Effect of CFRP Wrapping Time on Expansion Development and Load Capacity of Circular Concrete Columns affected by Alkali-Aggregate Reaction

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Abstract

Fibre reinforced polymers (FRPs) are one of several techniques used to rehabilitate affected concrete members by alkali-aggregate reaction (AAR). A number of circular concrete columns 200 mm in diameter and 500 mm in height were cast from reactive and normal concrete. During the AAR process, the columns affected by AAR were confined by carbon fibre reinforced polymer (CFRP) at the ages of 15, 30, 45, 60, 90 and 120 days after casting, which represent different levels of expansion. The expansion of concrete was monitored, before and after confinement, up to six months after casting. The results indicate the efficiency of using CFRP as a confinement material to limit the AAR expansion of the affected columns. The results also show that the enhancement of ultimate load capacity of the affected columns depends upon the time of CFRP wrapping as related that to expansion level.

Keywords: carbon fibre reinforced polymer (CFRP), alkali aggregate reaction (AAR), confinement efficiency, radial expansion, load capacity.

1 INTRODUCTION

Structural effects of AAR in concrete derive from two causes [1]: first, the occurrence or development of micro-cracks within the concrete matrix has an effect on gaining strength with time; second, the restraining forces which develop against expansion within the concrete mix or from any internal and external confinement. The effect of AAR on the mechanical properties of concrete has been studied by many authors [2, 3], and many have found that AAR has a negative influence on the tensile strength and modulus of elasticity [4, 5] and less influence on the compressive strength of concrete [6, 7].

In a review of the management of AAR-affected structures [8], it has been stated that several treatments can be applied to manage AAR-affected concrete structures to control moisture access, slow the AAR process, release the stresses developed as a result of AAR, or restrain the expansion forces. Treatments such as surface coating to control moisture access are considered temporary methods and cannot provide a long-term solution for concrete in direct contact with water or any moisture source [9]. Seven years of monitoring of surface coatings was not as effective as expected in reducing the expansion in large-sized columns [10].

The use of composite materials such as FRP to restrain the expansion forces due to AAR is a novel and effective method to limit AAR [11]. The method also restricts access to water and enhances the structural capacity to the application of confinement stresses [12]. In certain situations, it may also protect against phenomena which affect the durability of concrete, such as steel corrosion and freezing and thawing [13]. The use of FRP is popular due to its high strength, light weight, flexibility, ease of installation and non-corrosive properties.

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The influence of uni-directional CFRP to confine small cylinders manufactured from reactive concrete was investigated [12]. The results showed that confinement by CFRP reduced transverse and longitudinal expansions by 75% and 21% respectively. The effectiveness of CFRP wrapping in the confinement of AAR-affected concrete piles was investigated [14]. Based on their results, the authors concluded that:

- The wrapping of damaged piles with CFRP only slowed down the expansion rate but deleterious expansion continued.
- CFRP wrapping did not completely contain the lateral expansion of columns with square cross-section, but this could not be fully attributed to the non-circular (square) cross-section of the piles, although CFRP is more effective in confining columns with circular cross-sections.
- Future research is required to include types of CFRP with different mechanical properties (moduli and tensile strength) and the use of sufficient numbers of CFRP layers which can be applied at different stages of AAR development to find the effect in restraining AAR expansion.

The present authors [15] have investigated the effectiveness of using CFRP to regain the integrity of concrete damaged by AAR. Eighteen cylindrical samples were selected for the rehabilitation of reactive and normal concrete using CFRP sheets at the age of six months after being stored in a chamber at 38°C and 98% relative humidity. One layer or two layers of CFRP were used to wrap the normal and reactive concrete. The results indicate that CFRP confinement increased the compressive strength of reactive and normal concrete by 466% and 179%, respectively, when one layer of CFRP sheet is used. For two layers of CFRP sheet, the increase in strength is greater and reaches 683% and 300% for reactive and normal concrete respectively. In the same manner, the axial and circumferential strains capacities of confined reactive and normal concrete are increased.

