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A Fundamental Study on Concrete Deterioration Caused by Combined Effects of ASR and Frost Attack

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ABSTRACT

This study investigates the combined effects of ASR and frost attack on the surface scaling and expansion of concrete. Concrete specimens containing reactive aggregates were deteriorated in a high-temperature and high-humidity chamber, and subjected to rapid freeze-thaw cycles. The test results indicated that ASR deterioration leads to severer frost damage. The ASR-deteriorated specimens continued to expand even during the freeze-thaw cycles, and suffered severer scaling.

Keywords. Concurrent Deterioration, Scaling, Frost Attack, Alkali Silica Reaction

INTRODUCTION

As concrete plays an important role in our lives, the problem of deteriorated concrete structures is growing more and more apparent. A significant number of concrete structures are suffering deterioration caused by a combination of several degradation mechanisms. In particular, combined effects of alkali silica reaction (ASR) and frost attack have been found in RC structures in cold regions (Dhir, 2003). This is attributable to the de-icing salt spread on the roads, which has been increasingly used after the enforcement of regulations on the use of studded tires. Sodium in the de-icing salt accelerates ASR, while chloride exacerbates frost damage. However, their interactive effects on the deterioration process are not elucidated yet.

In this study, concrete specimens that have been deteriorated by ASR and then subjected to freeze-thaw cycles were investigated to clarify the combined effects of ASR and frost attack.

EXPERIMENTAL PROCEDURE

Materials and Mixtures. Table 1 shows two concrete mixtures. A Pessimum test was carried out in advance in order to determine the reactive/non-reactive aggregates ratio that would maximize the ASR expansion of concrete (Table 2). NaCl was added only to the specimens that would be subjected to ASR acceleration in such an amount that the equivalent alkali content of the mixture would be 12.0kg/m^3. Ordinary Portland cement was used for both mixtures.

Table 1. Concrete mixtures

Type of deterioration	W/C (%)	s/a (%)	Air (%)	Unit mass (kg/m3)			
				Water	Water reducer	AE agent	NaCl
Combination of ASR and frost attack	57.0	47.4	3.0	168	0.295	0.059	19.5
			6.0			0.398	
Frost attack only			3.0			0.059	-
			6.0			0.266	

Table 2. Mixing ratio of aggregate

Ratio of fine aggregate (%)		Ratio of coarse aggregate (%)	
Reactive	Non-reactive	Reactive	Non-reactive
70	30	50	50

Specimens. Figure 1 illustrates the dimensions of the three types of specimens used in this study. The specimen with two D10 rebars arranged at its bottom simulates eccentric confinement against expansion of concrete (hereinafter referred to as "Bottom-rebar"). The specimen with rebars in the center simulates uniform application of confinement ("Center-rebar"). The specimen without rebars simulates a concrete member without confinement ("No-rebar"). As shown in Figure 1, contact gauges were embedded in the top and bottom surfaces with a gauge length of 250mm.

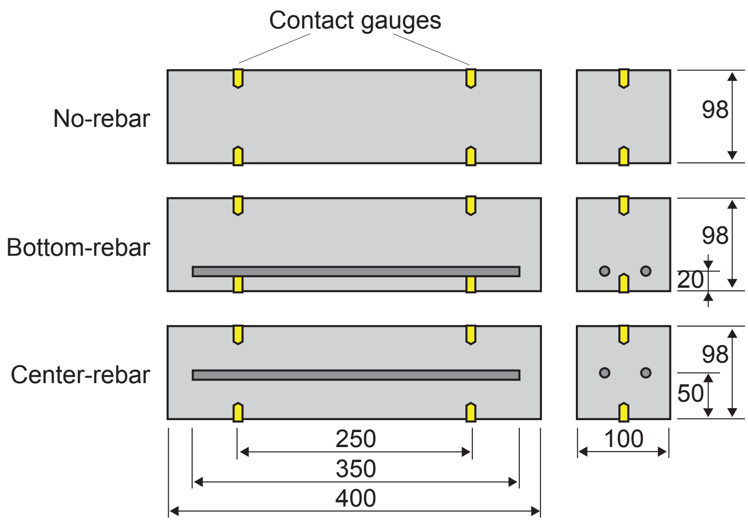


Figure 1. Dimensions of specimen (unit: mm)

Table 3 shows a list of specimens that simulate three types of deterioration processes:

- Non-reactive concrete specimen only subjected to freeze-thaw cycles (hereinafter referred to as "F&T");

- Reactive concrete specimen suffering a moderate degree of ASR expansion and then subjected to freeze-thaw cycles (“Comp-M”); and
- Reactive concrete specimen suffering a severe degree of ASR expansion and then subjected to freeze-thaw cycles (“Comp-S”).

