Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Mitigation of Alkali-Silica Reaction in Mortar with Limestone Addition and Carbonation

Chun-Tao Chen[1*] and Wei-Cheng Yang[1]

[1]*Department of Construction Engineering, National Taiwan University of Science and Technology*
[*]*No.43, Sec.4, Keelung Rd., Taipei 106, Taiwan (ROC), chuntaoc@mail.ntust.edu.tw, M10005407@mail.ntust.edu.tw*

ABSTRACT

This study explores the strategies for mitigating the alkali-silica reaction (ASR) in mortar. Specimens in accordance to ASTM C1260 were prepared using Type I Portland cements and partly replaced by the limestone powders by volume. Some of those specimens were further subjected to the accelerated carbonation using 50% carbon dioxide. Results showed that the ASR was significantly mitigated by both the limestone addition and the accelerated carbonation. The expansion was decreased by the increased limestone addition and the carbonation depth. Such mitigation of ASR was attributed to the reduced alkalis in the specimens with either limestone addition or carbonation.

Keywords. alkali-silica reaction, mortar, limestone, carbonation

INTRODUCTION

Concrete is one of the construction materials widely used in the world. Numerous reinforced concrete buildings and structures were built with the rapid economic growth in the last century. Those buildings and structures are now getting closer to the end of the designed service life. Therefore, the deteriorations of the buildings are now important issues. Among all the deteriorations, the durability of reinforced concrete is an important concern, such as carbonation, alkali-silica expansion, and salt attack.

The alkali aggregate reaction (AAR) was firstly proposed to explain the spalling of the hydraulic concrete structure (Stanton, 1940). The destruction of the structure was due to the expansive gel in concrete. The AAR was further classified into three categories based on the aggregate compositions: the alkali-silica reaction (ASR), the alkali-carbonate rock reaction (ACR), and the alkali-silicate reaction (Gillott, 1975). Among those deteriorations, the ASR is the most common and thus focused in this study.

The ASR involves the reactions between the reactive silica and the alkalis from the cements. Several strategies have been proposed to inhibit the ASR. First, the best strategy is to avoid the application of reactive aggregates. The expansion of cement mortar is increased by the amounts of reactive aggregates (Stanton, 1940). Second, the application of low-alkali Portland cement is encouraged. The ASR is inhibited by reducing the alkalis from the cement. In ASTM C150, the equivalent alkali content (Na_2O+0.658 K_2O) of the Portland cement is limited to 0.6%. Third, the application of granulated slag (Fernandez-Jimenez and Puertas, 2002) or pozzolanic materials in concrete inhibits the ASR expansion, such as fly ash (Shehaha and Thomas, 2000; Shon et al., 2004) and silica fume (Boddy et al., 2000). In addition to these strategies, some studies show that the ASR can be inhibited by replacing the alkalis with the lithium (McCoy, 1951; Lawrence, 1961; Diamond and Ong, 1992). The lithium compounds that can be transferred into concrete by electric currents are found to reduce ASR expansion (McCoy and Caldwell, 1951). The gel formed by the silica the lithium is not expansive (Diamond and Ong, 1992). However, the lithium compounds are relatively costly and not quite common in practice. In contrast, this study tries to mitigate the ASR by the limestone addition. The limestone is one of the raw materials for producing Portland cements. It has stable properties and abundant resources (Bonavetti et al., 2003). The addition of limestone is supposed to mitigate the ASR in mortar by reducing the dosages of the Portland cement.

The carbonation is another durability issue in concrete. The CO_2 in air reacts with the $Ca(OH)_2$ in concrete and forms $CaCO_3$, thereby reducing the pH in pore solution (Neville, 1981). The reactions can be summarized as (Papadakis et. al, 1989):

$$CO_2 + H_2O \rightarrow H_2CO_3 \tag{1}$$

$$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O \tag{2}$$

The $CaCO_3$ fills up the micropores in concrete so the mechanical properties of concrete can be improved. This study tries to mitigate the ASR by carbonation. The carbonation is supposed to mitigate the ASR not only by reducing the pH in solution but also by increasing the mechanical properties that resist the expansion.

