Received: 10 May 2016 | Revised and accepted: 19 July 2016
DOI 10.1002/suco.201600090

WILEY fib CEB-FIP

TECHNICAL PAPER

Engineering field tests for alkali-aggregate reaction

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The Paulo Guerra Bridge in Recife, Brazil, was constructed in 1977. After about 15 years some pathological symptoms appeared, such as map cracking, concrete expansion, steel corrosion, and leaching stains. This paper presents a discussion of the specific inspections conducted, which included visual observation of the foundation blocks (pile caps), core extraction, ultrasonic pulse velocity tests, carbonation tests, measurements of chloride concentration, electrochemical resistivity, corrosion potential, compressive strength, and modulus of elasticity as well as X-ray diffraction and microscopy evaluations. The results of the inspection showed the occurrence of generalized alkali-aggregate reactions (AARs) on the pile caps (foundation blocks) of the bridge. The recommended repair for the pile caps was confinement to resist tensile stresses of 4 MPa.

KEYWORDS
alkali-aggregate reaction, field tests, Paulo Guerra Bridge

1 | INTRODUCTION

The Paulo Guerra Bridge in Recife, Brazil, links the district of Boa Viagem Beach and the center of Recife and was constructed in 1977. As the bridge is subjected to marine spray as well as wet and dry cycles, it can be considered to be in a marine environment, corresponding to a high or very high risk of deterioration (exposure class XS3 to EN 206: Concrete,[1] tidal, splash, and spray zones). The action of aggressive agents from the urban and industrial atmosphere of the City of Recife was also considered. Additionally, the marine water was examined, and high levels of sulfate, magnesium, and chloride were detected.

It is therefore not surprising that early signs of deterioration were evident on the deck, superstructure, and substructure about 15 years after the end of construction (Figure 1). This article presents a discussion of the inspection and the recommended repairs to the bridge foundation blocks (pile caps). These blocks were constructed using precast reinforced concrete boxes that served as permanent formwork for cast-in-place footings connecting the bridge piers to the supporting piles. The original project specified a compressive strength of 20 MPa (2,900 psi) for the pile caps, with an expected modulus of elasticity of 21 GPa (3,050 ksi) according to ACI 318-14.[2]

2 | REVIEW OF ALKALI-AGGREGATE REACTION (AAR)

According to the literature, AAR is a chemical reaction between some constituents present in certain types of aggregates and alkali components that are dissolved in the solution in concrete pores, which are usually derived from cement. The occurrence of this type of reaction is conditional upon the simultaneous presence of three conditions: potentially reactive aggregate, sufficient moisture, and a high concentration of alkali hydroxides in the pore fluid.[3]

Grattan-Bellew and Mitchell[4] explain that the phenomenon occurs when some minerals present in aggregates react chemically with alkali (Na, K) mainly (but not exclusively) from the cement, thus forming a hygroscopic gel. Hasparik[5] points out that the consequences of AAR in concrete include expansion due to the water absorption of the hygroscopic gel, cracking, and negative effects on the concrete's properties: reduction in the modulus of elasticity due to the cracking produced by expansion, reduction in tensile, and compression strengths. Sanchez[6] states that AAR can decrease both the loadbearing capacity of a structure or structural concrete element, also its functionality and durability, thus affecting its service life.

FIGURE 1 Signs of deterioration at the Paulo Guerra Bridge (foundation blocks, i.e., pile caps).

Mehta and Monteiro[7] and Neville[8] indicate that there are five main conditions that influence the occurrence and intensity of deterioration of AARs:

1. Cement alkali content and cement content in concrete: Laboratory and field studies in the United States report that Portland cement containing >0.6% of equivalent Na_2O (Na_2O_{eq}, which is expressed as a percentage and calculated according to the following expression: $Na_2O + 0.658\ K_2O$) combined with reactive aggregates can cause the major expansion associated with AAR. Investigations in Germany and the United Kingdom also showed that if the alkali content of the concrete (from all sources) is <3 kg/m^3, the risk of AAR can be minimized.
2. Contribution of the alkali ion from other sources: Additives, admixtures, salt-contaminated aggregates, water penetration by the sea, or deicing salts solution containing sodium chloride can penetrate the concrete and increase its alkali content, thus enhancing the deleterious effect. Seawater containing sulfates, magnesium, and chlorides was one the aggressive agents in the case of the Paulo Guerra Bridge.
3. Number, size, and reactivity of siliceous constituents in the aggregate: The results are influenced by form, texture, and fracture conditions, the type and concentration of aggressive agents, duration of and temperature during exposure to aggressive conditions, and so on. It should also be emphasized that the more chemically disorganized and unstable the structure of the minerals making up an aggregate, the more reactive the aggregate is likely to be. As stated by Godart et al,[9] reactive constituents that may be present in aggregates include opal, cristobalite, tridymite, siliceous, and intermediate volcanic glass, chert, glassy cryptocrystalline volcanic rock, artificial glasses, some argilites, phyllites, schists, gneisses, gneissic granites, vein quartz, quartzite, impure sandstone, and chalcedony. Moreover, in the case of the Paulo Guerra Bridge, the aggregates were reactive.
4. Moisture availability for the concrete structure: Figueirôa and Andrade[10] explain that water participates in the process as a means of transport for reagent elements. Foray et al,[11] by exposing mortars to different relative humidities, concluded that when water availability increases, AAR expansion increases, too. ACI 221.1R-98[12] states that the pressures generated by expansion are, in general, of an order of magnitude of 4 MPa. As expected, in the Paulo Guerra Bridge foundations, a high relative humidity and aggressive water were readily available.
5. Environmental temperature: According to the Arrhenius law, and like most chemical reactions, AAR intensifies with increasing temperature.[13] For this reason, many of the accelerated methods to identify the occurrence of AAR employee high temperatures, for example, 80°C.[14,15] For long-term AAR tests, the standard temperature is generally about 38°C.[16] As reported by INMET (Brazilian National Meteorology Institute), the Recife region experiences high temperatures, with an annual maximum average of 29.6°C and annual minimum average of 23.9°C. The offset average is 26.1°C.

Given the above, some measures can be undertaken to prevent or at least minimize AAR:

1. Aggregate selection: The most effective solution for avoiding AAR is certainly the use of nonreactive aggregates. A petrographic examination and other laboratory tests should be conducted to determine the aggregate's potential for causing deleterious reactions, so the material can be replaced. However, it is recognized that this measure may not be an economical option in many regions.
2. Cement selection: The use of a cement with a low alkali content may contribute to mitigating the occurrence of AAR. Once again, however, this measure may not be an economical option in many regions.
3. Limiting the alkali content in the concrete: AAR can be significantly reduced and even prevented by limiting the alkali content of the concrete to <3 kg/m^3 Na_2O_{eq}.[3]
4. Using mineral additions: A great variety of material is available for controlling AAR. A means of preventing or minimizing the risk of alkali-silica reaction (ASR) can be to replace part of the cement by mineral additions such as pozzolanic materials, granulated blastfurnace slag, fly ash, silica fume, rice husk, and metakaolin.[17]
5. Using chemical additives: ACI 212.3R-10[18] discusses the use of lithium admixtures to reduce deleterious expansion due to ASR. The document explains that, in the concrete pore solution, dissolved silica can combine

with sodium or potassium ions to form the basis for an alkali–silica gel that can absorb water and expand—with deleterious effects on concrete. If lithium ions are present in a sufficient ratio with respect to the sodium or potassium ions, then lithium will preferentially combine with the available silica to form relatively stable, insoluble lithium silicates. Nevertheless, as stated by Nixon and Sims,[19] the lithium dosage levels depend on the alkali level in the concrete and the nature of the aggregate. Some aggregates require much higher doses of lithium than others to control the expansion, so it is recommended to perform tests in order to evaluate its effectiveness and determine the appropriate lithium dosage for each case.

6. Limiting moisture: According to ACI 221.1R-98,[12] reducing the permeability of concrete to external moisture and salt can reduce the potential for expansion. This might be achieved by using a concrete mix with a low water–cement ratio.

If none of the measures outlined above has been taken and the deleterious effects of AAR are discovered after the placement of the concrete, some care should be taken. So far, there is no consensus how to repair structures suffering from AAR. When a structure under action of AAR needs to maintain its intended function, surface protection measures or waterproof membranes can be used to stopping or decreasing the expansion caused within the concrete by blocking or reducing moisture presence. Sanchez et al[20] found, for example, that silicone and epoxy coatings can potentially prevent expansion due to AAR, decreasing the expansion by about 75 and 50% on average.

Hasparik[21] states that chemical treatments with lithium solutions can potentially mitigate the residual expansion. However, Fournier et al[22] remind us that these treatments are limited to a small penetration depth, and so more refined monitoring of a global efficiency treatment is necessary.

FIGURE 2 Leaching stains and map cracking (foundation block 7).

Fournier and Bérubé[3] mention that structural strengthening or physical restraints achieved by confining or encapsulating the concrete or structural element affected can contain the deformations and expansion. Figueirôa and Andrade[10] reached this conclusion when discussing an experimental study in which cylindrical cores were submitted to confinement pressures, verifying that, in specific cases, the internal pressure of the gel was not sufficient to overcome the external pressure applied.

