Experimental and finite element analysis of mechanical behavior of concrete damaged by Alkali Aggregate Reaction (AAR) and repaired with CFRP Layers

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Abstract. Concrete structures is affected by a deleterious reaction, which is known as Alkali Aggregate Reaction (AAR). AAR can be defined as a chemical reaction between the alkali content in the pore water solution of the cement paste and reactive forms of silica hold in the aggregate. This internal reaction produces expansion and cracking in concrete, which can lead to loss of strength and stiffness. Carbon fiber-reinforced polymer (CFRP) is one of the methods used to suppress further AAR expansion and rehabilitate and support damaged concrete structures. In this research, thirty-six cylindrical specimens were fabricated from non-reactive and reactive concrete, which contained fused silica as 7.5%. In addition, twelve concrete prisms were fabricated from non-reactive and reactive concrete in which three different percentages of fused silica are used, 5%, 7.5% and 10% of the total aggregate. This paper investigates the impact of AAR expansion on the physical and mechanical properties of concrete. It also reports the effective use of one and two CFRP layers on wrapping concrete cylinders. The experimental results show that CFRP is effective in confining damaged concrete by AAR and results in concrete strength enhancement of up to 560%. A comparison of finite element (FE) analysis using ATENA 3D software and the experimental results indicated that FE analysis is capable of modelling the behavior of AAR-damaged concrete repaired with CFRP.

Keywords: AAR, CFRP, ATENA 3D, finite element.

1. Introduction
Alkali Aggregate Reaction (AAR) is a deleterious reaction which occurs in concrete structures and can be defined as a chemical reaction between the hydroxide ions (OH-) associated with the alkali content (NaOH) in cement and certain minerals contained in the aggregate. This reaction produces alkali gel which tends to absorb water and expand, leading to different problems in concrete [1]. AAR can appear as visual symptoms on concrete structures such as expansion, cracks, pop-outs and efflorescence [2]. A combination of three conditioning factors allow AAR to occur: reactive aggregate, humidity and alkaline
content. In the 1930s in California, it was first recognized as a potential source of distress in concrete, when cracking and expansion were investigated in concrete structures such as school buildings, bridges, sea walls and road pavements [1].

AAR is a slow progressive process of deterioration and the first visible sign may take from a few months to several years to develop. It produces expansion in concrete and leads to a loss in strength and stiffness, causing undesirable deformation and generating instability in the equilibrium of the internal force of concrete [3]. AAR has a great effect on the mechanical and physical properties of concrete, resulting in great damage to concrete structures [4]. Many authors have studied AAR the effect of AAR on the mechanical properties of concrete: compressive strength, tensile strength and modulus of elasticity. Swamy and Al-Asali [5], stated that the compressive strength is reduced in magnitude by as much as 30-40% at an expansion rate of about 0.6%, while Hobbs [6], stated that the concrete loses 60%-80% in compressive strength at an expansion rate of about 1.5%. Many studies on the loss in compressive strength of concrete were reviewed. It was concluded that 10-60% of concrete compressive strength is lost, depending on the magnitude of the expansion, which is related to the reactivity level of aggregate [7]. The tensile strength and modulus of elasticity of concrete are more influenced and reduced in concrete structures affected by AAR than compressive strength [7]. According to Swamy and Al-Asali [5], the loss in splitting tensile strength of concrete varies between 16% and 64% for expansion ranging from 0.023% to 0.6% at ages of 28 and 200 days, respectively. Based on experimental investigations, the modulus of elasticity of concrete consisting of highly reactive aggregates is reduced by 80% and 20% for concrete containing moderately reactive aggregate [4].

Currently, various methods are used to suppress further AAR expansion and rehabilitate the concrete structures damaged by AAR. One of these methods is the use of fiber-reinforced polymer (FRP). FRP is recognized as an excellent and effective material due to its high strength, light weight, corrosion resistance and high flexibility [8]. Conventional methods, such as steel reinforcement jacketing or chemical products, are expensive and a waste of money. FRP wrapping is an effective method to repair and minimize further occurrence of AAR in existing contaminated infrastructures [9]. The external restraint of expansion can be activated by using FRP composite materials. As stated in Karbhari [9], FRP is an effective material, which enhances the strength and ductility and load-carrying capacity of damaged concrete structures. Such damage is caused by AAR or any other phenomena, which can reduce the strength of concrete, such as steel corrosion, extensive cracking due to freezing and thawing, and rapidly changing load levels and intensity.

