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EFFECT OF CFRP WRAPPING TIME ON REHABILITATION OF CONCRETE DAMAGED BY ALKALI AGGREGATE REACTION

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ABSTRACT

Alkali aggregate reaction (AAR) is a chemical reaction between alkali in the pore solution of cement paste and reactive forms of silica in the aggregate, which can reduce the durability and mechanical strength of concrete. Carbon fibre-reinforced polymer (CFRP) is one of several techniques used to rehabilitate concrete affected by AAR. Fused silica was used as fine aggregate at the replacement rate of 7.5% of the total aggregate in the mix ingredients of concrete to simulate reactivity. During the expansion process of the reactive concrete, three different times, representing three levels of expansion were selected for wrapping the affected concrete with CFRP. This paper investigates the effect of the level of expansion of reactive concrete on the mechanical properties of concrete. It also investigates the effect of wrapping and testing time on the efficiency of CFRP to confine concrete damaged by AAR. The results indicate that wrapping at low levels of expansion could more effectively limit the effect of AAR and improve the strength and ductility of affected concrete.

KEYWORDS

AAR, expansion, CFRP, confinement , compressive strength.

INTRODUCTION

Alkali aggregate reaction (AAR) is a chemical reaction between alkali in the pore solution of cement paste and reactive forms of silica in aggregate, which can reduce the durability and mechanical strength of concrete. A large number of concrete structures around the world are affected by deterioration induced by AAR, and many countries suffer from the effects of AAR on their concrete structures, especially on its durability. Broekmans (2012) has noted that many countries around the world have problems of AAR in their concrete structures and in the future other countries could be added to the list, due to discovery of new cases of AAR, and the fact that this phenomenon is time-dependent.

The mechanism of AAR has been explained and demonstrated by several authors (e.g. Farny and Kosmatko 1997 ; Chatterji 2005). Briefly, the chemical reaction between the reactive form of silica in aggregate and alkali hydroxide present in the pore solution of cement leads to the formation of alkali-

silica gel. The absorption of water by the gel makes it expand and internal pressure is developed, leading to expansion and cracking if the pressure is greater than the tensile strength of the concrete. Expansion of concrete is measured as change in length (linear expansion) with time. It is expressed as "μs" or as percentage of length. AAR expansion is manifested as S-curve when plotted against time (Larive 1998).There are four phases in AAR development :-
(a) dominant phase, when alkali hydroxide accumulates in and around reactive aggregate.
(b) initiation phase, when aggregate is attacked and sufficient AAR gel forms to cause first cracks.
(c) aggressive phase, when reaction is at its strongest stage .
(d) stabilization phase, when much of the reactants have been used up and the rate of expansion is significantly reduced, but may continue at a lower rate until completion of reaction, when one or more reactant are exhausted and expansion stops.

Significantly, the results of AAR have a negative effect on the mechanical properties of concrete, such as its strength and stiffness. Tensile strength and modulus of elasticity of concrete are considered the most sensitive parameters that are affected by AAR, while the compressive strength of concrete is affected to a lesser extent (ISE 1992) .The level of expansion has an effect on the strength . Swamy and Al-Asali (1988) showed that at 28 and 200 days, the modulus of rupture of concrete decreased by 13% and 78% after the expansion had reached 0.023% and 0.6% respectively. In addition, Shayan et al. (2003) found that flexural strength of concrete was reduced by as much as 40-50% when the expansion exceeded 0.12% . According to Shayan et al. (2003) and Ferraris (1995), the compressive strength of concrete is less affected by the expansion due to AAR than flexural strength of concrete.

For new concrete structures, there is a significant opportunity to avoid the problems caused by AAR. There are several ways to minimize or limit the effects of AAR, as described by Stark (1994) and other researchers. These are :-

- reactive aggregate should be avoided.
- alkali content must be limited .
- admixtures like supplementary cementing materials (SCMs) may be used.