Air content in the concrete was set to be 3.0 and 6.0%, which are the upper and lower limits of the normal range of air content of 4.5±1.5% in concrete. Two beams each were prepared for the discrete type of specimens.

Table 3. List of specimens

Air volume	Type of deterioration	Rebar arrangement
3% or 6%	F&T, Comp-M or Comp-S	Bottom-rebar, Center-rebar or No-rebar

After being demolded, the specimens were wrapped in wet cloth and cured for 28days at 22 degrees Celsius before carrying out various tests. Figure 2 shows the process steps applied to each specimen for accelerating deterioration.

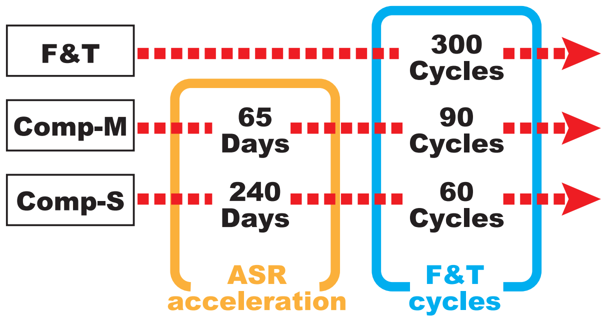


Figure 2. Three types of deterioration process

ASR Acceleration. ASR deterioration was accelerated by leaving the specimens in a chamber where the temperature was kept beween 35 and 40 degrees Celsius with a relative humidity of 100%. Comp-S beams were left in this chamber for 240 days. Comp-M beams were kept in the chamber until cracks were formed due to ASR. During this acceleration period, the ASR expansion rate was measured several times with a contact gauge method. Primary resonant frequency was also measured, and the relative dynamic modulus of elasticity was calculated, to determine the degree of degradation inside the beams. Surface crack distributions and crack widths were measured, too.

Freezing and Thawing Cycles. According to an ASTM C666-A method, the specimens were subjected to freezing and thawing cycles between 5 and -18 degrees Celsius. Each cycle took three hours. The relative dynamic modulus, expansion rate, and mass were measured every 30 cycles for F&M and Comp-M beams, and every 20 cycles for Comp-S beams.

RESULTS AND DISCUSSIONS

Effect of Frost Attack. Figure 3 shows the mass changes of F&T beams. The figure shows a clear difference in the mass change between the beams with the air content of 3%

and of 6%, which does not contradict with the generally known theorem that concrete with a higher air volume is more durable against frost attack.

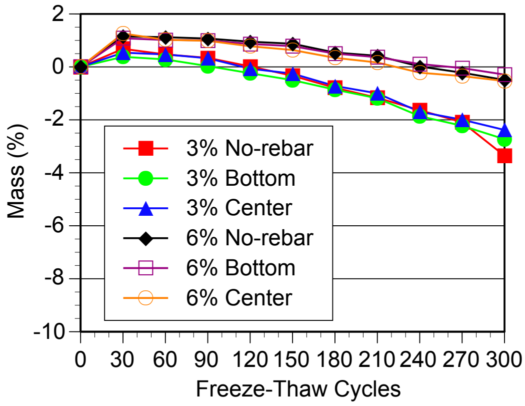


Figure 3. Mass changes of F&T beams

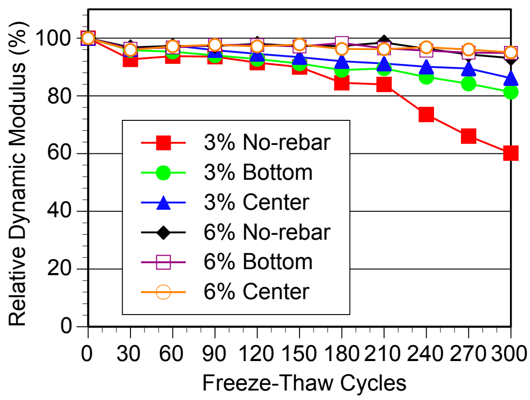


Figure 4. Relative dynamic modulus of F&T beams

Figure 4 shows the relative dynamic moduli of F&T beams. Similarly to the mass changes, the beams with an air content of 3% showed a greater decrease in relative dynamic modulus. No-rebar beams showed a drop to as low as 60% after 300 cycles of freezing and thawing. On the other hand, the dynamic modulus did not reduce significantly in the beams with rebars. Since reinforced specimens have a composite structure, the measured resonant frequencies do not necessarily indicate the properties of concrete itself. Therefore, it is not clear whether the existence of the rebar alleviated the deterioration caused by frost attack. However, it is reasonable to suppose that the reduced dynamic modulus shows internal deterioration of reinforced specimens and to use the relative dynamic modulus as an index of deterioration when comparing the beams with the same rebar arrangement.

