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STRAIN MONITORING OF CFRP WRAPPED RC COLUMNS DAMAGED BY ALKALI AGGREGATE REACTION

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Abstract

One method of repairing structural elements damaged by alkali-aggregate reaction (AAR) is confining them by wrapping with epoxy-impregnated carbon fibre reinforced polymer (CFRP) material. This paper presents the results of experimental investigations involving strain measurements in reinforced concrete (RC) columns, damaged by AAR, before and after the application of CFRP. Square and circular RC columns were cast, incorporating fused silica as reactive aggregate, and stored at 38°C and 100% relative humidity for periods of one and two months. They were then wrapped with one or two layers of normal modulus (240 GPa) CFRP.

Various types of strain gauges were used to monitor strain development in the horizontal and vertical direction in the concrete and in the longitudinal and transverse bars in the columns. The strain measurements continued after the columns were repaired. Strains were also measured on the CFRP wrapping for another 250 days. For comparison, expansion measurements were also carried out on concrete prisms, according to ASTMC1293, using the same mixture as that used in the columns.

The results of the strain measurement were analyzed with respect to the effect of internal and external reinforcement, provided by the reinforcement bars and the applied CFRP on the strain developments in the columns before and after CFRP wrapping. The results show that the effectiveness of CFRP wrapping depends on the shape of the columns and the number of CFRP layers used for wrapping them. Most importantly, the time of CFRP wrapping has a major influence on the effectiveness of CFRP in confining the expansion of the AAR-affected columns, earlier application being more effective.

Keywords: RC column, fused silica, CFRP

1 INTRODUCTION

It is generally recognized that AAR is a deterioration process by which ongoing expansion may eventually result in concrete cracking, hence affecting the integrity of structures. Since the process is time-dependent, the repair of

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affected structures is challenging because it involves two objectives; to repair the existing cracks and control further expansion in the concrete. Surface protection is the only preventive approach that can be performed to control further deterioration by minimizing moisture absorption from external sources. A number of considerations must be taken into account before initiating the repair of AAR-affected structures, such as the condition of the concrete and the repair material. The assessment of the concrete includes the stage of expansion, the moisture level in the concrete and the area of repair coverage (Wang et al., 1996). Lack of information on the condition of the affected structures may result in an ineffective solution for any given material used for repair.

There are a number of materials used for the immediate repair of AAR-affected structures, such as cement-based material and various types of epoxies, which provide only a temporary solution and do not improve the overall performance of the concrete. The use of FRP strengthening systems has recently become an option for the repair of defective structures caused by excessive loading and damage. However, the technique of repairing AAR-affected structures with FRP is still relatively new and the knowledge of it is limited. A study conducted by the authors has revealed that carbon fibre reinforced polymer (CFRP) significantly improves to the load-carrying capacity and ductility of RC columns damaged by AAR in comparison with untreated columns (Siti et.al, 2010). The reason for this improvement was further investigated by examining the strain development of CFRP-wrapped columns over time. The study was undertaken with the following objectives;

- To examine strain development in RC columns before and after CFRP wrapping
- To investigate the effect of wrapping time, number of CFRP layers and column shape on the strain development of CFRP-wrapped columns

2 MATERIALS AND METHODS

2.1 Mixture proportions, materials and specimens

The concrete mix used had a cement: sand: coarse aggregate ratio of 1:1:2.7 with 420kg/m^3 cement and a water-cement ratio of 0.44. Fused silica was used as reactive aggregate replacing the fine aggregate by 7.5%. Sodium hydroxide was added to the mixing water of the concrete mixture to increase the alkali level to 1.25% Na_20 equivalent. Eight columns consisting of 4 circular and 4 square columns were prepared for the investigation. The circular columns had a diameter of 215mm and 1.56% of longitudinal reinforcement. The square columns had a cross section of 200x200mm and were reinforced with 1.17% longitudinal steel. The volumetric transverse reinforcement ratio was 0.23% for the circular columns and 0.39% for the square columns. Both types of columns were 550mm in height. The columns were placed in 38°C, 100% humidity environment for a maximum period of 60 days.