For existing concrete structures damaged by AAR, several techniques are used to suppress AAR or its effects in concrete, one of which is the application of fiber-reinforced polymers (FRP). FRP composites with unidirectional fibers have been commonly used in the rehabilitation and strengthening of concrete members since the early 1980s when the application of composite material was used for the first time (Fardis and Khalili 1982). Currently, the use of FRP is widespread due to its high strength, light weight, flexibility, ease of installation and noncorrosive properties (Lacasse et al. 2003; Seniwongse 2008). According to Curtil et al. (2003), FRP is a novel method to limit AAR, to increase the ductility and to improve the load capacity.

Abdullah et al. (2012) studied the performance of CFRP-wrapped columns damaged by AAR, using one layer and two layers of CFRP to wrap AAR-damaged square and circular columns at different times of polymer application. Based on the results, the following conclusions were drawn :-

- the wrapping time and the number of layers have positive effects on strength enhancement as related that to the level of expansion of affected concrete and stiffness of wrapping material respectively.
- the time of CFRP wrapping affects the level the expansion that has occurred in the concrete before the columns were repaired.

This research investigates the effect of three different expansion levels during the AAR process on mechanical properties of concrete damaged by AAR . At these levels of expansion, the paper also investigates the effects of wrapping time with CFRP and testing time on the strength of the repaired concrete.

EXPERIMENTAL PROGRAM

The experimental program can be divided into two sections. The first deals with the effect of expansion levels on the mechanical properties of concrete affected by AAR, whereas the second deals with the effect of confinement on affected concrete with one layer of CFRP. The physical and mechanical properties of affected concrete before and after confinement will be explained.

Concrete Mix and Curing Conditions

One concrete mix was cast for the entire research program to simulate reactive concrete. The mix proportion was fixed according to ASTM C1293 requirements. To simulate AAR in concrete, fused silica of 0-1 mm particle size was added to the mix ingredients such that it formed 7.5% of total aggregate content. The appearance of fused silica is shown in Figure 1. Table 1 shows the ingredients of the concrete mix. All samples were stored under the conditions 38 ℃ and 98% relative humidity (RH) from demoulding until the time of testing including the confinement period.

Table 1. Quantities of concrete ingredients

Ingredients (Kg/m^3)	Reactive concrete
Cement	420
Water	176
Fine aggregate	597
Coarse aggregate	1072
Sodium Hydroxide	4.07
Fused silica	135

CFRP Material

One type of CFRP was used throughout the research to wrap the affected concrete. Five coupon samples prepared from one layer of CFRP were tested to measure its tensile properties according to ASTM D3039. A MTS machine of 250 kN capacity was used, as shown in Figure 2. The manufacturer's data and the average of the coupon test results are shown in Table 2.

Table 2. CFRP properties

Characteristics	Manufacturer's data	Test result
Tensile strength(MPa)	4900	4220 ± 145
Tensile strain capacity %	2.1	1.813 ± 0.26
Fiber modulus (GPa)	230	233
Fiber density (gm/cm^3)	1.7	-------
Thickness (mm)	0.227	-------
Fiber weight (gm/m^2)	400	-------

Figure 1. Fused silica

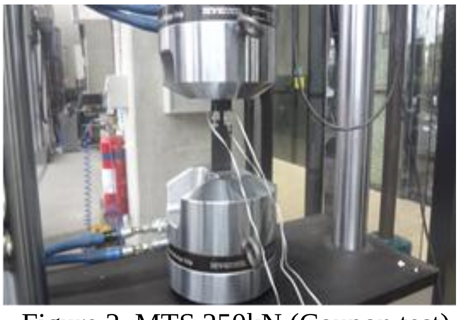


Figure 2. MTS 250kN (Coupon test)