Few researchers have investigated the application of CFRP wrapping of large reinforced columns damaged by AAR [16, 17]. This paper investigates the effect of CFRP wrapping times at the ages of 15, 30, 45, 60, 90, and 120 days after casting, which represent different levels of AAR expansion, on a number of circular reinforced concrete columns. Two main objectives were studied in this research: first, the expansion behaviour (before and after confinement) through six months of storage at 38°C and 98% relative humidity (RH); and second, the load capacity of confined and unconfined columns at the age of six months.

2 EXPERIMENTAL PROGRAM

2.1 Mix design

Two types of concretes were cast in accordance with the ASTM C1293-08b[18] requirements. Fused silica of 0-1 mm particle size, a highly reactive and uniform artificial aggregate, was used to simulate reactivity. The latter material was used at the dosage rate of 7.5% by mass of total aggregate, and replaced the same quantity of fine aggregate. According to [17], this percentage leads to the highest expansion in concrete compared to other dosage rates.

2.2 Confinement

One type of high tensile CFRP (CF 230/4900 400/50) fabric was used throughout the research to wrap the columns. MBrace Saturant was the type of epoxy adhesive used as a bonding material to wrap the columns with CFRP. The adhesive epoxy consists of two parts and is mixed at a specified volume ratio of 3(resin): 1(hardener).

2.3 Storage conditions

All columns were stored under the conditions specified by ASTM C1293 from demoulding until the time of testing in order to accelerate the reaction. A special saturated cabinet 6000 x 720 x 880 mm (length x width x depth) was built for the purpose. The cabinet is supplied with a controlled condition fan-forced airflow and digital controls to provide accurate conditions of 38°C and saturated humidity of 98% or above.

2.4 Column details and distributions

Sixteen circular columns200mm in diameter and 500mm in height were cast from both concretes, reactive and normal. All columns were reinforced longitudinally with 5Ø10 mm deformed bar and laterally with 4 ties of Ø6mm deformed bar. Of 16 columns, 12 columns were confined by one layer of CFRP at the ages of 15, 30, 45, 60, 90 and 120 days after casting. Table 1 shows the distribution of columns throughout the research.

2.5 Strain gauge installation

To measure the radial expansions in concrete, embedded strain gauges model PML-60-2LT were used. This type of strain gauge is provided with a strain transducer to enable long-term use. Thin wires were used to fix the strain gauge at the centre of the concrete core as illustrated in Figure 1. A PX1 data-logger was used to take readings of strain gauges during the storage period of the columns. Readings of expansion were taken regularly up to the age of 180 days after casting. A view of the storage cabinet and the arrangements for expansion measurements is shown in Figure 2.

2.6 Capping

Capping is essential to give surface levelling for circular columns and avoid any eccentric on application of load. Surface levelling grout (Ardex LQ92) was used for capping all the columns at the upper ends with the minimum thickness possible. A special ring was used as a form to confine the capping material during placement. The capping was carried out before the confinement of columns with CFRP.

2.7 Method of confinement

The wet lay-up method was used in confining the columns with CFRP sheets. Before wrapping, the columns were sandblasted to provide a rough surface for better bonding between the concrete and the CFRP. After sandblasting, a thin layer of primer was applied to fill all the voids in the concrete surface and then cured for 30 minutes. MBrace Saturant epoxy was then applied on the surface of the primer and on the CFRP layers. A hand roller was used with sufficient pressure to squeeze out all air bubbles between the primer and the CFRP layers. CFRP strips 500mm wide were used to wrap the columns with 150mm overlap between rounds of CFRP to overcome failure due to debonding at the overlap zone. A curing time of seven days was allowed for the CFRP-confined columns before testing.

2.8 Load capacity measurement

All columns (unconfined and confined) were tested under compression. To measure the load capacity of the columns, a uniaxial compression machine (Instron) of 5MN was used at a displacement rate of 0.25 mm/min. A view of a column under testing is shown in Figure 3.