As will be discussed below, this principle was employed in the treatment of the Paulo Guerra Bridge.

3 | INSPECTION AND TESTING

A visual inspection of the pile caps (foundation blocks) was performed to evaluate the general state of the bridge, observe the nature of the pathological manifestations and estimate their gravity, and define the regions for detailed inspections and tests.

Stains typical of corrosion and leaching were detected as well as cracks with defined paths (Figure 2).

Figure 3 shows schematic view of the bridge showing the relative locations of the pile caps. Of the total of 20 blocks, four are buried in the soil next to the junctions and the other 16 are in direct contact with water. Of these 16 blocks, five were chosen for inspection (blocks 1, 4, 7, 10, and 12), selected according to their condition in order to be representative in relation to the pathological problems evident—from the most deteriorated to those with a better visual appearance.

A commercially available pachometer[23] was used to detect bars, their sizes, and their concrete covers. Ultrasonic pulse tests were conducted[24] as well as tests for carbonation,[25] chloride concentration,[26] electrochemical resistivity,[27] and corrosion potential.[28] Concrete cores[29] were obtained at several locations (blocks 1, 4, 7, 9, 10, and 12) and, after visual inspection, were used to determine compressive strength[30] and modulus of elasticity.[31] Further, portions of these cores were used for petrographic evaluations.

4 | TESTS RESULTS AND DISCUSSION (PILE CAPS)

Ultrasonic pulse velocity tests indicated that velocity increased with depth, showing that the cracks observed externally were heavily concentrated in the cover region. Furthermore, there was uniformity of the concrete deeper than the concrete cover as well as the presence of concrete with a strength higher than the design strength and good conservation conditions in the core of the foundation blocks (with wave propagation velocity values > 4,000 m/s).

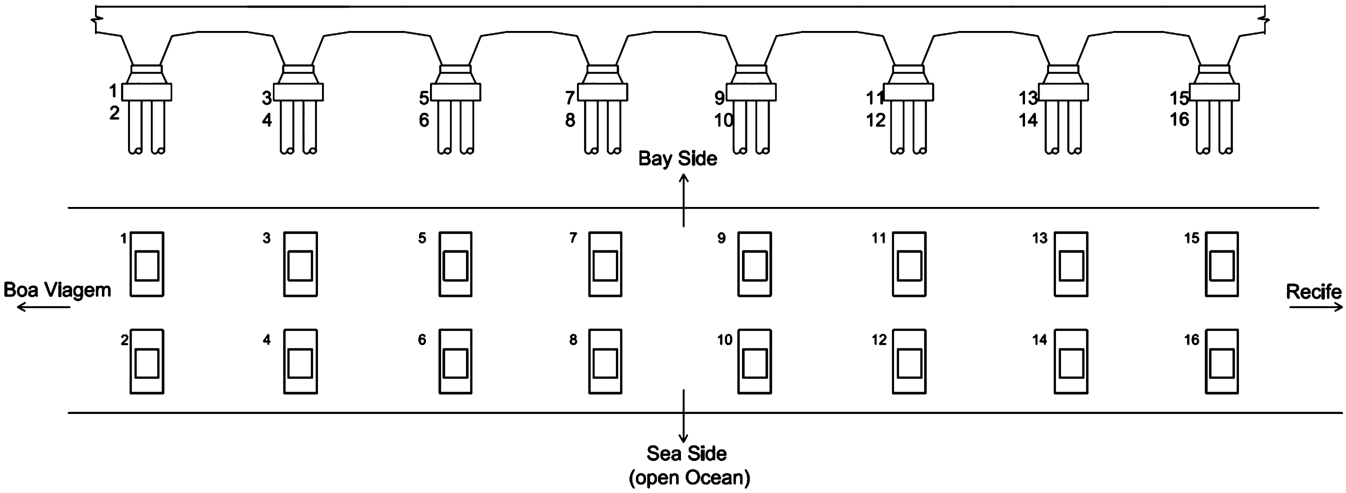

FIGURE 3 Overall schematic view showing foundation block locations.

As expected in a marine environment, diffusion of the CO_2 into the pores of saturated concrete is difficult and the depth of carbonation was insignificant.

The chloride concentration profiles (Table 1) also indicated that the corrosion threshold had not been reached (0.4% by cement content according to CEB[32]). In the concrete cover region, the total levels of chloride ranged from 0.20 to 0.67%, and in the region near the steel reinforcement, contamination fell to levels < 0.4% by cement content.

