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Carbonation cracking of reinforced AAC panel

ABSTRACT: Carbonation cracking and its mechanism of AAC have not been reported at all. One of the possible mechanisms of carbonation cracking caused by carbonation shrinkage is investigated. Carbonation shrinkage at the occurrence of cracking was approximately 0.12% both for field study and accelerated carbonation, while carbonation degree was approximately 50% and 35%, respectively. Tensile stress in AAC was calculated to reach tensile strain capacity (0.04–0.05%) at the occurrence of cracking both for field study and accelerated carbonation data. In other words, the proposed mechanism of carbonation cracking was certified.

KEY WORDS: carbonation, shrinkage, cracking, tensile strain capacity

1. Introduction

When carbonation degree of AAC was more than 50%, the growth of lattice-like cracking was observed as shown in the previous study [1]. The lattice-like cracking is understood as the homogeneous stress in the surface of an AAC panel. In general, causes of cracking include mechanical stress, thermal stress, stress due to corrosion of reinforcing steel bars, stress due to drying shrinkage, and stress due to carbonation shrinkage. Characteristic shrinkage phenomena during carbonation of AAC are increasing of drying shrinkage and carbonation shrinkage. The drying shrinkage for fully carbonated field-AAC is approximately 0.06%, which is just twice as much as that of control AAC [2]. On the other hand, carbonation shrinkage of fully carbonated AAC in the accelerated treatment is approximately 0.25% which is 6 to 7 times larger than the drying shrinkage of control AAC [3], while carbonation shrinkage of field-AAC was impossible to measure as a matter of course. Consequently, carbonation shrinkage is considered to be one of the main factors affecting the carbonation cracking. Another possible factors of carbonation cracking include the shrinkage gradient over the thickness. If carbonation progresses in the surface part more than in the center part, the surface part should have shrinkage stress. However, carbonation cracking can be observed at a carbonation degree higher than 50%, regardless of the gradient of carbonation degree over the thickness [1].

Carbonation cracking and its mechanism have not been reported at all. In this paper, one of the possible mechanisms of carbonation cracking caused by carbonation shrinkage is investigated.

2. Mechanism of carbonation cracking

2.1. Initial stress

At the first consideration of stresses in AAC, the initial stresses due to the difference in thermal expansion coefficient of AAC and of reinforcing steel bars must be mentioned. AAC has much lower thermal expansion coefficient than that of steel that there will be a tensile stress in reinforcing steel bars and a compressive stress in AAC matrix after autoclaving. Koponen and Nieminen [4] indicated that initial stresses was influenced by materials of anti-corrosion coating applied on the reinforcing steel bars and reported the initial
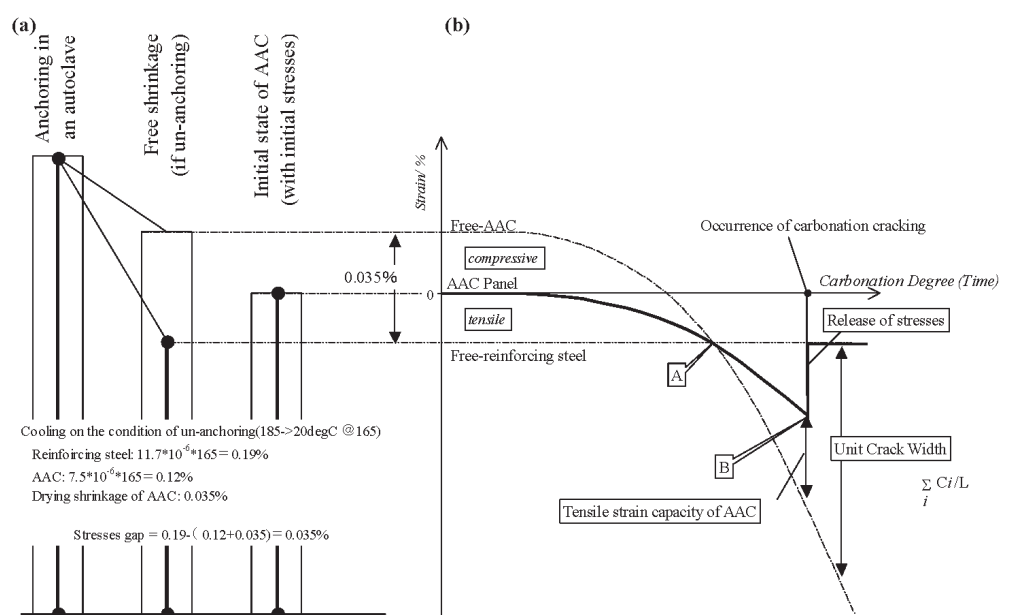

