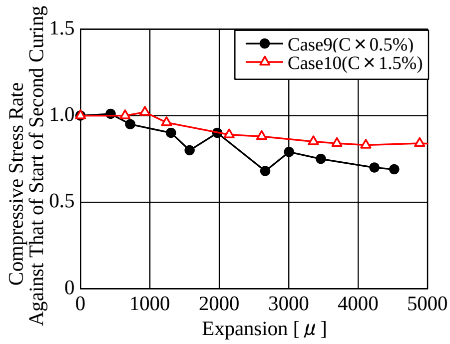

Figure 12: Compressive stress rate vs expansion at varying alkali rate (Glass Cullet).

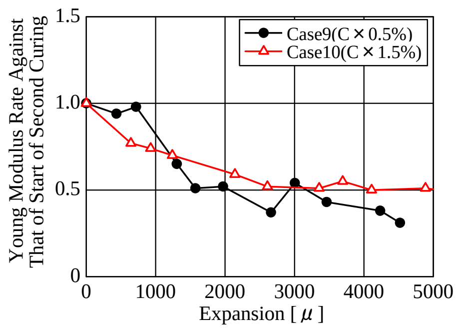

Figure 13: Youngs Modulus rate vs expansion at varying alkali rate (Glass Cullet).

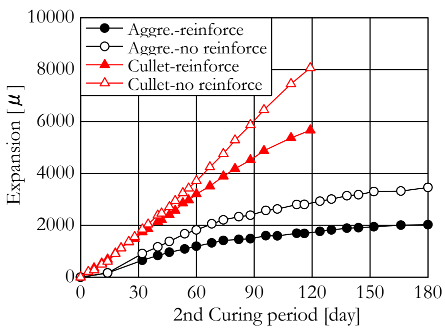

Figure 14: Expansion vs second curing period (reinforced concrete and no reinforced concrete).

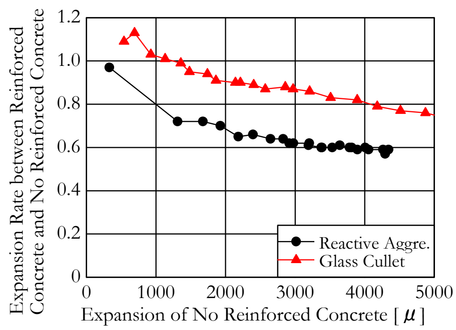

Figure 15: Expansion rate of bonding test.

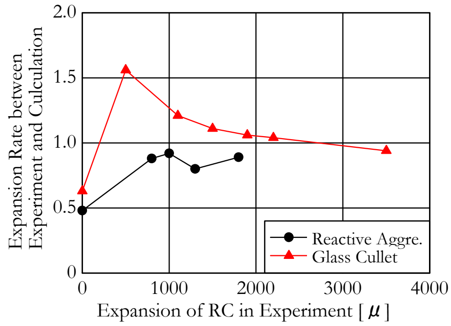

Figure 16: Expansion rate vs experiment and calculation.