Mohamed et al. [10] studied the effectiveness of the use of carbon fiber reinforced polymer (CFRP) and the influence of confined damaged concrete affected by AAR on the mechanical behavior of concrete. The results showed that confining reactive concrete mitigated longitudinal expansion by 21% and 7.5% for traversal expansion. The strength of the reactive concrete confined with CFRP was increased by 31.4% and 24% for normal confined concrete. In addition, there was an improvement in the strength of CFRP-wrapped damaged cylinders compared to reference cylinders without CFRP wrapping. Abdulla [11] investigated the performance of concrete structures damaged by AAR by using finite element (FE) analysis and compared the results with experimental results. Circular columns and 2-D axis symmetry software were used in the research. Comparison of the results showed that FE analysis can be used to predict AAR effects on damaged concrete columns wrapped with CFRP.

The research reported here investigates the effect of AAR on the mechanical and physical properties of concrete. The mechanical properties of concrete tested in this research are, the compressive strength, modulus of elasticity and tensile strength, and the physical properties of concrete prisms are the free expansion and mass variation. It also studies the effectiveness of using one and two layers of CFRP on concrete cylinders and compares the results with those of FE simulation.

2. Experimental work
2.1. Concrete mixture

In this research project, two forms of concrete samples were cast: normal (NC) and reactive (RC). The quantities of materials used in the concrete mix were specified according to the requirements of the ASTM C1293 [12]. Fused silica was added to the reactive concrete mixture as a replacement for the fine aggregates to stimulate reactivity in concrete. Three different percentages of fused silica (5%, 7.5% and 10%) were added to the reactive concrete mixture. Based on ASTM C1293 [12], the percentages of the materials used in the experiment were: water-to-cement ratio 0.42, cement 1: fine aggregate 1.7: and coarse aggregate 2.54 by mass of concrete mix. The ingredients of the concrete mix were described in table 1.

| Ingredients       | Normal concrete (NC) | Reactive concrete (RC) |
|-------------------|----------------------|------------------------|
| Cement            | 420                  | 420                    |
| Fine aggregates   | 732                  | 597                    |
| Fused silica      | ---                  | 135                    |
| Water             | 176                  | 176                    |
| Coarse aggregate  | 1072                 | 1072                   |
| sodium hydroxide  | 4.07                 | 4.07                   |

2.2. Storage conditions

All samples were put in a closed storage at 38° C and relative humidity (RH) of 98%, as stated in ASTM C1293b [12]. The samples were stored in the chamber from 24 hours after demolding until the time of testing as shown in figure 1.

![Figure 1. All samples inside the chamber (98% RH and 38C°).](image)

2.3. CFRP materials

CFRP materials were used to confine eighteen cylinders for both normal and reactive concrete, at the age of three months. Table 2 shows the properties of the CFRP, taken from the manufacturer’s data sheet.

| Properties | Manufacturer’s data |
|------------|---------------------|

Table 1. Proportions of ingredients used in concrete mix.

Table 2. The properties of CFRP.
Fiber modulus (GPa) 230
Tensile strength (MPa) 4900
Tensile strain capacity % 2.1
Fiber density (gm/cm³) 1.7
Thickness (mm) 0.227
Fiber weight (gm/m²) 400

2.4. Adhesive epoxy
“MBrace saturant” epoxy was used as bonding ingredient to confine the concrete cylinders with CFRP. This adhesive epoxy is manufactured in two components, resin and hardener, and the two parts are used at a fixed ratio to maintain the bond of the concrete cylinder with the CFRP. The properties of the adhesive epoxy provided by the manufacturer are shown in Table (3).

Table 3: Adhesive epoxy properties.

| Properties                  | Manufactured data |
|-----------------------------|-------------------|
| Tensile strength (MPa)      | 55                |
| Elastic Modulus (MPa)       | 3034              |
| Thickness (mm)              | 0.176             |
| Ultimate tensile elongation % | 0.025          |

2.5. Sample preparation
To understand AAR effect on concrete and how to maintain damaged concrete with CFRP, small cylinders and prisms were mixed from reactive and normal concrete, as shown in table 4. All samples were stored at 38°C and 98% RH. Twelve concrete prisms were fabricated from 3 samples of normal concrete, 3 samples with 5% fused silica, 3 samples with 7.5% fused silica and 3 samples with 10% fused silica of the total aggregate, as shown in figure 2. The length change and mass variation of the concrete prisms were measured at the age of 1, 7, 14, 21, 28 days and then every 15 days. Thirty six cylinders samples were fabricated from normal and reactive concrete using 7.5% of fused silica. Eighteen cylinders out of 36 cylinders were confined with 1 and 2 layers of CFRP sheets at the age of 3 months after being stored. Both normal and reactive concrete cylinders were wrapped with CFRP sheets, as shown in figure 3. The method of wet lay-up was applied for wrapping the concrete cylinders with CFRP sheets. Before applying CFRP, a sandblasting machine should be used to create a rough surface on concrete cylinders. The concrete surface was covered with a thin layer of primer to fill the voids, and then cured for 30 minutes. A layer of MBrace epoxy was then applied over the primer, and a CFRP sheet placed and fixed using a hand roller to get rid of the air bubbles between the CFRP sheets and the primer layer. The concrete cylinders were cured for 7 days until the day of testing. A digital image correlation technique (DICT) was utilised to measure the surface strain and compressive strength of the concrete cylinders.