Fig. 1. Schematic drawing of (a) initial stresses and (b) mechanism of carbonation cracking.

steel stresses when converted to the strain, were approximately 0.1% (1 mm/m) for a cement-based anti-corrosion coating.

Fig. 1(a) shows the linear schematic drawing of initial stresses of both AAC and reinforcing steel bars. AAC and reinforcing steel bars bond during autoclaving approximately at 180°C. After autoclaving, the reinforcing steel bars shrink due to cooling until normal temperature, and AAC also shrinks due to cooling and drying from water saturated condition to an equilibrium state of a normal condition. If AAC and reinforcing steel bars have no bond, they would show free shrinkage and shrinkage gap would be generated. The gap due to the free shrinkage can be calculated as an equipment strain of 0.035%, which corresponds to the sum of tensile stresses in reinforcing steel bars and compressive stresses in AAC. The allocation of total stresses over the reinforcing steel bars and the AAC depends on the panel size and the amount of reinforcing steel bars.

2.2. A hypothetical mechanism of carbonation cracking

The linear schematic drawing of mechanism of carbonation cracking is proposed as shown in Fig. 1(b). In this figure, the length changes of free-AAC and free-reinforcing steel as well as AAC panel are shown as a function of carbonation degree. The "free-" means no bond and the distance from "AAC panel" indicates the initial stresses, in which positive value means compressive stress and negative value means tensile stress. At the initial stage, AAC and reinforcing steel have compressive and tensile stresses, respectively. Therefore, AAC is shown above while reinforcing steel below.

The length of free-reinforcing steel shows no change under a constant temperature during carbonation, as a matter of course. Free-AAC shrinks due to carbonation at a constant carbonation condition. AAC panel as a whole thus shrinks due to the shrinkage of free-AAC during carbonation. When carbonation shrinkage of free-AAC reaches the total initial strain of AAC and reinforcing steel (at point A in Fig. 1(b)), there should be no stresses both in AAC and reinforcing steel. Subsequently, tensile stresses and compressive stresses occur respectively in AAC and reinforcing steel. When tensile strains in AAC reach their capacity (at point B in Fig. 1(b)), carbonation cracking should occur and strains both in AAC and reinforcing steel should be released. The unit width of carbonation cracking should be the difference in strain of free-AAC and free-reinforcing steel when strains are fully released.

3. Carbonation cracking and stresses in field AAC panels

3.1. Samples

To verify the proposed mechanism of carbonation cracking by field AAC panels, cracking width and stresses of AAC and reinforcing steel were measured and adopted to the mechanism shown in Fig.

1(b). Field AAC panels aged 4 to 33years and brand-new AAC panels made by Sumitomo Metal Mining Siporex Co., Ltd were subjected to analysis.

3.2. Experimental

Carbonation degree was determined as shown in the previous study [5]. Stresses of AAC and reinforcing steel were measured by strain gauges in a manner explained below. Surface of AAC over the reinforcing steel bar was sandpapered to be flat and smooth. Strain gages with a 10 mm-length detector, Tokyo Sokki Kenkyujo Co. PFL-10-11-3LT, were adhered on the surface with a quick-hardening adhesive. After zero adjustment of the strain gage, AAC surrounded the strain gage was removed to release the initial stresses of AAC. The measured strain after the removal indicated the initial stresses of AAC.

Subsequently, AAC surrounded the reinforcing steel and anti-corrosion materials were torn off to have bare reinforcing steel. Surface of reinforcing steel was sandpapered to be smooth. Strain gages with a 2 mm-length detector, Tokyo Sokki Kenkyujo Co. FLK-2-11-3LT, were adhered on the surface with the quick-hardening adhesive. After zero adjustment of the strain gage, reinforcing steel beside the strain gage was cut off to release the initial stresses of reinforcing steel. The measured strain after the cutting off indicated the initial stresses of reinforcing steel.