In nature, the concrete is subjected to air so the carbonation and the ASR occur concurrently. However, most of the studies focused on individual deterioration. The proposed models and mechanisms may not fully explain the deterioration in nature. In view of this issue, this study tries to explore the effect of combined deterioration including the ASR and carbonation. In addition, the interactions between the carbonation and ASR in nature are difficult to be simulated in an accelerated environment. The temperature, environmental humidity, and CO_2 concentrations are all to be determined. This study thus uses a tentative method based on ASTM C1260 by alternating the carbonation and ASR. Further studies on improved accelerated approaches are suggested.

MATERIALS AND METHODS

Specimen. Three mortar bars (25×25×285 mm) were prepared in accordance to ASTM C1260 for each mix. The Pyrex glass that contains reactive silicate was used for the fine aggregates. In addition to the w/c of 0.47, this study used w/c of 0.6 for the specimens so that the effect of carbonation was better observed. Portions of the cements were replaced by limestone powders with an average size of 14.2 μm by volume to show the effect of limestone addition. The experimental parameters are summarized in Table 1.

Table 1. Experimental Parameters.

Parameters	Values
w/c	0.47 (ASTM C1260), 0.6
Limestone Replacement (%)	0, 5, 10, 15, 20, 25
Carbonation Time (hrs)	0, 3, 6, 18, 24, 72

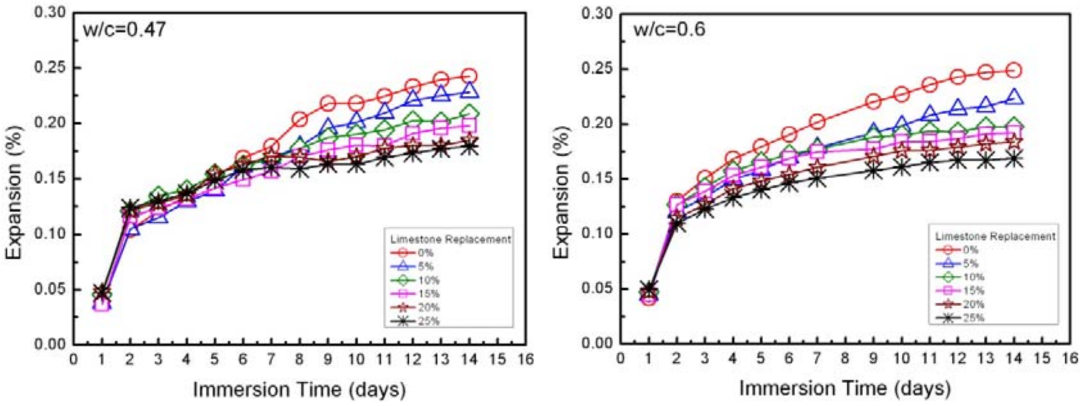
Methods. The ASR in the specimens was accelerated in accordance to the procedures described in ASTM C1260. Specimens were immersed in 80 °C hot water for one day after demold. The initial length was measured and then the specimens were cured in 1N NaOH at 80 °C. The length change of the specimen was measured each day. To explore the effect of carbonation, the preparation procedures before the length measurements each day were modified. The specimens were oven-dried at 105 °C to constant weight for one day, subjected to accelerated carbonation with 50% CO_2 by volume at 70% RH, 25 °C for certain days, and then cured in 1N NaOH at 80 °C. To explore the effect of alternating accelerated carbonation and ASR, the specimens were cured in 1N NaOH at 80 °C for 1 day, oven-dried at 105 °C to constant weight for one day, and accelerated carbonation for another day. Such procedure was repeated for 14 days.

RESULTS AND DISCUSSION

Limestone Addition. The effect of limestone addition is shown in Figure 1. The expansion was increased with time and slowed down at later hydration time. The limestone addition effectively reduced the ASR expansion at both w/c of 0.47 and 0.6. However, such mitigation was not clear during the first week of the ASR acceleration at w/c of 0.47 (Figure 1(a)). It is likely that the hydration at that time was still low so the effect of limestone addition was not dominant. In general, the mitigation effect at w/c of 0.6 was larger than that at w/c of 0.47.