3 RESULTS AND DISCUSSION

The affected columns were confined by one layer of CFRP at selected times after casting which represent different level of expansions during the active stage of AAR development. The two main objectives of this research are to investigate the efficiency of CFRP application as a confinement material to reduce the effect of AAR-induced expansion on the concrete and improve the load capacity of the affected concrete.

3.1 Confinement effect on expansion development

Table 2 presents the strain measurements including readings before and after confinement up to the age of 180 days. Unfortunately, the strain gauges in the columns with the CFRP wrapping time of 45 days stopped working at 45 days. The confinement efficiency for different wrapping times was calculated at the age of 180 days, as listed in Table 2. The confinement efficiency with respect to expansion at 180 days is calculated according to Equation 1, which represents the actual decrease in the expansion value after wrapping, compared with the expected residual expansion value for unconfined column at the time of wrapping. In addition, the values of expansion, before and after confinement and the total at 180 days are plotted in Figure 4 against wrapping time. Figure 4 and Table 2 show that the wrapping with CFRP reduced the rate of radial expansion of the affected columns compared with the unconfined columns. However, the expansion still continued, i.e., CFRP wrapping did not arrest the AAR-induced expansion. The same observation has been reported by other researchers [14, 16]. The results also show a reduction in the final expansion value at the age of 180 days for columns which were wrapped at earlier ages. These values are smaller than those for unconfined columns at the same age, even though the wrapping was applied at later ages. Clearly, CFRP confinement of columns at early ages is more effective in reducing the expansion value at the age of 180 days.

$$\text{Confinement efficiency} = \frac{\text{The expected residual exp. after conf.} - \text{The actual measured of exp. after conf.}}{\text{The expected residual exp. after conf.}} \quad (1)$$

3.2 Confinement effect on load capacity

Table 3 shows a summary of the measured ultimate load capacity at the age of 180 days of unconfined columns for normal and reactive concrete and confined columns for reactive concrete at different wrapping times. The load capacity of the damaged columns was reduced by 57% compared with the unaffected columns due to AAR expansion. Generally, the confinement at any time during the AAR process increased the load capacity compared to unconfined columns. As shown in Table 3, the confinement efficiency as a result of confinement varied from 348% to 397%. At the early ages of wrapping, the efficiency of confinement may be higher than confinement at later ages. The confinement efficiency with respect to load capacity improvement represents the actual strength of the confined column compared with that of the unconfined column (an average of the results for two columns was taken). The values of load capacities of confined and unconfined columns with the confinement efficiencies of confined columns in Table 3 are plotted in Figure 5. As shown in Figure 5, the confinement of the damaged columns with one layer of CFRP was sufficient to reach the load capacity of the unconfined normal concrete columns and exceed it.

4 CONCLUSIONS

Sixteen reinforced columns were fabricated from AAR and normal concrete. CFRP wrapping material was used to wrap the affected columns at the ages of 15, 30, 45, 60, 90 and 120 days after casting. These times represent different levels of expansion during the active stage of AAR development. One layer of CFRP was used to confine the affected columns. The radial expansion values in concrete were recorded and analysed, before and after confinement, up to the age of 180 days. At this age, all columns were tested under compression to measure the ultimate value of load capacity. Based on the results of expansion measurements of columns during the period of 180 days and the load capacity at the latter age, the following conclusions can be drawn:

- CFRP performs well in limiting AAR and also improves load capacity.
- Confinement of affected columns with CFRP reduces the rate of radial expansion compared to unconfined columns. However, expansion still occurs.
- The CFRP confinement of affected columns at early ages shows better performance than in reducing the expansion values at later ages.
- AAR has an adverse influence on the load capacity of affected columns. The load capacity of AAR concrete columns was reduced by 57% compared with the columns of normal concrete.
- CFRP confinement was more effective on load capacity of confined affected columns at early ages than later ages.
- Confinement efficiency with respect to load capacity improvement reached a value of more than 300% for all different wrapping times.
- One layer of CFRP confining the affected columns was sufficient to reach the load capacity of unconfined normal concrete columns.

