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Experimental simulation of surface cracking in concrete structures affected by AAR

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ABSTRACT: Alkali-aggregate reaction (AAR) is a slow expansive reaction that occurs in concrete between the alkali in cement and reactive aggregates, leading to spalling and strength loss of the concrete. This reaction takes years to develop and the speed of reaction depends on several material and environmental parameters. In order to develop and test corrective solutions to this problem in a reasonable laboratory timeframe, it is possible to accelerate AAR by using extremely reactive materials under carefully controlled environments. This paper presents a new approach that was developed to simulate AAR-like expansion and random surface cracking in just a few days without the need for a controlled environment. After testing different approaches, the successful approach consisted of the combined use of pervious concrete and expansive cement paste. It was found that the cracking patterns obtained on cylindrical and prismatic concrete specimens were very similar to those found in real structures affected by AAR.

1 INTRODUCTION

Alkali-aggregate reaction (AAR) is a very slow deleterious reaction that occurs in concrete between the alkali in cement and silicon dioxide found in common aggregates. This reaction produces a gel that expands in contact with the moisture in concrete, which can lead to spalling and strength loss of the concrete and ultimately to the failure of the affected structure. This problem is known to affect large concrete structures, however, severe cases of AAR were recently observed in building foundations of smaller concrete structures. For instance, Andrade (2006) presented eight confirmed cases of AAR in Recife-PE, Brazil. It was emphasized that this problem of AAR in small concrete structures could be more common than what is actually known to the scientific community. The rehabilitation of AAR-affected structures represents a considerable engineering challenge and the corrective actions are usually costly, especially for building foundations that are not directly accessible, often requiring the demolition of the concrete slab and excavation to gain access to the buried foundation. Once the repair work is completed and the area reopened for use, it is very difficult to evaluate the long-term effectiveness of the corrective action and the possible re-occurrence of the problem. The prediction of the progress (or lack) of the deterioration is uncertain, as different deterioration rates can be observed in structures, even made of similar concretes, because deterioration rates are strongly dependent on the various exposure conditions to which these structures are subjected (Fournier et al. 2009).

One of the possible ways to manage the AAR problem in building foundations is to monitor their expansion until some specific threshold values are reached, thus indicating the need to take corrective actions. Existing remote monitoring strategies for small AAR-affected structures with specific needs are scarce. In order to develop a monitoring strategy for AAR in small concrete structures, it became necessary to simulate the AAR expansion and cracking within a reasonable laboratory timescale, as AAR usually take years to develop in the field. It is possible to accele-

rate the AAR process by using extremely reactive materials under carefully controlled environments in order to obtain typical AAR-like crack patterns and intensity. For example, Toma et al. (2007) achieved a simulation of AAR in concrete using an expansive agent based on lime hydration under wet curing and isothermal conditions. They obtained a 0.7% restrained expansion after 6 days, but the crack pattern was different from AAR-like cracking since the cracks had small openings and a preferential orientation. A new approach was therefore developed to simulate AAR-like expansion and random surface cracking in just a few days without the need for a controlled environment. The whole process of developing the material formulations for achieving the desired expansion and crack pattern is presented in this paper, while the structural health monitoring aspect of this study is presented in a companion paper (Nery et al. 2010).

2 DEVELOPMENT OF APPROACH TO SIMULATE AAR EXPANSION & CRACKING

2.1 1st preliminary approach: Expansive concrete

Based on the approach proposed by Toma et al. (2007), several concrete mixes using different blends of ordinary portland cement (OPC) and expansive calcium sulfoaluminate additive were prepared. Seven concrete mix formulations were developed with proportions of 0.5:1:2:3 for water, OPC (Type GU, equivalent to ASTM Type I), concrete sand, and coarse limestone aggregate (10 mm maximum size), respectively, and with increasing quantities of expansive additive (0, 20, 40 & 60 kg/m³ of concrete). Two expansive additives were used: a regular Type-K component made of calcium sulfoaluminate and calcium sulfate (referred to as CSA), and a chemically-similar Type-K component designed to provide more expansion and less heat of hydration (referred to as Power CSA). For each formulation, concrete was cast into three prismatic steel moulds (75 x 75 x 295 mm) with the top surface sealed to prevent drying shrinkage.

The free linear expansion of each concrete was measured from the time of setting with two linear variable displacement transducers (LVDT) attached to each steel mould before the placement of concrete (Fig. 1). To ensure free expansion of the specimen in the steel mould, the inside walls of each mould were lined with a 3 mm layer of closed cell foam rubber and cellophane to prevent friction between concrete specimen and the mould. A detailed description of this test apparatus can be found in Cusson & Hooeveen (2007).