The results in Figure 1 suggest an optimum limestone addition of 10%, which effectively reduced the expansion at both water-cement ratios. With limestone addition of 15% or more, the mitigation at 14 days was not far from that with 10%. In consideration of other side effects by the limestone addition, such as the strength reduction at high dosages, the limestone addition of 10% appears to be the most appropriate.

The ASR expansion was attributed to the reactions between the active glass and the alkalis from the cements. By adding the limestone, the cement dosages were reduced. The limestone is comparatively inert in those mortar bars, thereby reducing the alkalis in the specimens and delaying the ASR expansion. In addition, the fine limestone powders dispersed the cement particles. They act as the barrier to water so the hydration of the cement and the release of the alkalis are retarded. The limestone powders can fill the microspores so the dense microstructure further resists the ASR expansion.



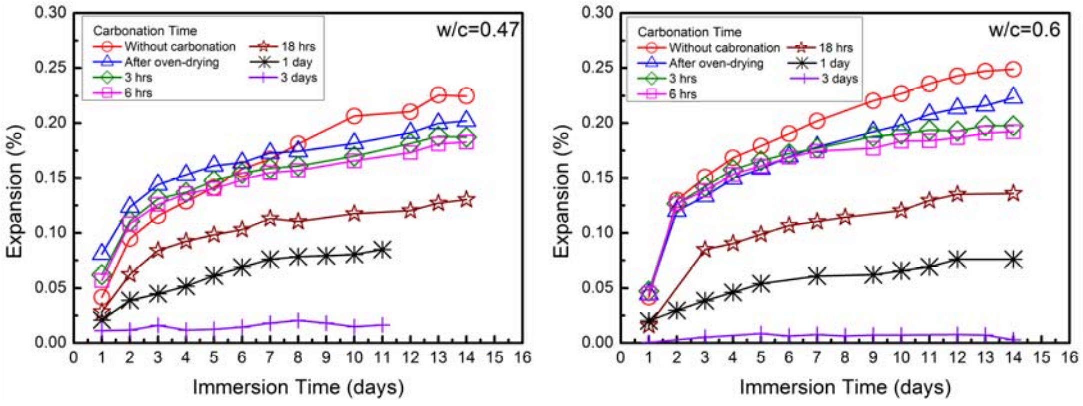
(a) (b)

Figure 1. The ASR expansions in specimens with different limestone addition at w/c of (a) 0.47, or 0.6.

Carbonation. The effect of carbonation is shown in Figure 2. The ASR expansion was greatly mitigated at both water-cement ratios. It should be noted that the specimens subjected to the accelerated carbonation were oven-dried. The carbon dioxide cannot enter the saturated specimens. The effects of oven-drying were firstly explored so the length changes of the specimens after drying were measured. Results showed that the drying at the very early hydration time reduced the expansion more at w/c of 0.47 (Figure 2(a)) than at w/c of 0.6 (Figure 2(b)). The internal free water was removed so the shrinkage occurred.

The carbonation further mitigated the ASR expansion. As the carbonation time increased, the expansion was reduced. Such mitigation was even more effective than the limestone addition, as stated previously. Similar mitigations in those specimens with 25% limestone addition were archived just by carbonation time of 3 hours. In addition, there was no ASR expansion in specimens subjected to carbonation time of 3 days. Such findings are encouraging. Results suggest that the onsite ASR can be effectively inhibited by proper surface treatments using carbon dioxide. The time for the treatment can be short.

The carbonation reduces ASR expansion more than limestone addition because the carbonation not only reduces the alkalis in the pore solution but also modifies the microstructure of the specimens. The calcium carbonate formed during the carbonation fills up the microstructure so the carbonated specimens have lower porosity and higher strength, all of which help to resist the ASR expansion.