2.2 FRP Application

Normal modulus CFRP was used to wrap the columns. The CFRP had an elastic modulus of 240GPa and a tensile strength of 3600 MPa. The columns were sandblasted to provide better adhesion for the CFRP wrapping. Each column was placed horizontally on a rolling machine designed for CFRP application (Figure 1) and wrapped using wet-layup technique. The columns were wrapped after 1 and 2 months exposure in the environmental chamber. After CFRP application, the columns were returned to the environmental chamber for another 250 days.

2.3 Installation of strain gauges

Concrete core

Two strain gauges with the length of 60mm (model PML-60-2LT) were used to measure the internal strain development of the columns. Each gauge was encapsulated in polymer to prevent moisture ingress. The gauges were arranged so that they were located at the centre of the column cross-section and at mid-height. Thin steel wire was tied on the strain gauges to hold the gauges in the horizontal and vertical positions, as shown in Figure 2.

Steel reinforcement

The waterproof strain gauge was attached to the steel reinforcement bar. This gauge was sealed with epoxy resin. For the transverse reinforcement, general purpose strain gauges were used due to the small surface area of reinforcement. Figure 3 shows photographs of both types of strain gauges for the steel reinforcement. After these strain gauges were glued to the surface of the steel reinforcement bars, they were protected with some layers of MCoat D to prevent moisture ingress.

CFRP layers

The exterior of the CFRP-wrapped columns was fitted with three strain gauges; two were placed horizontally opposite each other and one in the vertical position. These strain gauges were positioned at the mid height of the column. Before attaching the gauges, the CFRP surface was smoothed with sand paper and cleaned with Isopropyl alcohol. Protection was provided on the glued strain gauges using one coat of MCoat D, followed by one coat of beeswax. Figure 4 shows a prepared strain gauge on the fibre.

2.4 Data collection

The strain gauges were connected to the data acquisition system. A program was developed to collect data from the strain gauges. Data were collected every 5 minites, resulting in approximately 250 data points per day.

3.0 RESULTS AND DISCUSSION

Free expansion

The expansion curve of the concrete prisms made with 7.5% fused silica is shown in Figure 5 and is used as the reference for analysing strain development in the columns. As the figure shows, the expansion occurred rapidly from the beginning of the exposure to about 90 days (3 months) with an expansion rate of about 110μs/day. After this period, the expansion slowed and stabilised. The total expansion in one year was about 11,000μs. Two lines are drawn in Figure 5 indicating the two time intervals chosen for the CFRP wrapping. The approximate expansion values at 30 days and 60 days were 3000μs and 7000μs, respectively.

Expansion before CFRP wrapping

The expansion in the centre of the columns and the steel reinforcement of the circular and square columns is plotted against time in Figure 6. For the circular column, the horizontal strain in the column centre was higher than the vertical strain. Whilst the horizontal strain was double the vertical strain for the circular column, the expansion behaviour for the square columns was almost the same. By comparing the strain in the concrete core with the free expansion graph (Figure 5), it was found that the expansion in columns was higher than the expansion thar occurred in the prisms, with a difference of 32% at 1 month and 24% at two months. As the expansion difference is due to the size effect, it is likely that the lower expansion of the prisms was due to alkali leaching from the smaller prism specimens.

Excessive expansion in the concrete causes deformation of the steel reinforcement. As shown in Figure 6, the deformation of the steel reinforcement is significant, approaching the yield strain of the steel (0.0022-0.0025). This indicates that the bond between the steel reinforcement and concrete was strong. If debonding occurs at the steel-concrete interface, the strain values for both elements are similar.

The differences in the strain in the concrete are related to the amount of steel reinforcement (Jones and Clark, 1996). Giving the volumetric reinforcement ratio of 0.23% for the circular columns and 0.39% for the square columns, the horizontal strain development in the centre of circular columns is higher than in the square columns. As the longitudinal reinforcement ratios of the circular and square columns are 1.55% and 1.17%, respectively, the vertical strain development in the centre of the square column is higher than that of the circular columns.

Expansion after CFRP wrapping

The analysis of CFRP-wrapped columns is divided into two parts; the effect of CFRP on the residual strain of the concrete and the effect of residual expansion on the deformation of the CFRP wrap. The analysis is limited to the strain development measured in the horizontal direction only.