The results obtained in electrical resistivity tests showed that, in "dry" regions, the resistivity of the concrete was high and the risk of electrochemical corrosion was lower. On the other hand, the resistivity was lower in humid and concrete subjected to reinforcement corrosion regions, that is, the concrete was porous, with considerable communication between the pores.

The specified concrete covers for the blocks (pile caps) were 100, 150, and 125 mm (4, 6, and 5 inch) for the top, bottom, and side bars respectively. Although the minimum cover measured using the pachometer was close to 80 mm (3.1 inch), corrosion potential was generally between +50 and −150 mV versus $Cu/CuSO_4$, indicating low corrosion probability. The divergence between the reality of corroded steel (Figure 4) and the expectation of little corrosion is due to the impossibility of measuring the corrosion potential of exposed steel or in regions where the concrete cover was already damaged, so the tests had to be carried out in locations remote from the few corroded regions. Additionally, most concrete covers were in the order of 10 cm (4 inch), passivating the steel and making it difficult to measure the corrosion potential in the pile caps.

All the cores that were evaluated showed evidence of whitish efflorescence formation, with storage of the substance at the interface between the aggregate and the cement paste (Figure 5). Some aggregates within the cores exhibited a friable aspect, being visible in these cases as the deteriorated interface between the aggregate and the cement paste. Despite the intensive cracks in the pile cap surfaces, the

TABLE 1 Chloride content in % by cement content

	Depth (mm)				
	5	10	20	30	Nucleus
Block 7	0.52	0.39	0.59	0.34	0.20
Block 10	0.48	0.54	0.53	0.53	0.20
Block 12	0.67	0.20	0.67	0.53	0.42

FIGURE 4 Severe steel corrosion on the superstructure of the Paulo Guerra Bridge.

FIGURE 5 Detail of the whitish efflorescence formation stored at the interface between aggregate and cement paste.

evidence indicated that the majority of these cracks did not exceed 10 cm (4 inch).

The compressive strength and modulus of elasticity values taken from cores are shown in Tables 2 and 3, respectively. As with the pulse velocity tests, the strength and elastic modulus values increased with depth, indicating better concrete at the nucleus of the blocks compared with the surface. As can be seen, there is a large scatter of results and the modulus obtained is very low. Hasparik[5] and Marzouk and Langdon[33] considered that a low modulus of elasticity is an important indicator of very severe AAR.

With that evidence, the differences between the severely deteriorated concrete surfaces of the blocks and the concrete cores of the blocks, which still provide convincing levels of good conditions, are clearly highlighted.

Petrographic[34,35] studies confirmed the degenerative aureole around the coarse aggregates, revealing AAR. Ettringite formation was also observed, but not with an intensity that could indicate a degenerative reaction of expansion by sulfates or Delayed ettringite formation (DEF) reaction.

5 | ASSESSMENT AND REPAIR RECOMMENDATIONS

Considering the results obtained in the analyses carried out, it can be affirmed that the two major pathological problems of premature and accelerated aging of the Paulo Guerra Bridge consisted of AAR in the pile caps (foundation blocks), and, consequently, steel corrosion in the bridge's superstructure.

Further, the modulus of elasticity and the strength data provided clear evidence of AAR-related cracking below the surface and internally as far as the concrete cover of the reinforcement. These results confirm the conclusions of studies by Hasparik[5] and Marzouk and Langdon,[33] where the modulus of elasticity is the concrete property with the most sensitive reaction to AAR.

AAR was verified through microscopy evaluations (which identified microgranulated quartz crystals and quartz crystals with strong undulating extinction) complemented by mineralogical analyses by X-ray diffraction. Figure 6a and b shows typical cracks and morphologies of AAR. Further, the lowest modulus of elasticity was found to correlate with typical gel salts on the edges of the aggregate and in the transition zone between the cement paste and aggregate. This behavior was found to extend from the concrete block surface down to about 400 mm (15.75 inch) from the concrete surface.[36]

Once AAR was confirmed, many corrective alternatives were studied, including induced carbonation and injection of lithium salts. Considering the local conditions and the advanced deterioration, confinement of the blocks appeared to be the best alternative. As keeping the concrete dry is not possible and the reaction is expected to continue, the designed confinement was required to have enough strength to resist the AAR expansion forces.