Table 4. Types of concrete samples prepared for the tests.

| Experiments                                      | Specimen size (mm) | No. of specimens |
|--------------------------------------------------|--------------------|------------------|
| Compressive strength, modulus of elasticity and flexural strength | Ø100x200           | 36               |
| Concrete prism test (CPT)                         | 75x75x280          | 12               |
3. Results and discussion

3.1. Physical properties of concrete

3.1.1. Free expansion and mass variation. The length change and mass variation measurements of the concrete prisms, as shown in figure 4, were taken at the age of 1, 7, 14, 21, 28 days and then every 15 days. Figure 5 shows the expansion curves of both normal and reactive concrete, which had three different percentages of fused silica. The expansion values of reactive concrete with 10%, 7.5% and 5% fused silica at 115 days were 9604.6µs, 8259.3µs and 6370.4µs respectively. Figure 6 illustrates the mass variation for the normal and reactive concrete. The mass variation values of reactive concrete with 7.5%, 10%, NC and 5% fused silica, at 111 days were 0.69, 0.37, 0.91, and 0.73 respectively. RC fabricated with 7.5% fused silica gave the highest mass variation, while the RC with 10% fused silica gave the highest expansion. The results indicates that the mass variation is not related to the change in length of concrete prisms.
3.2. Mechanical properties of concrete

3.2.1. Compressive and tensile strength. AAR produces expansion and cracking in the concrete and has an adverse effect on the mechanical properties of concrete. Figure 7 illustrates AAR effects on the compressive strength. The figure shows the maximum reduction in the compressive strength of RC of about 63% compared to NC at 3 months.

Tensile strength is more influenced by AAR expansion than compressive stress. Figure 8 indicates the influence of AAR on the tensile strength of concrete. The tensile strength shows an average reduction of about 71% compared with NC at 3 months.
3.2.2. Modulus of elasticity (MOE). AAR has a great influence on the reduction of the MOE. Figure 9 shows that at age 28 days the reduction in the MOE for RC was 73% in comparison to the NC at the same age, while the reduction in the MOE of RC was about 93% with respect to NC at the age of 3 months. The MOE at age 28 days was measured by using strain gauges installed in the middle half of the concrete cylinder, while the digital image correlation technique system (DICT) was used to determine the surface strain in the middle half of the concrete cylinders at age 3 months.

3.3. CFRP wrapping effect

3.3.1. Compressive and tensile strength. As shown in table 5, the compressive stress of concrete is enhanced because of CFRP confinement. Figure 10 shows the confined concrete after failure under the compressive load. The compressive stress of RC is improved by 412% and 563% due to CFRP wrapping with 1 and 2 layers respectively. For the NC, the CFRP resulted in enhancement of up to 94% and 192% with 1 and 2 layers respectively.
Figure 10. The CFRP wrapped concrete after failure

Table 5. The effect of CFRP sheets on the compressive strength of normal and reactive concrete at age 3 months.

| Samples   | No. of CFRP layers | Compressive Strength (MPa) | Percentage Increases (%) |
|-----------|--------------------|-----------------------------|--------------------------|
| NC        | 0                  | 48                          | -----                    |
| NC        | 1                  | 94                          | 94%                      |
| NC        | 2                  | 142                         | 192%                     |
| RC-7.5%   | 0                  | 18                          | -----                    |
| RC-7.5%   | 1                  | 92                          | 412%                     |
| RC-7.5%   | 2                  | 119                         | 563%                     |

3.3.2. Strain capacity. The results show a great enhancement in the radial and axial strains of both NC and RC due to confining concrete cylinders with 1 layer and 2 layers of CFRP compared with unconfined concrete. As shown in Table 6, the radial strain capacity of both NC and RC confined with 1 layer of CFRP was higher than the radial strain for 2 layers of CFRP. The axial strain is improved for both NC and RC confined with 1 and 2 layers of CFRP.