Sample Preparation

Small cylinders and prisms were cast from the reactive concrete, as listed in Table 3. To understand the effect of wrapping and testing time, fifteen cylinders 100 mm in diameter and 200 mm in height were cast and confined with one layer of CFRP at the ages of 1, 3 and 6 months, which represent three levels of expansion of 0.37%, 0.76% and 1.23% respectively after being stored in a chamber at 38°C and 98% RH. Six cylinders were selected at 1 and 3 months of age to be wrapped with CFRP, of which three were tested immediately after wrapping (1 month or 3 months) and the others were tested at 6 months. Another three concrete cylinders were wrapped at six months with CFRP and tested after completing the curing time of epoxy resin. Table. 4 shows the distribution of the confined concrete samples.

Table 3. Types of samples prepared for various tests

Test	Specimen type	Specimen sizes (mm)	Number of specimens
Free expansion Mass variation	Concrete prism	75*75*280	3
Compressive strength Modulus of elasticity	Cylinder	ϕ 100*200	6
Flexural strength	Beam	100*100*400	12
Compression test for confined specimens	Cylinder	ϕ 100*200	15

Table 4. Distribution of number of samples according to confinement and testing time

		Time of confinement (month)		
		1	3	6
Time of testing (month)	1	3	-------	-------
	3	-------	3	-------
	6	3	3	3

RESULTS AND DISCUSSION

Free Expansion and Mass Variation

Readings of the expansion and mass variations of reactive concrete, as shown in Figures 3 and 4, were taken several times up to 6 months. Figure 3 shows that the expansion increased dramatically in the period between 7 and 30 days (0.37%) and then the rate of expansion slowed and reached 0.76% and 1.24% at 3 and 6 months, respectively. For mass variations, as shown in Figure 4, similar behavior can be observed over , except that the reading at 4 months could be in error.

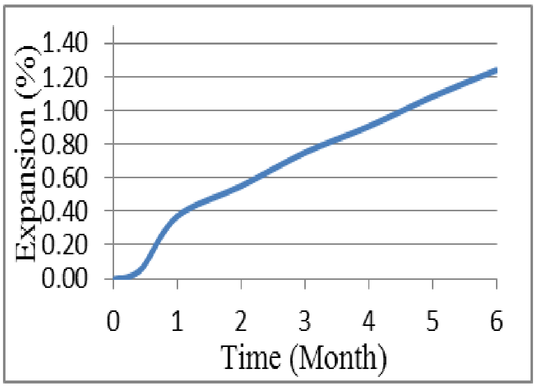


Figure 3. Expansion with time

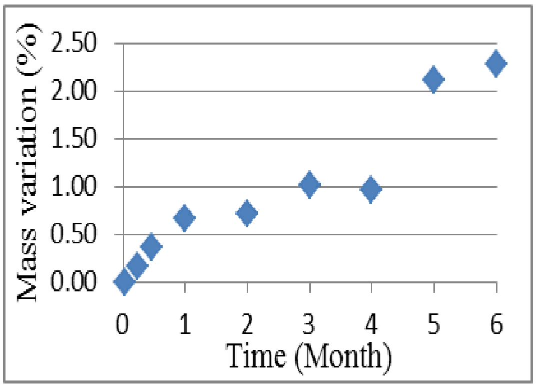
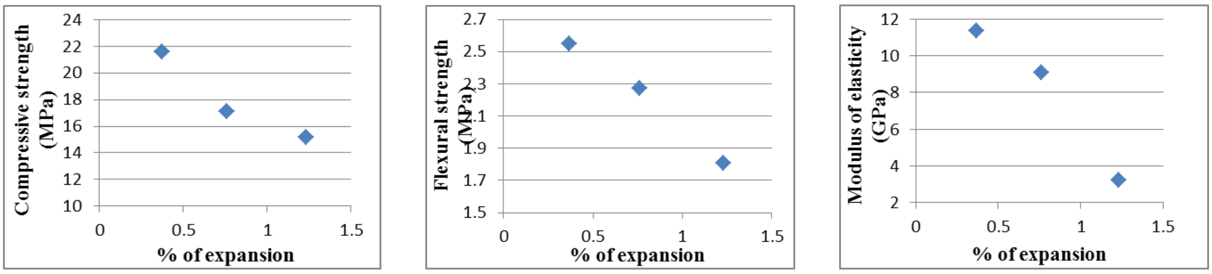