Width of carbonation cracking was measured by using crack gage. Measured positions were perpendicular to the length of a panel. Width of carbonation cracking was normalized by the length of the panel and was calculated in percentage as shown in Fig. 2.

Cn: Width of each cracking

Width of carbonation cracking (%)
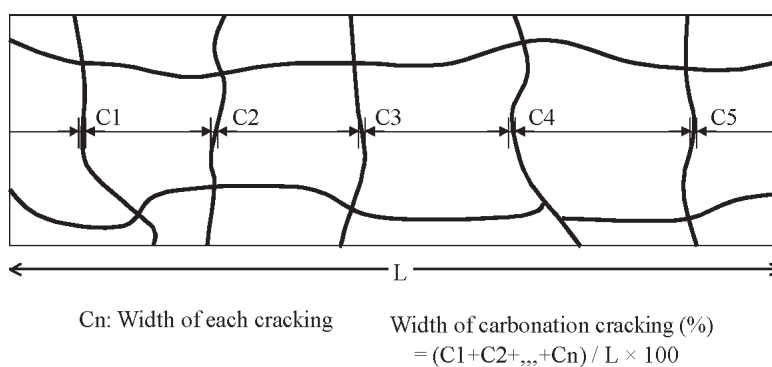= (C1+C2+,,,+Cn) / L × 100

Fig. 2. Schematic drawing of unit width of carbonation cracking.

3.3. Results and discussion

Fig. 3 shows strain of AAC panel as a function of carbonation degree. Positive strain means compression. At the initial state, strain ranged from 0.02 to 0.035% and was almost unchanged at a carbonation degree less than 20%, which agreed well with the absence of carbonation shrinkage at the same carbonation degree [3]. At a carbonation degree around 35%, strain became smaller than initial state. Finally at a carbonation degree more than 50%, strain decreased less than 0 or -0.01%.

Fig. 4 shows strain of reinforcing steel as a function of carbonation degree. Negative strain means tension. At the initial state, strain
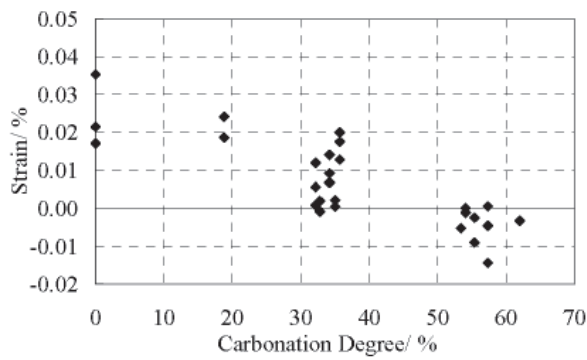
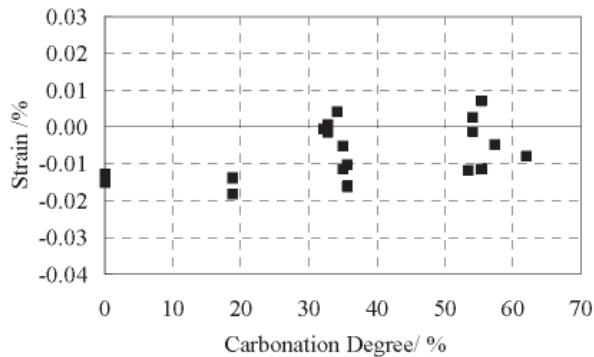Fig. 3. Strain of AAC in field AAC panels as a function of carbonation degree.