Figure 1: Diagram of test apparatus (Cusson & Hooeveen 2007).

Three prisms of each system were monitored under sealed condition, and Figure 2 presents the average expansion strain curves measured for each expansive concrete and reference concrete. Each curve is identified according to the quantity of CSA additive used in a cubic meter of concrete. Figure 3 presents the same information for the Power CSA mixtures. It is seen that the onset of expansion occurred at about 3 hours after setting, and that significant expansion of up to 450 µε in 3 days for the regular CSA additive and up to 4400 µε in 6 days for Power CSA additive. It is also observed that the expansion increased with the amount of expansive additive used, except for the dosage rate of 60 kg/m³ of the regular CSA additive (Fig. 2), which did not perform as well as the 40 kg/m³ mix. It is hypothesized that the 60 kg/m³ CSA mix developed too many microcracks, which impaired the transmission of expansive forces in the system, as discussed by Morioka et al. (2003).

Despite the large quantity of CSA additive used in the concrete mixes (with some dosage rates exceeding the manufacturer's recommendations), the expansions were not large enough to produce macrocracks. For instance, the most successful expansive concrete tested in this study developed free expansion of 0.44% after 6 days, without any visible signs of cracking. However, observations under the electron microscope revealed many microcracks in this specimen. Ettringite was also observed throughout the system, indicating a high Al/S environment as would be expected in a CSA system. Nevertheless, it was concluded that this approach did not provide the desired crack pattern (i.e. large random cracks).

Figure 2. Expansion of CSA expansive concrete prisms measured over 3 days.

Figure 3. Expansion of Power CSA expansive concrete prisms measured over 6 days.

Figure 4. Microcracks in CSA specimen at 1000x magnification (a), and ettringite crystals in cavity of same system at 10,000x magnification (b).

2.2 2nd preliminary approach: Normal concrete with drilled holes filled with expansive paste

In order to delay the expansion to a time when the concrete matrix is more brittle and susceptible to cracking, a second approach was considered. The three old control prisms (without CSA additive) tested in the previous experiment were cut to make nine cubes for additional testing. Cylindrical holes (diameter of 10 mm) were drilled part way through the cubes using different alignment patterns. The drilled holes were then filled with expansive cement paste made of a mixture of water, OPC and CSA additive (proportions of 0.5:1:1 by mass), respectively. Large cracks developed in the cubes within 1 day, but the crack pattern was predictable and aligned with the patterns of holes, and thus not representative of typical AAR crack patterns.

2.3 Selected approach: Pervious concrete filled with expansive cement paste

A third approach was developed by combining pervious concrete and expansive cement paste. Typically, pervious concrete has no fine aggregate and has just enough cement paste to coat the coarse aggregate particles while preserving the interconnectivity of the large voids. Pervious concrete is normally used for flatwork applications (like parking areas) allowing rain water to pass directly through, thereby reducing runoff from a site.

In a first step, pervious concrete was prepared to cast cylinders (100 x 200 mm) using the mix formulation proposed by Wang et al. (2006). The proportions were 0.4:1.0:4.5 for water, OPC, and coarse aggregate (Table 1). Two sieved sizes of coarse aggregate were tried separately: a finer size from 6.3 to 12.5 mm (A), and a coarser size from 12.5 to 25.0 mm (B). Wet curing was applied for 3 days. Volume measurements of the pervious concrete voids by the water displacement method revealed 32% voids when using Aggregate A, and 34% voids with Aggregate B, and both aggregates displayed good adherence to the paste. Twenty-four hours after casting, the outer surface of each cylinder was coated with a thin layer of ordinary mortar with mass proportions of 0.6:1:2 for water, OPC and sand, respectively. The top and bottom surfaces were left opened to provide an opening to introduce the expansive paste into the pervious concrete when fully cured. The coated surfaces of the cylinders were smoothed to easily track the formation of cracks over time, and the cylinders were returned back to the curing room.

The next step was to fill the voids of the pervious concrete cylinders with expansive cement paste, which is expected to expand around the coarse aggregate, inducing internal forces in all directions within the pervious concrete. The expansive paste swelling around the aggregate is close to what actually happens in AAR-affected concrete, where the gel produced by the reaction forms around the aggregate and expands further when in contact with moisture (Newman & Choo 2003). Different blends of OPC and CSA additive were used to prepare expansive cement pastes (Table 1) in order to optimize the expansion within the pervious concrete. Table 2 presents the maximum crack openings produced on the test cylinders by the different blends.

Table 1. Mass proportions of pervious concrete and expansive cement pastes (kg).