Figure 4. Mass variation with time

Mechanical Properties of Concrete

AAR has an adverse influence on the mechanical properties of concrete such as compressive and tensile strength and modulus of elasticity. Figure 5 shows the values of mechanical properties at the selected levels of expansion. As the expansion level increased, more deterioration of mechanical properties of the concrete was observed, especially the modulus of elasticity. Similar observations were made by Shayan et al. (2003).



(a) Compressive strength (b) Flexural strength (c) Modulus of elasticity

Figure 5. Effect of expansion level on mechanical properties of concrete affected by AAR

Wrapping and Testing Time

At testing, a 1 MN compression machine was used to record load capacity by applying a displacement of 1mm/min, and a camera with a Vic-3d digital image correlation system was used to monitor strain, as shown in Figure 6. Failure occurred as a result of rupture of CFRP. The failure of most confined concrete specimens was initiated at a distance ranging from 30-50 mm from the top and bottom of samples to include the middle part of the samples, as shown in Figure 7. The effects of wrapping and testing time on the compressive strength and strain capacity of concrete damaged by AAR are shown in Table 5. The results show the importance of CFRP wrapping time for concrete damaged by AAR when confinement efficiency is compared between different wrapping times during the expansion process. The application of CFRP wrapping at an early age for AAR concrete, i.e., when the expansion level is low, could improve the compressive strength of confined concrete in addition to the advantage of using CFRP as a waterproof layer. At the same time, the CFRP confinement also improved the strain capacity of the confined affected concrete compared to that of the non-confined concrete.

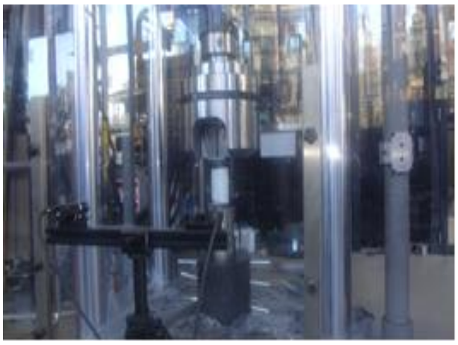


Figure 6. 1MN machine and Vic-3d camera

Figure 7. Confined concrete at failure

CONCLUSIONS

AAR-affected concrete can be managed and repaired in several ways. FRP is an effective composite material for enhancing the strength and ductility of concrete affected by AAR. The paper has focused on the effect of AAR on the physical and mechanical properties of concrete at three levels of expansion and showed that these properties are adversely affected by AAR expansion. At these selected levels of expansion, which represent three different ages during the expansion process, CFRP wrapping was applied to find the effect of wrapping time on the effectiveness of the use of CFRP as a confinement material. Results indicate that CFRP wrapping at an early age, i.e., at a low level of expansion, could limit the AAR effect and improve the strength of AAR-affected concrete as well as the strain capacity of the confined concrete at selected wrapping times was significantly improved compared to the non-confined concrete.

Table 5. Effect of wrapping and testing time on CFRP-confined concrete affected by AAR

Measured property	Type of concrete							
	Unconfined concrete			Confined concrete				
				Time of confinement (month)				
				1		3		6
	Time of testing (month)							
	1	3	6	1	6	3	6	6
Compressive strength (MPa)	21.6	17.1	15.2	102	104	98	102	89
Axial strain (%)	0.32	0.37	0.40	1.75	2.25	3.1	2.33	2.47
Radial strain (%)	----	----	0.44	1.61	1.52	1.65	1.24	1.27

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