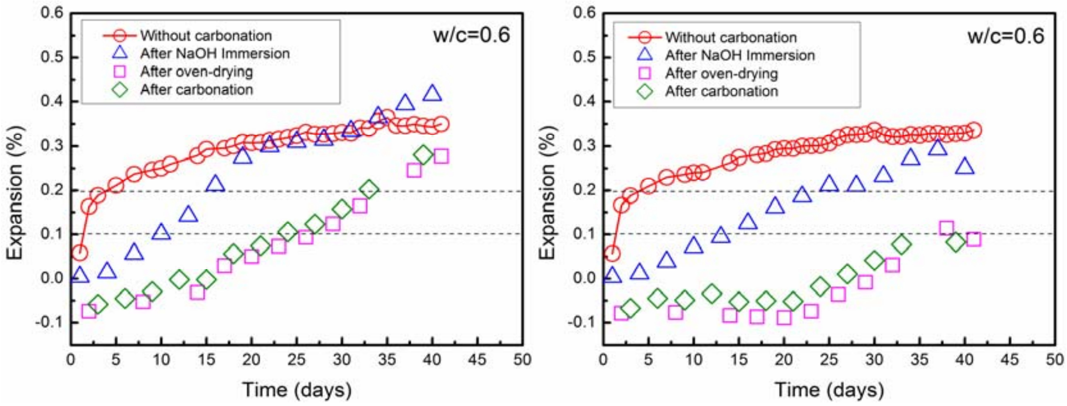
(a) (b)

Figure 2. The ASR expansions in plain specimens with different carbonation time at w/c of (a) 0.47, or 0.6.

Alternating Accelerated Carbonation and ASR. In contrast to the accelerated carbonation conducted prior to the accelerated ASR, this study tried a new approach by alternating the carbonation and ASR to study the combined deterioration. The effect of alternating carbonation and ASR is shown in Figure 3. During the accelerated tests, the lengths of the specimens were measured after each stage was complete, including the NaOH immersion, oven drying, and the accelerated carbonation. Results in Figure 3(a) show that the specimens expanded after each NaOH immersion and shrunk after each oven drying and carbonation. Such alternating approach effectively mitigated the ASR expansion at early time. However, by comparing the results in Figure 2(b), the alternating carbonation did not mitigate the ASR very well. In Figure 2(b), the accelerated carbonation was only conducted prior to the accelerated ASR. The expansion was reduced and the length of the specimen stabilized at immersion time of 14 days. On the other hand, in Figure 3(a), several times of accelerated carbonation were conducted, but the expansion continued throughout tests, suggesting that the alternating carbonation could worsen the ASR expansion. The crack patterns in Figure 4 agree with the findings in Figure 3(a). Those specimens subjected to alternating carbonation and ASR had more cracks and broken apart early.

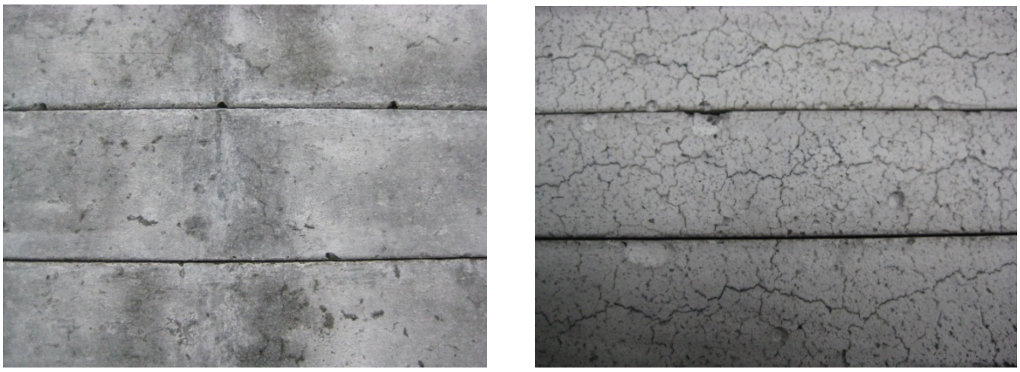
Results in Figure 3 imply that the combined deterioration due to both the ASR and carbonation can be detrimental. The alternating expansion due to the ASR and the shrinking force due to the carbonation induce microcracks so the mortar cracks easily. Results also suggest that the protocol in ASTM C1260 may overestimate the ASR potentials for reactive aggregates in nature. The carbonation mitigates the ASR expansion and the effect of combined deterioration only dominates in the long term.