Figure 5 shows the expansion rates of F&T beams. Expansion was hardly observed in F&T specimens during the freezing and thawing cycles. The beams with the air content of 3% only slightly suffered scaling.

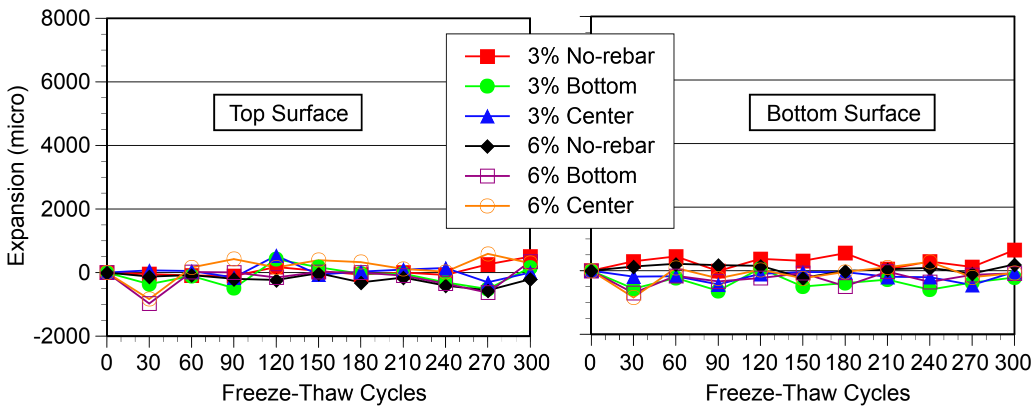
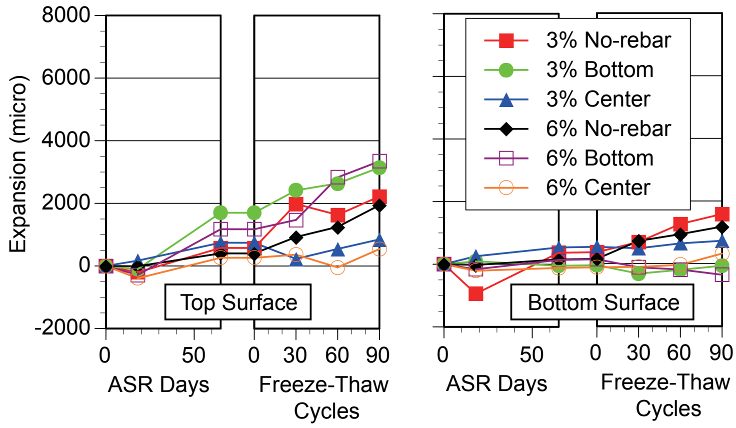


Figure 5. Expansion of F&T beams

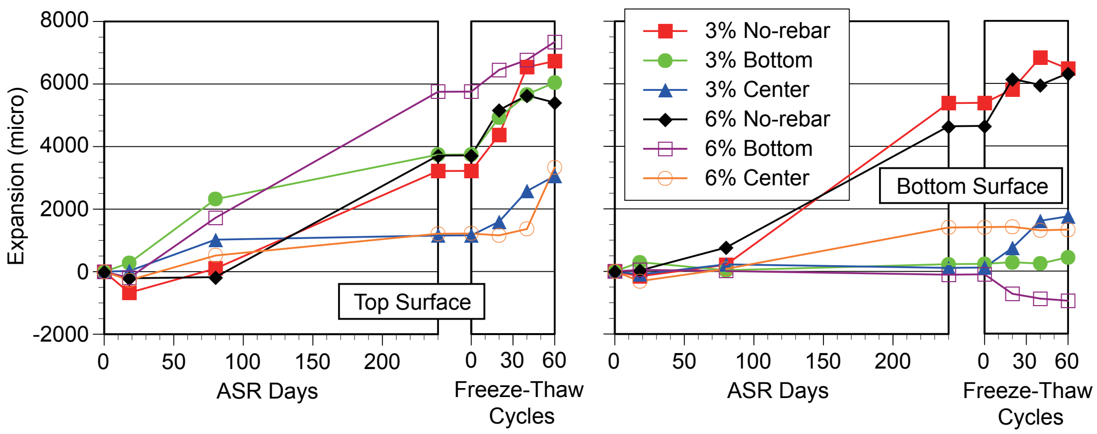
Effect of ASR. The deterioration process of Comp-S beams during the 240days of ASR acceleration period is discussed below.