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TABLE 1: Distribution of columns.

Type of concrete	*Reactive concrete*							*Normal concrete*
Time of wrapping (days)	15	30	45	60	90	120	Unconfined	Unconfined
No. of columns	2	2	2	2	2	2	2	2

TABLE 2: Confinement efficiency of CFRP at the age of 180 days for different wrapping times.

Wrapping time (days)	***Expansion measurement (µs)***		***Residual expansion at the age of 180 days***	***Confinement efficiency***
	Before confinement	*After confinement*		
15	1200	7900	19750	0.6
30	2770	6844	18180	0.62
45	---	---	---	---
60	7730	3650	13220	0.72
90	8440	5364	12550	0.57
120	13400	2420	7550	0.68
180	20950	0	0	---

Wrapping time (days)	Load capacity (kN)	Load capacity (kN)	Confinement efficiency %
15	2524 2441	2483	397
30	2264 2292	2278	364
45	2244 2327	2286	365
60	2239 2279	2259	361
90	2262 2134	2198	351
120	2115 2247	2181	348
180 (unconfined with reactive concrete)	619 633	626	100
180 (unconfined with normal concrete)	1429 1480	---	---

TABLE 3: Confinement efficiency of different wrapping times at the age of 180 days.

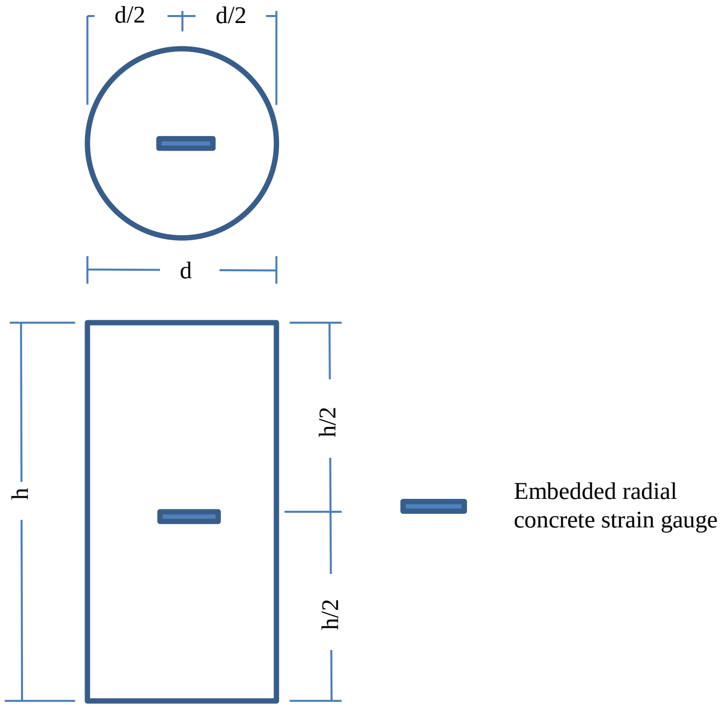

FIGURE 1: Column schematic: position of embedded radial concrete strain gauge.

FIGURE 2: Expansion measurement.

FIGURE 3: Column under compression machine.