Effect of CFRP wrapping on the strain development in the core

Using the free expansion value from the concrete prism test, the total expansion that can develop in the columns can be estimated. As previously mentioned, the total strain from the concrete prism was 11,000 μs. Hence it was expected that the remaining strain in the columns would be as follows;

- 7400μs and 4800 μs for the circular columns wrapped after 1 and 2 months, respectively
- 7800μs and 3800 μs for the square columns wrapped after 1 and 2 months, respectively

Figure 7 and Figure 8 present the strain development curves of the columns wrapped after 1 and 2 months measured at the centre of columns. For the columns wrapped after 1 month (Figure 7a), wrapping with 2 layers of CFRP reduced and delayed the initial expansion of the columns in comparison with the columns wrapped with 1 layer of CFRP. The maximum core expansion for circular columns recorded in 45 days for 1 and 2 layers of CFRP was 7000μs and 3500μs, respectively. The net core expansion of the columns wrapped after 1 month can therefore be estimated as 11,000μs (1 layer CFRP) and 7900μs (2 layers CFRP). For the columns wrapped after 2 months, the net expansion of the columns with 1 layer of CFRP is 3800μs (Figure 8a). However, the residual expansion of the columns wrapped with 2 layers of CFRP is nearly 8000μs and this value is doubtful.

In the case of the wrapped square columns, the expansion of the column with 2 layers occurred a little later than that for the columns wrapped with 1 layer of CFRP. However, the initial rates for both 1 and 2 layers of CFRP wrap are identical (Figure 7b). Similarly, for the columns wrapped after 2 months, no difference was found between the expansions of the column with 1 and 2 layers of CFRP (Figure 8b). The strain values of the columns wrapped after 2 month are not reasonable as they exceed the estimated residual expansion of 3800μs.

Effect of residual expansion on deformation of CFRP wrap

The ongoing expansion will cause the CFRP wrap to stretch, thus activating the confinement of CFRP on the columns. The maximum calculated confinement pressures for the circular columns with 1 and 2 layers of CFRP are 4.57MPa and 9.33 MPa, respectively, whereas for the square columns wrapped with 1 and 2 layers of CFRP the results are 3.8MPa and 7.6 MPa, respectively. The increase in the confining pressure means that the tensile strain of the fibre is also increased.

Figure 9 and Figure 10 present the deformation curves of circular and square columns wrapped with 1 and 2 layers of CFRP at two different times. It is apparent from both figures that the time of wrapping influenced the deformation of the columns. The columns which were wrapped after 1 month had higher deformation in comparison with the columns wrapped after 2 months. This may be due to the residual strain of the columns which were wrapped earlier being higher than that of the columns wrapped at later stage.

In the circular columns (Figure 9), it is observed that the deformation of 2 layers of CFRP wrap is higher than the deformation of 1 layer of CFRP wrap. This indicates that the confinement effect provided with 2 layers of CFRP is more pronounced. This findings support the theory that the increase in the confinement effect is related to the number of CFRP layers. However, contarary to expectations, this study found that the deformation of the square columns wrapped with 1 layer of CFRP was higher than the deformation with 2 layers of CFRP (Figure 10). A possible explaination for this might be that the confining pressure exerted by CFRP wrap on square column concerntrates on the corners of the column rather than the circumferential area, as for circular columns. This causes deformation differences across the cross-sectional area of CFRP-wrapped square columns.

4.0 CONCLUSION

The investigation reveals that the strain development of wrapped columns varies according to the number of CFRP layers and the shape of the columns. Most importantly, the time of CFRP wrapping is critical. If the column is wrapped earlier with sufficient layers of CFRP, better confinement is provided to the concrete. Later CFRP application provides only passive confinement to the concrete as the CFRP acts only as protective layer.