It was decided to use a confining force sufficient to resist 4 MPa (580 psi) tensile stresses, with inspections

TABLE 2 Results of compressive strength tests (MPa)

		Location					
Core no.	Region	B_{01}	B_{04}	B_{07}	B_{09}	B_{10}	B_{12}
01	Surface region (concrete cover)	19.1	22.5	—	29.4	13.1	40.1
02	Intermediate region	23.6	29.4	32.5	35.4	23.6	49.2
03	Deeper region (block nucleus)	35.4	31.8	32.5	44.4	28.6	44.7

TABLE 3 Results of modulus of elasticity tests (GPa)

Block	Core no.	Compressive strength (MPa)	Expected modulus of elasticity[2]	Measured modulus of elasticity[31]
01	01	19.1	20.7	10.4
	02	23.6	23.0	17.2
	03	35.4	23.9	24.4
10	01	13.1	17.1	8.0
	02	23.6	23.0	13.2
	03	28.6	25.3	16.6

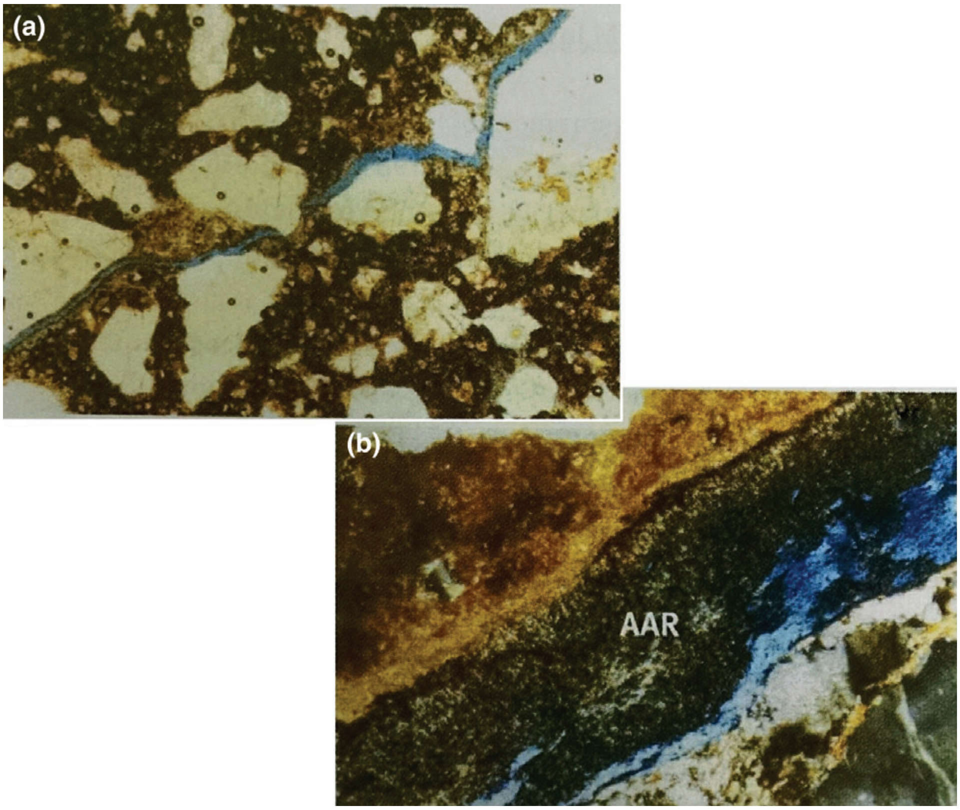

FIGURE 6 Photomicroscopy sequence showing evidence of AAR.

every 4 years. This solution provided benefits over demolition, saving money and inconvenience for urban citizens.

6 | CONCLUSION

The authors observed that all the tests conducted were important for understanding the AAR phenomenon, identifying its influence on concrete properties and durability. The greatest mechanical indicators of a deleterious reaction were the modulus of elasticity tests, which showed this property to be the one most sensitive to the deterioration caused by AAR. Even taking into account the severe deterioration in the concrete cover region, the pile caps could be recovered. From the indications of this study, to strengthen the blocks with confinement sufficient to resist expansion tensile stresses in the order of 4 MPa, a structural design using Dywidag bars was developed. Apart from the confinement, the pile caps were waterproofed to provide an additional barrier to the progression of the degenerative phenomenon. The strengthening work was conducted with success and is now finished, and the bridge is in normal operation.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Pedro Castro-Borges of CINVESTAV-Mérida for his help and support during the preparation of this paper.

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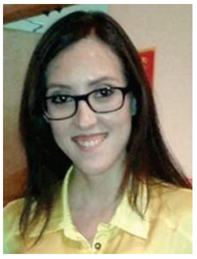

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How to cite this article: Helene P, Carvalho M, Pacheco J. Engineering field tests for alkali-aggregate reaction. *Structural Concrete*. 2017;18:349–355. https://doi.org/10.1002/suco.201600090