The addition of limestone mitigated the combined deterioration, as shown in Figure 3(b). Similar to the results in Figure 3(a), the expansion was increased after each NaOH immersion. However, the expansion appeared to be stabilized at later time and was always less than those without experiencing the alternating carbonation and ASR, suggesting that the ASR can be effectively reduced by both the limestone addition and accelerated carbonation.



(a) (b)

Figure 3. The ASR expansions in specimens (a) without or (b) with 10% limestone addition under alternating accelerated carbonation and ASR.



(a) (b)

Figure 4. The crack patterns in specimens (a) without carbonation or (b) with alternating accelerated carbonation and ASR at time of 40 days.

CONCLUSION

The ASR expansion of the cement mortar was mitigated by the limestone addition and the accelerated carbonation. With increased limestone addition and carbonation time, the ASR expansion of the mortar was reduced. The accelerated carbonation was more effective than the limestone addition. The reduced expansion by the limestone addition of 25 % was archived by the carbonation within 1 day. With alternating accelerated carbonation and ASR, the expansion was mitigated only during early time but further aggravated in the long term.

ACKNOWLEGEMENT

The authors acknowledge the financial support from the Taiwan Building Technology Center at National Taiwan University of Science and Technology, Taipei, Taiwan.

REFERENCES

Boddy, A. M., Hooton, R. D. and Thomas, D. A. (2000). ″The effect of product form of silica fume on its ability to control alkali-silica reaction.″ Cement and Concrete Research, 30, 1139-1150.

Bonavetti, V., Donza, H., Menendez, G., Cabrera, O. and Irassar, E. F. (2003). ″Limestone filler cement in low w/c concrete: A rational use of energy.″ Cement and Concrete Research, 33, 865-871.

Diamond, S. and Ong, S. (1992). ″The mechanisms of lithium effects on ASR.″ *Proceeding of the 9th International Conference on Alkali-Aggregate Reaction in Concrete*, The Concrete Society, London, 269－278.

Fernadez-Jimenez, A. and Puertas, F. (2002). ″The alkali-silica reaction in alkali-activated granulated slag mortars with reactive aggregate.″ Cement and Concrete Research, 32, 1019-1024.

Gillott, J. E. (1975). ″Alkali-aggregate reaction in concrete.″ Engineering Geology, 9, 303-326.

Lawrence, M., and Vivian, H. E. (1961). ″The reactions of various alkalis with silica.″ Australian Journal of Applied Science, 12, 96-103.

McCoy, W. J., Caldwell, A.G. (1951). ″New approach to inhibiting alkali-aggregate expansion.″ Journal of the American Concrete Institute, 22, 693-706.

Neville, A. M. (1981). *Properties of Concrete*, Pitman, New York, NY.

Papadakis, V. G., Vayenas, C. G. and Fardis, M. N. (1989). ″A reaction engineering approach to the problem of concrete carbonation.″ AIChE Journal, 35, 1639-1650.

Shehata, M. H. and Thomas, M. D. A. (2000). ″The effect of fly ash composition on the expansion of concrete due to alkali-silica reaction.″ Cement and Concrete Research, 30, 1063-1072.

Shon, C. S., Sarkar, S. L. and Zollinger, D. G. (2004). ″Testing the effectiveness of class C and class F fly ash in controlling expansion due to alkali-silica reaction using modified ASTM C 1260 test method.″ Journal of Materials in Civil Engineering, 16, 20-27.

Stanton, T. E. (1940). ″Influence of Cement and Aggregate on Concrete Expansion.″ Engineering News-Record, 124, 59-61.