5.0 REFERENCES

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Figure 1: Rolling machine

Figure 2: Arrangement for embedded gauges

Figure 3: Insulated and normal strain gauges

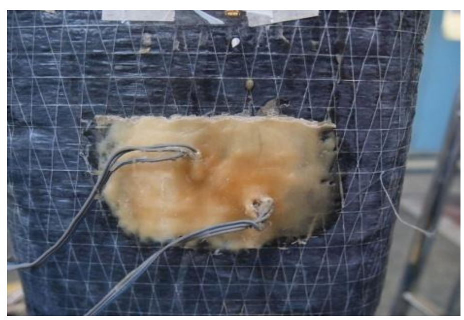


Figure 4: Exterior strain gauges with extra protection on fibre

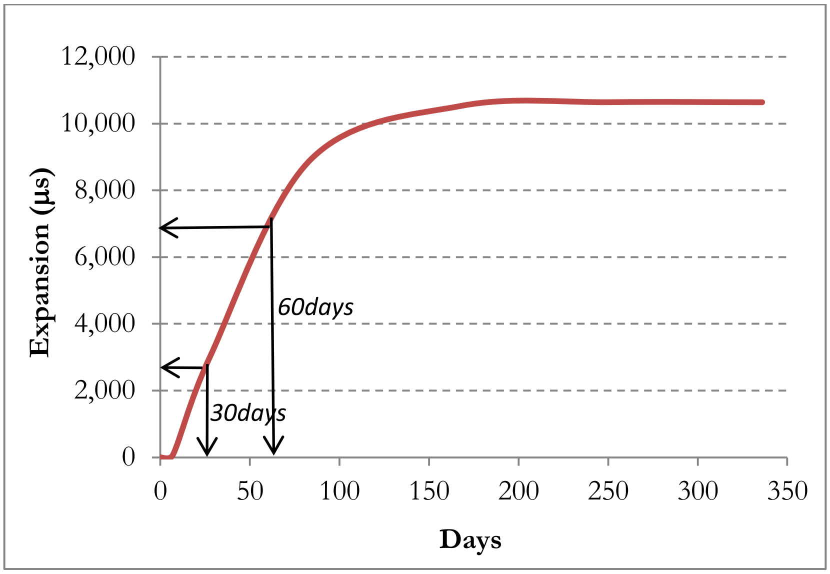
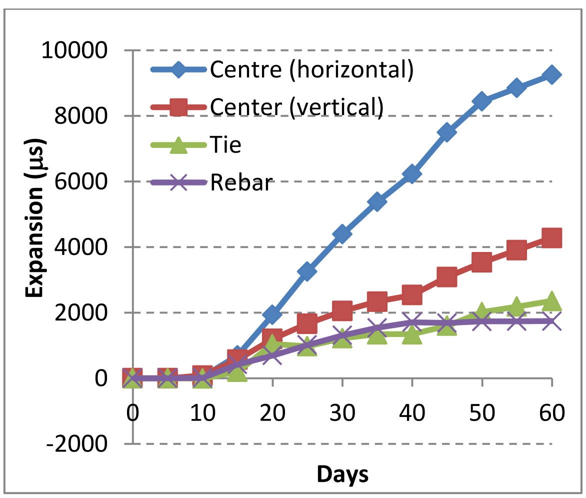
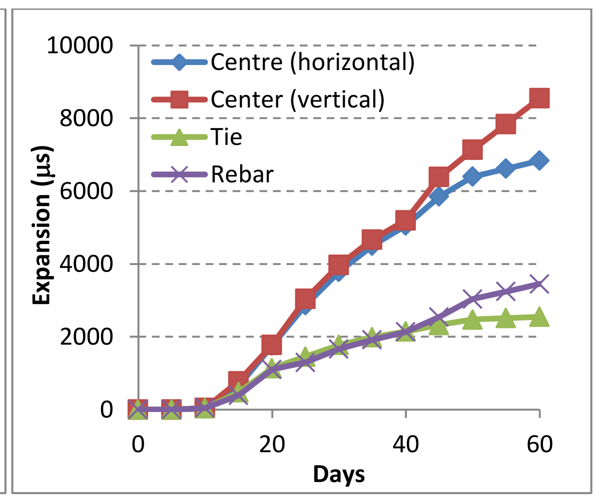