Figure 6 shows the expansion caused by ASR deterioration. No-rebar and Center-rebar specimens showed a larger expansion on the top surface than the bottom surface. This can be attributed to a difference in coarseness of cement matrix, which is higher in the upper part than the lower part due to the effects of sedimentation and bleeding.

Bottom-rebar specimen showed an expansion on the top surface as high as 6000 micro. On the other hand, the expansion rate was very low on the bottom surface. This uneven expansion is due to the eccentric arrangement of the rebars that confined the bottom part of the beams, in addition to the effects of sedimentation and bleeding as described above.



(a) Expansion of Comp-M

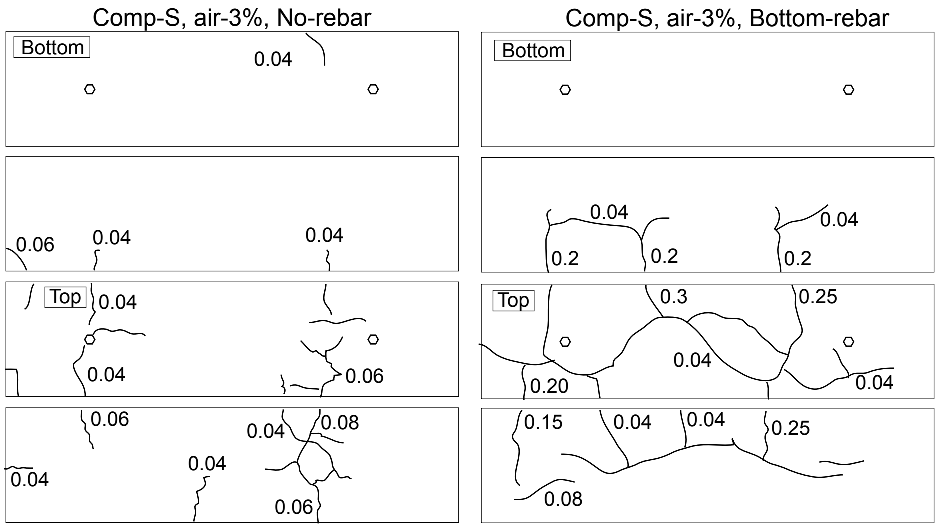


(b) Expansion of Comp-S

Figure 6. Expansion of Comp-M and Comp-S beams. (a) Comp-M. (b) Comp-S

Figure 7 shows examples of crack distributions on the concrete surface after 80days of ASR acceleration. Cracks were formed in a honeycomb-like pattern on the No-rebar beams. On the other hand, the reinforced specimens had crack(s) distributed generally longitudinally along the rebars.

Table 4 shows the maximum crack widths on the respective surfaces. The crack width was generally larger in the top surface in all the specimens, which conforms to the measurement results of expansion shown in Figure. 6. In addition, it was observed that the surface with the widest crack had the highest number of cracks in each specimen (see Figure 7).



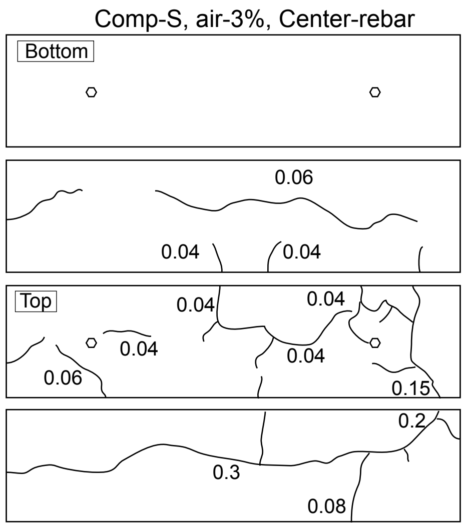


Table 4. The maximum crack widths on the respective surfaces after 80days of ASR acceleration