Table 6. Effect of CFRP confinement on radial and axial strains for normal and reactive concrete at age 3 months.

| Samples   | No. of CFRP layers | Radial strain (µs) | Axial strain (µs) |
|-----------|--------------------|--------------------|-------------------|
| NC        | 0                  | 239                | 1310              |
| NC        | 1                  | 9509               | 11828             |
| NC        | 2                  | 9392               | 22430             |
| RC-7.5%   | 0                  | 14133              | 6383              |
| RC-7.5%   | 1                  | 12967              | 26167             |
| RC-7.5%   | 2                  | 7550               | 27533             |

3.4. Finite element analysis (FEA)

Non-linear finite element analysis (NLFEA) was used to predict the behavior of the tested specimens. The software ATENA (Advanced Tool for Engineering Nonlinear Analysis)-3D was used for this purpose [13]. The concrete was modeled with type CC3DNonCementitious 2 which combines plasticity with fracture. The material properties of concrete cylinders at the age of three months: compressive and
tensile strength and elastic modulus were inserted manually in the program, as shown in table 7. The selected model has proven represent effects of confinement in concrete quite adequately [14]. The combined CFRP/epoxy wrap was modelled as membrane elements rigidly connected to the concrete. It is reasonable to assume perfect bond between CFRP and concrete in confinement applications. Orthotropic material properties were assumed for the CFRP-epoxy elements since the fibers are unidirectional. Linear elastic properties are assumed with fracture of CFRP to occur when the stress reaches the breaking strength of the CFRP.

Six quarter-cylindrical models were constructed for both NC and RC cylinders. Figure 11 shows the geometrical design of the circular columns. The columns consist of two elements for non-confined columns: concrete and steel plates and three elements for confined columns: concrete, steel plates and CFRP sheet. For each type of concrete, the simulation was carried out to determine the maximum load at which the concrete failed. As shown in table 8, the loads predicted by FEA were consistent with the failure loads found in the experiments. The maximum difference is about 11.8% between the predicted and the measured values of load at failure, i.e., FEA is consistent with the measured results and can be used to model the behavior of AAR-damaged concrete repaired with CFRP sheets.

![Figure 11. FE Model of circular columns confined with CFRP.](image)

| Samples  | No. of CFRP layers | Compressive strength (MPa) | Tensile strength (MPa) | Modulus of elasticity (MPa) |
|----------|--------------------|----------------------------|------------------------|-----------------------------|
| NC       | 0                  | 48                         | 4.42                   | 37800                       |
| NC       | 1                  | 94                         | -----                  | -----                       |
| NC       | 2                  | 142                        | -----                  | -----                       |
| RC-7.5%  | 0                  | 18                         | 1.27                   | 2660                        |
| RC-7.5%  | 1                  | 92                         | -----                  | -----                       |
| RC-7.5%  | 2                  | 119                        | -----                  | -----                       |

Table 8. Comparison of loads between the predicted load from FEA and the measured load from the tests.
| Samples | No. of CFRP layers | Load (Experimental) (KN) | Load (FEA) (KN) | Differences % |
|---------|------------------|--------------------------|----------------|---------------|
| NC      | 0                | 380                      | 416            | 8.7%          |
| NC      | 1                | 741                      | 772            | 4.0%          |
| NC      | 2                | 1114                     | 1123           | 0.8%          |
| RC-7.5% | 0                | 141                      | 160            | 11.8%         |
| RC-7.5% | 1                | 724                      | 764            | 5.2%          |
| RC-7.5% | 2                | 937                      | 1008           | 7.0%          |

4. Conclusions
CFRP is an effective composite material used to confine concrete damaged by AAR and enhance the strength and ductility of concrete. This paper focused on the influences of AAR expansion in concrete on the mechanical and physical properties of concrete, using thirty-six cylindrical samples of NC and RC with 7.5% of fused silica, and twelve concrete prisms of NC and RC which contained fused silica at 5%, 7.5% and 10% of the total aggregate. It studied the effectiveness of using 1 and 2 layers of CFRP for the rehabilitation of concrete damaged by AAR, using eighteen concrete cylinders at the age of 3 months. The main conclusions can be summarized as follows:

- The physical properties of RC were affected significantly by AAR expansion. The expansion values of RC with 5%, 7.5% and 10% fused silica at 115 days were 6370.4µs, 8259.3µs and 9604.6µs respectively. The mass variation values of RC with 5%, 7.5% and 10% fused silica at 115 days were 0.47, 0.96 and 0.73, respectively. RC fabricated with 7.5% fused silica gave the highest mass variation, while the RC with 10% fused silica gave the highest expansion.
- The mechanical properties of RC were reduced significantly. The maximum reductions of up to 63% for the compressive strength of RC and 71% for tensile strength compared to NC at 3 months. The reduction in the MOE was about 93% compared to NC at the age of 3 months.
- CFRP wrapping is effective in confining damaged concrete and resulted in concrete strength enhancement of up to 192%, 412% and 560% for NC and RC wrapped with one and two CFRP layers respectively.
- Radial and axial strain were also improved for NC and RC.
- The finite element analysis was consistent with the experimental results.

5. References

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