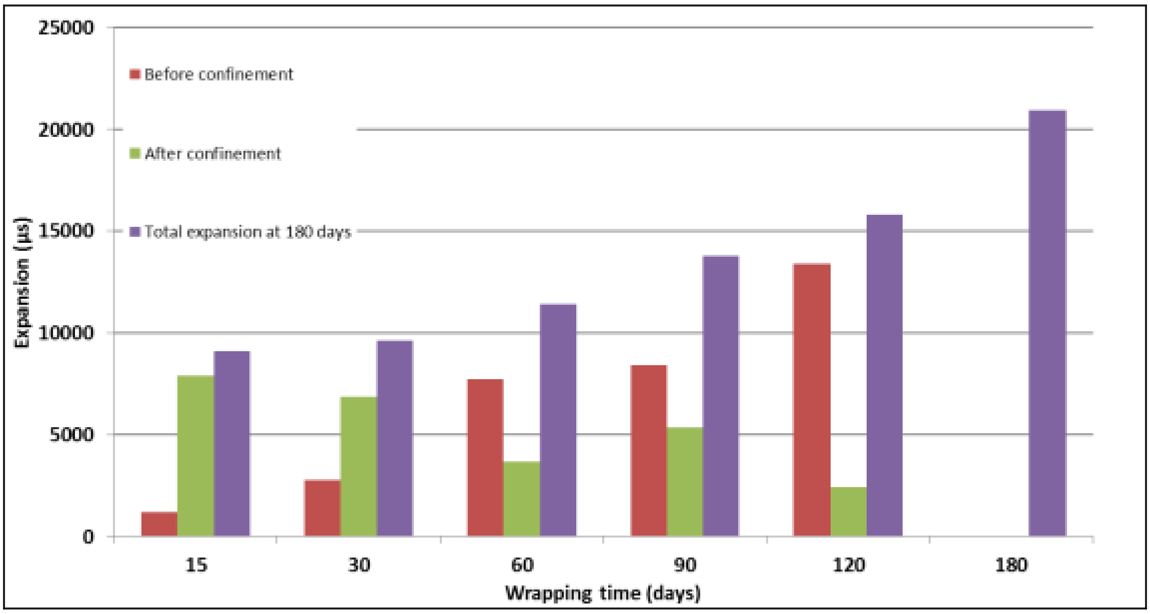

FIGURE 4: 180 days expansion measurement for confined columns wrapped at different times including expansion measurements, before and after confinement.

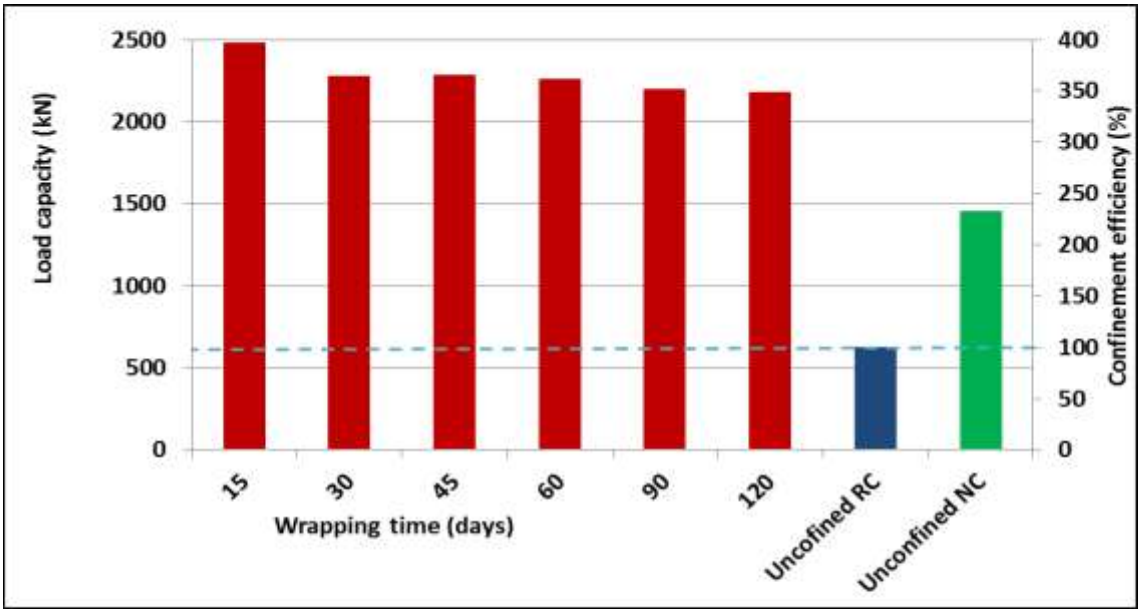

FIGURE 5: 180 days load capacities values for confined affected columns wrapped at different times and unconfined columns.