	Top surface	Bottom surface	Side surface
3%-No-rebar	0.06	0.04	0.08
3%-Bottom	0.3	0.1	0.25
3%-Center	0.15	-	0.3
6%-No-rebar	0.25	0.08	0.3
6%-Bottom	0.15	0.08	0.12
6%-Center	0.12	-	0.2

Figure 7. Examples of crack distributions on the concrete surface after 80days of ASR acceleration

Figure 8 shows the changes in dynamic modulus of Comp-S beams during the ASR acceleration period relative to the dynamic modulus measured at 18days after the start of ASR acceleration as a reference. The relative dynamic modulus decreased with time in all the beams, indicating a progress of internal degradation caused by ASR. The decrease in dynamic modulus tended to be smaller in all the beams with 6% air content than the beams with 3% air content irrespective of the presence or arrangement of rebar. This is because of the entrained air having absorbed the expansive pressure of ASR.

Combined Effects of Frost Attack and ASR. Figure 6 shows the expansion rates of Comp-M and Comp-S specimens during the freezing and thawing cycles after being deteriorated by ASR. Changes in expansion of Comp-M and Comp-S beams during the ASR acceleration period are also shown.

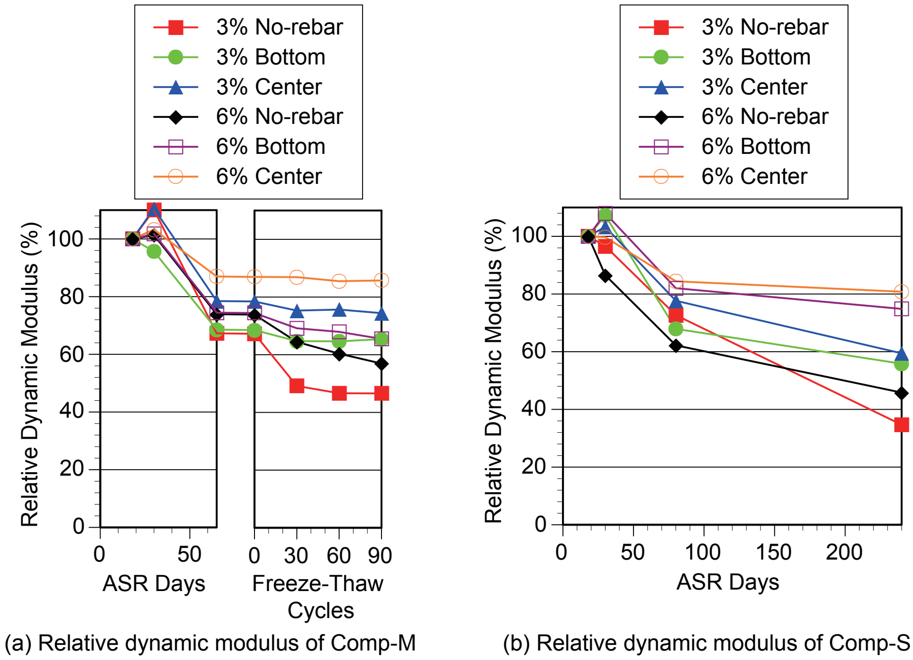


Figure 8. Relative dynamic modulus of Comp-M and Comp-S beams. (a) Comp-M. (b) Comp-S

While the expansion of F&T specimen did not exceed 1000 micro even after 300 cycles of freezing and thawing, the complex deterioration specimens continued to expand even during the freezing and thawing cycles. No-rebar beams of Comp-M specimen showed an expansion of as high as 2000 micro at 90 cycles of freezing and thawing, and Comp-S specimen showed an expansion of a maximum of more than 3000 micro at only 60 cycles. It is considered that internal expansion was accelerated by expansion of water, as it froze, which has penetrated into the microstructure loosened by ASR or through cracks. These results confirm that ASR and frost attack, when acting in combination, cause large synergistic effects.

As for the reinforced specimens, a comparison of the expansion amount on the top and bottom surfaces of the beams indicated a large influence of the rebar arrangement on the expansion rate during the freezing and thawing cycles.

Figure 9 shows the mass changes of Comp-S and Comp-M specimens during the freezing and thawing cycles. It is clear from this figure and Figure 3 that the complex deterioration specimens suffered a larger loss in mass than the specimens that underwent frost attack alone. Photo 1 shows an example of severe surface scaling on a Comp-S beam after the freezing and thawing test. The possible cause of this accelerated surface scaling is the expansive pressure during freezing that destroyed the microstructure of concrete loosened by ASR. Note, however, chloride ions cause severe scaling when combined with the freezing action. Therefore, to preclude the effect of sodium chloride contained in the complex deterioration specimens in this study, and to further clarify the reason for the severe scaling, additional tests are being carried out with specimens that use sodium nitrate as an ASR accelerator.