Figure 5: Free expansion measured on the concrete prism

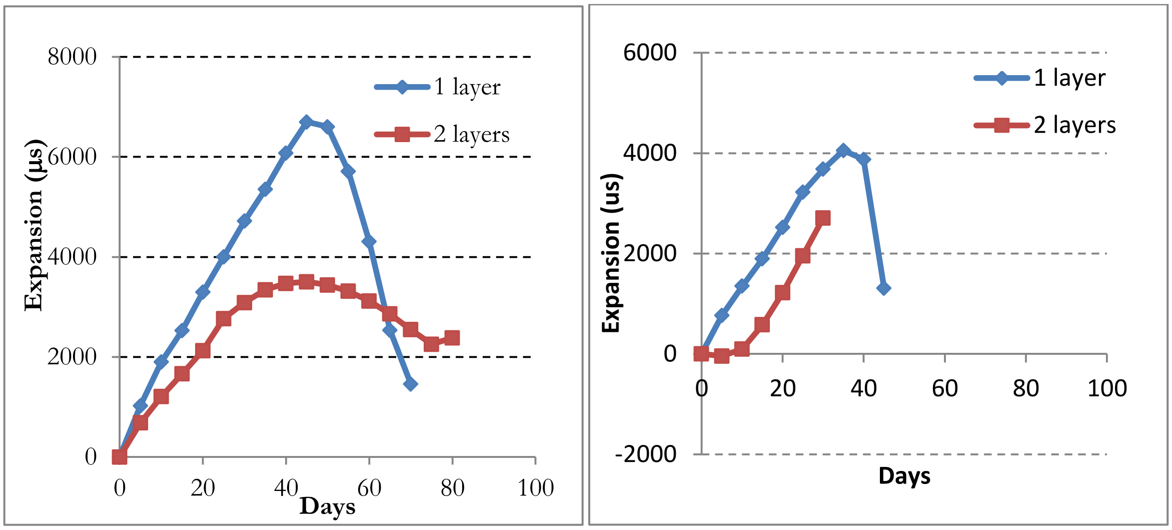


(a)



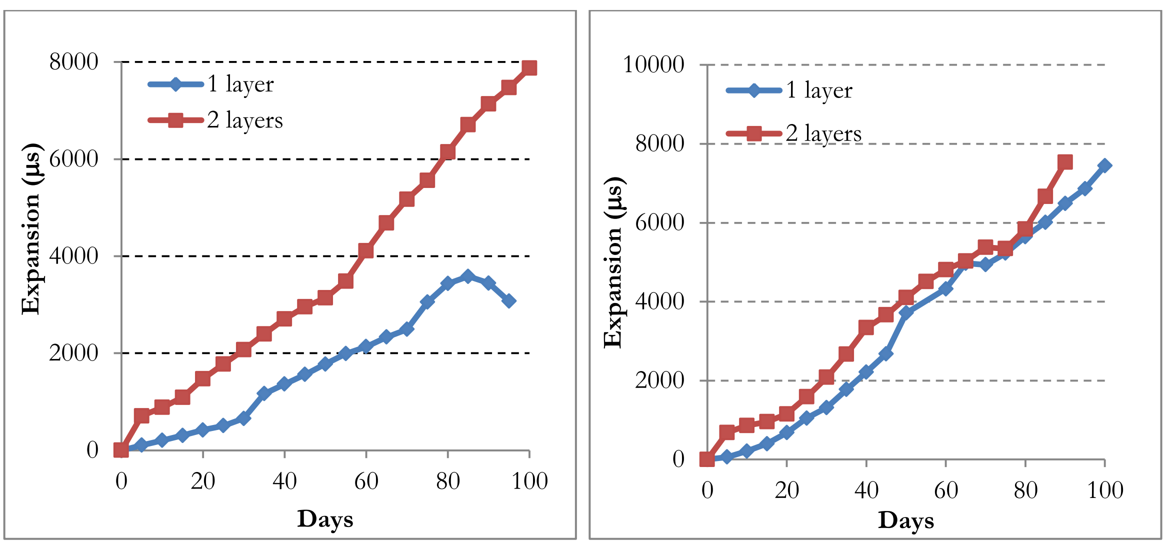
(b)

Figure 6: Strain development in the concrete and reinforcement steel in (a) circular column and (b) square column



(b) (b)

Figure 7: Expansion in the centre of circular (a) and square (b) columns wrapped after 1 month



(a) (b)