Fig. 4. Strain of reinforcing steel in field AAC panels as a function of carbonation degree.
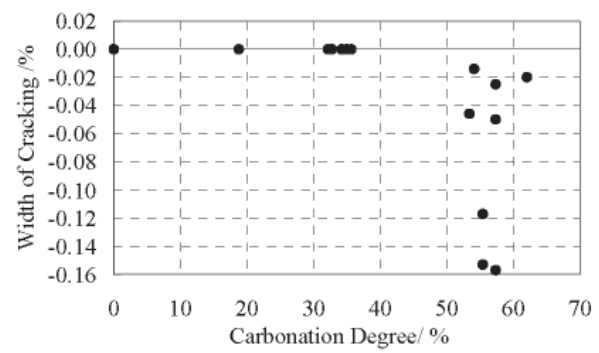

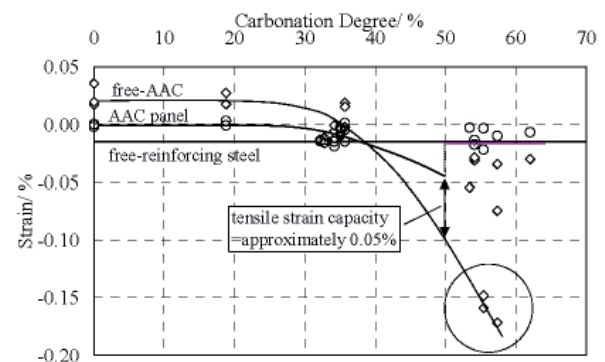Fig. 5. Width of carbonation cracking for AAC panels as a function of carbonation degree.

Fig. 6. Calculated results by field AAC panels on the proposed mechanism of carbonation cracking as shown in Fig. 1(b).

was approximately -0.015% and was almost unchanged at a carbonation degree less than 20%. This agrees well with the strain of AAC as mentioned above and shows no carbonation shrinkage at the same carbonation degree [3]. The total initial stresses of AAC and reinforcing steel can be calculated from 0.035% to 0.05% in strain. At a carbonation degree around 35%, strain became larger than the initial state. Finally at a carbonation degree more than 50%, strain increased more than -0.01%.

Fig. 5. shows unit width of carbonation cracking as a function of carbonation degrees less than 50%. Cracking was observed in all specimens with a carbonation degree more than 50%, while its unit width scattered widely from 0.02 to 0.16%.

In the proposed mechanism of carbonation cracking, actual length change occur only in AAC matrix. In other words, the total strain change of AAC, reinforcing steel and unit width of cracking are due to the carbonation shrinkage of AAC matrix. Consequently, carbonation shrinkage of field AAC panel could be obtained as the sum total of them. Fig. 6 shows the calculated results on the proposed mechanism of carbonation cracking with the measured data imposed. In this figure, carbonation shrinkage of free-AAC was drawn with reference to that under accelerated carbonation condition as shown in [3]. AAC panel was drawn at a fixed ratio of strain of AAC and that of reinforcing steel.

Carbonation shrinkage of free-AAC from accelerated data shows good agreement with the relatively large unit width of cracking as shown on the circle in Fig. 6. Also, the tensile strain of AAC was attributed to the limit of tensile strain capacity (approximately

0.04–0.05%) at a carbonation degree of approximately 50%. The value of carbonation shrinkage of free-AAC at the occurrence of cracking was considered to be approximately 0.12% (0.02% (initial stress) + 0.10%). However this was not applicable to cracks with smaller width. It could be attributed to inivisible cracks, such as micro-cracking, or relaxation by creep. Anyway, carbonation shrinkage of free-AAC from accelerated data could explain the occurrence of carbonation cracking by proposed mechanism with the relatively large unit width of cracking.

4. Carbonation cracking and stresses in accelerated carbonation

4.1. Samples

To verify the proposed mechanism of carbonation cracking by accelerated carbonation, unit cracking width and stresses of AAC and reinforcing steel were measured and adopted to the mechanism as shown in Fig. 1 (b). Brand-new AAC panels and blocks made by Sumitomo Metal Mining Siporex Co., Ltd were subjected to analysis. The panels were dried in a room sufficiently to an equilibrium state under the normal condition.

The blocks were shaped in 40 mm x 40 mm x 160 mm and dried at 105°C for 2 hours. After that, a pair of 20 mm-brass pins was fixed on both ends by an adhesive for the length change measurement. Subsequently, the panels and the blocks were cured under the condition of 20°C and 60%R.H. for 2 weeks, following

by accelerated carbonation under the condition of 20°C, 60% R.H. and 3 vol.% CO_2.