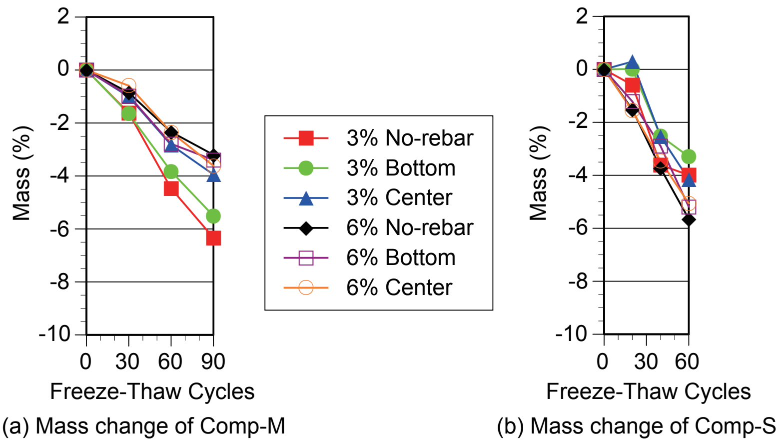


Figure 9. Mass changes of Comp-S and Comp-M specimens during the freezing and thawing cycles. (a) Comp-M (b) Comp-S

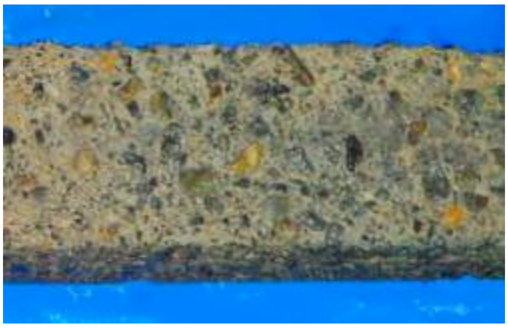


Photo 1. An example of severe surface scaling on a Comp-S beam after the freezing and thawing test

Figure 8 shows the relative dynamic moduli of Comp-M beams during the freezing-thawing cycles. Some beams had a dynamic modulus of as low as 50% after the ASR acceleration and freeze-thaw processes, indicating severe internal deterioration in addition to the surface scaling. As for Comp-S beams, the degree of deterioration was so high that the resonant frequencies were immeasurable during the freeze-thaw cycles.

The effects of the air volume in the concrete were not ascertainable in the complex deterioration specimens. This is probably because the high expansive pressure caused by ASR nullified the pressure absorbing function of minute entrained air.

While the fine and coarse aggregates used in this study were both reactive aggregates, many actual structures suffering ASR use a reactive aggregate only for the coarse aggregate. In this case, the mortar component in the concrete stays relatively intact and the concrete may be resistant to destruction of microstructure even under frost attack. Accordingly, we are conducting an additional research in this respect.

CONCLUSIONS

This study investigated the combined effect of ASR and frost attack on the concrete deterioration. Specimens were prepared with different air contents and different rebar arrangements, and were deteriorated by ASR followed by rapid freeze-thaw cycles. Two levels of ASR deterioration, moderate and severe, were simulated by specimens Comp-M and Comp-S, respectively.

The results obtained by this study can be summarized as follows.

(1) While the expansion of F&T specimen was within 1000 micro after 300 rapid freeze-thaw cycles, the ASR-deteriorated Comp-M specimen showed an expansion of as high as 2000 micro only within 90 freeze-thaw cycles. Comp-S specimen showed an expansion of as high as 3000 micro within 60 freeze-thaw cycles.

(2) Both Comp-M and Comp-S specimens suffered severe scaling during the freeze-thaw cycles, resulting in a large mass loss.

(3) The relative dynamic modulus of Comp-S specimen reduced largely with the progress of ASR. In the freeze-thaw cycles that followed, the resonant frequencies were immeasurable in more than half of Comp-S beams.

(4) Entrained air somewhat alleviated ASR deterioration, but was not effective in slowing down the deterioration caused by the combined action of ASR and frost damage.

REFERENCES

Dhir, R. K., Newlands, M. D., and Paine, K. A. (2003). "Synergetic Effects of Combined Destructive Action on Concrete." *Proceeding of the International Symposium Dedicated to Professor Surendra Shah*, ASCE and Thomas Telford Limited.