Figure 8: Expansion in the centre of circular (a) and square (b) columns wrapped after 2 months

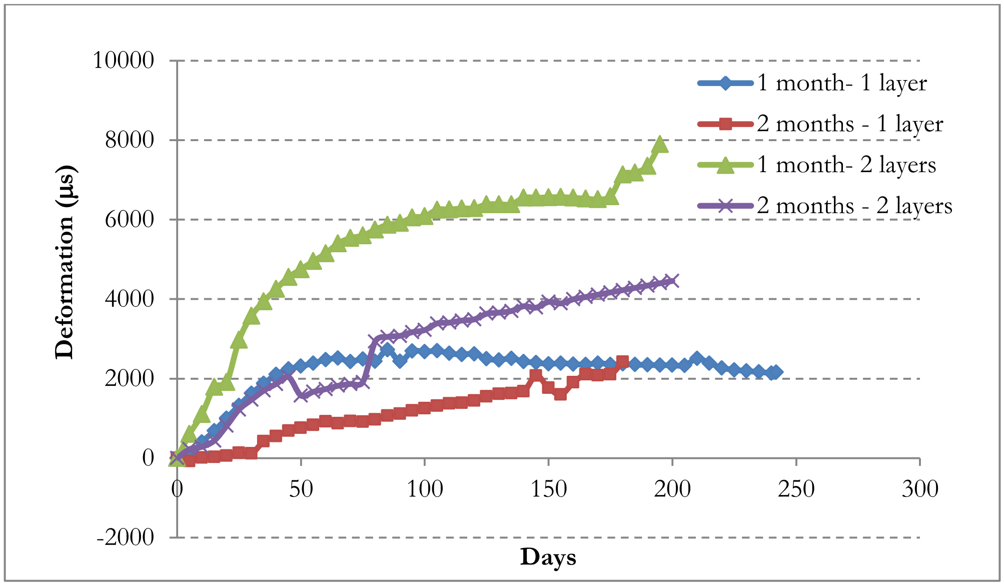


Figure 9: Deformation of CFRP wrap on the circular columns

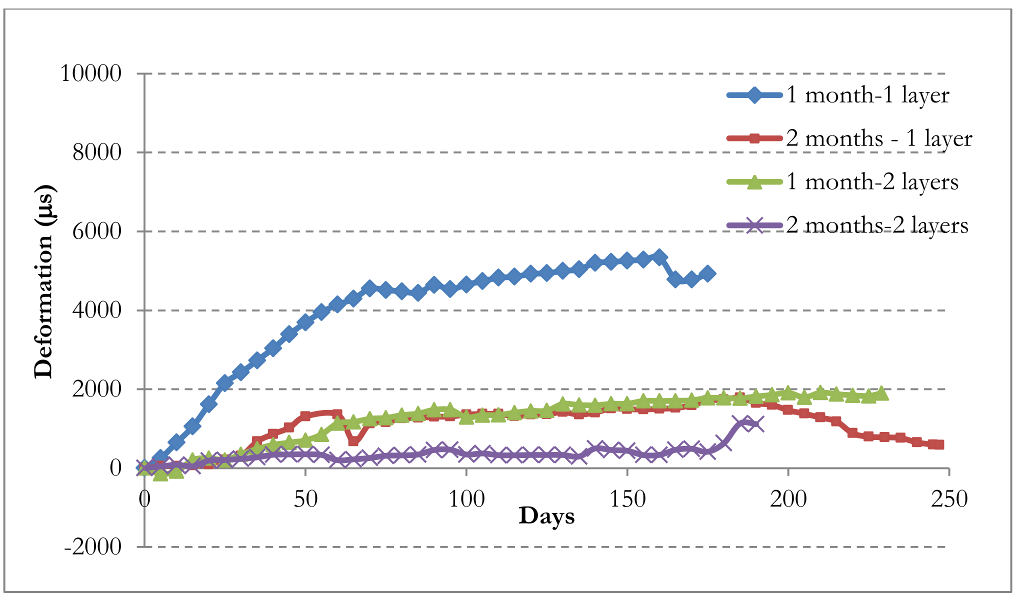


Figure 10: Deformation of CFRP wrap on the square columns