4.2. Experimental

Carbonation degrees at every 10 mm in the direction of thickness were measured. Unit width of cracking and stresses of AAC and reinforcing steel were measured as shown in the section 3.2. Shrinkage strain δ due to carbonation can be given by,

$$\delta = [(l - l_0)/l_0] \times 100, \tag{1}$$

where l and l_0 were a length and the initial length after pre-treatment under conditions of 20°C and 60% R.H. for 1 week. Measurement was always done in the carbonation chamber under conditions of 20°C, 60% R.H. and 3 vol.% CO_2.

4.3. Results and discussion

Carbonation degree at every 10 mm in the direction of thickness as a function of treated time is shown in Fig. 7. Difference in carbonation degree from the surface to the center was very small so that the carbonation progressed uniformly in AAC panels.

Cracking was observed at 42-day treatment when carbonation degree was approximately 35%. Subsequently, it spread in a lattice-like form.

Carbonation shrinkage as a function of carbonation degree is shown in Fig. 8. The value of carbonation shrinkage at a carbonation degree of 35%, when cracking was observed, was approximately 0.12%, which was in good agreement with the results from field AAC panels shown in the section 3.3.

Stresses of AAC and reinforcing steel bars and unit width of cracking as a function of carbonation degree are shown in Fig. 9. Initial stresses of AAC and steel bars were approximately 0.02% in compression and approximately 0.035% in tension, respectively. At a carbonation degree of approximately 20%, stresses of AAC and steel bars were almost released. At a carbonation degree of approximately 30%, tensile stress occurred in AAC and compressive stress in steel bars, contrarily. At that time tensile strain in AAC was approximately 0.02%, which was smaller than tensile strain capacity (0.04–0.05%). This explains why cracking had not been occurred yet. At carbonation degree of approximately 35% with the occurrence of cracking, stress of steel bars was released again. Subsequently, unit width of cracking increased with the progress of carbonation. On the other hand, stress of steel bars was almost zero and stress of AAC stayed in tension and the corresponding strain ranged Carbonation Shrinkage (%) from 0.02% to 0.03%, which was smaller than tensile strain capacity (0.04–0.05%). Therefore, it was considered that most of carbonation shrinkage was converted to cracking at carbonation degree greater than 35%.

Changes in strains of AAC and steel bars, unit width of cracking and sum total of them as a function of carbonation shrinkage are shown in Fig. 10. Until carbonation shrinkage of approximately 0.14%, change in strains and unit width of cracking corresponded to carbonation shrinkage. After carbonation shrinkage of 0.2% with increase in unit width of cracking, change in strains and unit

Fig. 9. Strain of AAC and reinforcing steel bars and width of cracking as a function of carbonation degree.
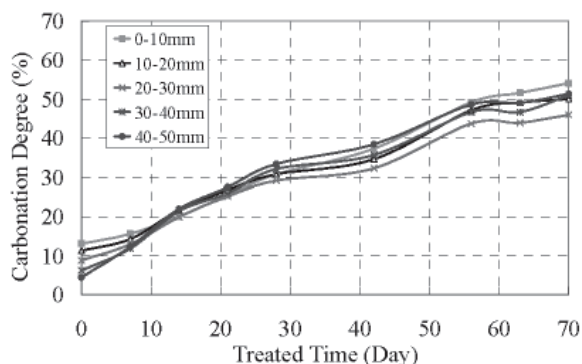
Fig. 7. Carbonation degree of AAC panel in direction of thickness at every 10 mm as a function of treated time.

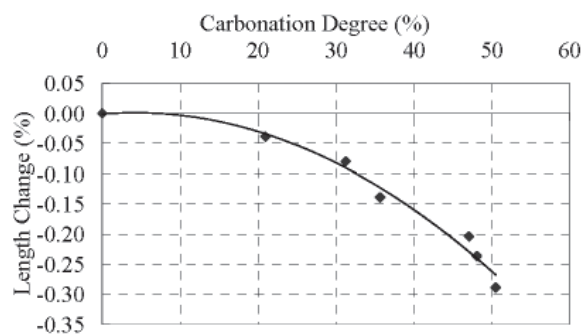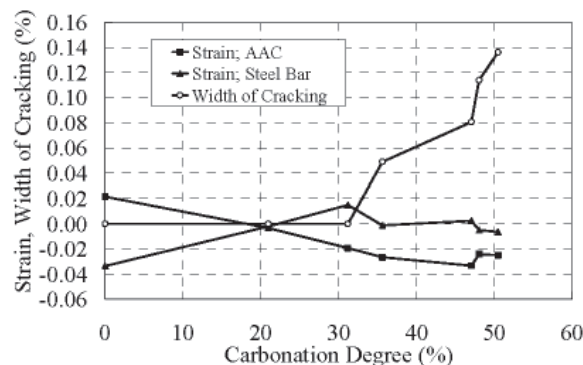Fig. 8. Carbonation shrinkage as a function of carbonation degree.
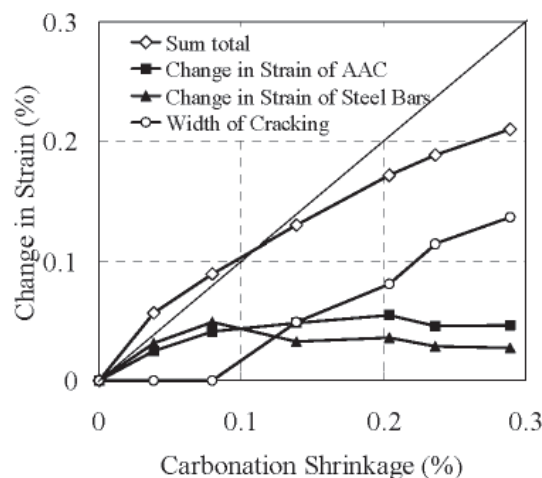
Fig. 10. Change in strain of AAC and steel bars, width of cracking and sum total of them as a function of carbonation shrinkage.
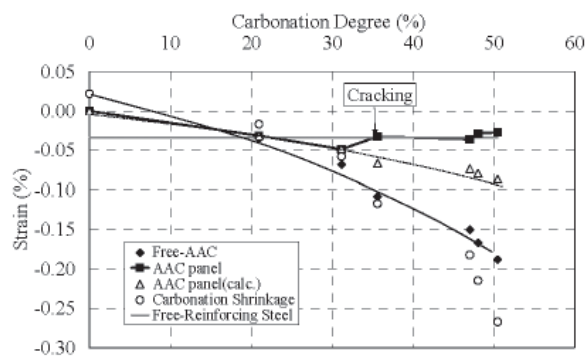
Fig. 11. Change in strain of AAC and steel bars, unit width of cracking and sum total of them as a function of carbonation degree.

width of cracking became smaller and was apart from the carbonation shrinkage. The reason was considered to invisible cracks or relaxation by creep. Anyway, it was considered that carbonation shrinkage was the fundamental factor of cracking.

Fig. 11 shows the calculated results of the proposed mechanism of carbonation cracking as shown in Fig. 1 (b) with measured data imposed. In this figure, carbonation shrinkage of free-AAC was also drawn. AAC panel (calc.) was drawn as triangles and dashed line under assumptions that elastic modulus did not change and cracking did not occur. At the occurrence of cracking when carbonation degree was approximately 35%, it was considered that tensile stress of AAC, which was the difference between AAC panel (calc.) and free-AAC, reached approximately 0.05%, which corresponded to the tensile strain capacity of AAC. In addition, carbonation shrinkage at the occurrence of cracking was calculated as approximately 0.12%, which corresponded to the data from field AAC. Consequently, it was considered that the proposed mechanism of carbonation cracking (Fig. 1 (b)) was verified.

5. Summary

Carbonation cracking and its mechanism were investigated. The results can be summarized as follows.

(1) One of the possible mechanisms of carbonation cracking due to stresses and carbonation shrinkage was proposed as shown in Fig. 1.

(2) Carbonation shrinkage at the occurrence of cracking was approximately 0.12% both in field study and in accelerated carbonation, while carbonation degree was approximately 50% and 35% for field study and accelerated carbonation, respectively.

(3) Tensile stress in AAC to reach the tensile strain capacity (0.04–0.05%) at the occurrence of cracking both in field study and accelerated carbonation was calculated. In other words, the proposed mechanism of carbonation cracking was certified.

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