Mix	Water	OPC	CSA	Aggregate
Pervious Concrete	0.4	1.0	–	4.5
Expansive Paste 1	0.6	1.0	0.5	–
Expansive Paste 2	0.8	1.0	1.0	–
Expansive Paste 3	0.6	0.5	1.0	–

Table 2. Maximum crack openings measured on test cylinders (mm).

Age / Mix	1A	1B	2A	2B	3A	3B
24 hours	1.4	1.0	no	no	0.3	0.1
48 hours	5.0	5.0	6.0	7.0	4.0	6.0

Expansive Paste 1 provided the most desired results, with considerable free expansion and large random cracks developing rapidly (Fig. 5a & 5b), which are similar to typical AAR-induced cracks found in affected reinforced concrete foundations (Fig. 6), despite their different restraint and loading conditions. In Expansive Paste 2, for instance, the crack formation was delayed and progressed too rapidly later on, which was not desired for the purpose of this study.

Figure 5. Pervious concrete cylinder 1A at 6 hrs (a) and 24 hours (b) after application of expansive paste.

Figure 6. AAR-affected concrete building foundation (Andrade 2006).

3 EXPERIMENTAL VALIDATION OF SELECTED SIMULATION APPROACH

The shape of the concrete specimen used for this part of the study was chosen to represent small building foundations and had overall dimensions of 600 x 400 x 400 mm. The concrete prism was slightly reinforced using 10-mm bars with a 40-mm concrete cover (Fig. 7). The pervious concrete formulation shown in Table 1 was used. Aggregate B with a size ranging from 13 to 25 mm was chosen for the larger voids created in pervious concrete in order to allow easier introduction of the expansive paste into the voids of the pervious concrete, which achieved a 28-day compressive strength of 7 MPa (which is typical of commercial pervious concrete).

The prismatic form was designed with double wood panels (Fig. 7) so that a mortar layer could easily be cast later over the side and bottom surfaces of the large pervious concrete prism (Fig. 8), which was done one day after casting the pervious concrete. A 20-mm steel tamping rod was used to compact the mortar. Moist curing with wet burlap was applied for 2 days, after which time the expansive cement paste was introduced, which had a formulation identical to Paste 1 in Table 1.

Figure 7. Double-panel wooden form used to cast reinforced pervious concrete prism.

Figure 8. Casting of external mortar layer on sides and bottom of pervious concrete prism.

Since the bottom surface of the concrete prism was sealed with the mortar layer, six drain holes were drilled through the mortar layer near the bottom of the concrete prism. This was done to allow trapped air to escape and the expansive paste to flow easily without resistance and to confirm the flow of the paste from the top to the bottom of the prism. On the first trial, the paste did not flow down to the bottom surface of the prism. To solve this problem, two vertical cores of 100 mm diameter and 300 mm height were drilled in the prism, confirming that the paste had filled only the top 100 mm of the prism (Fig. 9). The drilled holes were then filled with additional expansive paste and a portable vibrator was used to induce energy to the paste making it more fluid during the placement (Fig. 10). Expansive cement paste was added to the two large openings until it started to flow through the six small drains, confirming the success of the operation. The small drain holes were then plugged with rubber stoppers.

Figure 9. Cores extracted from concrete prism.

Figure 10. Expansive paste poured through drilled holes.

During the fabrication of a second prism, two cylindrical shapes (e.g. 100 x 200 mm cylindrical moulds) were secured to the reinforcing steel cage before casting the pervious concrete into the prismatic form to provide openings so that holes would not need to be drilled later. After one day, when the pervious concrete was sufficiently hard, the two plastic moulds were removed from the pervious concrete prism. The two empty cylindrical holes were then used for the placement of the expansive cement paste and to introduce the portable vibrator in order to improve the flow of the expansive paste into the voids of the pervious concrete. Finally, two 100 x 200 mm cylinders of pervious concrete, which had been cast when the large prism was made, were used to fill the openings after the placement of the expansive paste in order to prevent high concentrations of expansive paste at these two locations.

Within 24 hours after the application of the CSA expansive paste, the prism started to crack severely and expanded for three additional days, after which time no more new cracks were observed. The obtained crack pattern was very similar to typical crack patterns observed in AAR-affected concrete foundations. For example, Figure 11a presents the simulated expansion and

cracking on the laboratory prism, and Figure 11b illustrates an existing concrete building foundation affected by AAR in Brazil (Andrade 2006).

Figure 11. (a) Simulated cracking in lab prism; (b) AAR-affected building foundation (Andrade 2006).

4 CONCLUSIONS

The main objective of the study presented in this paper was to develop an accelerated experimental simulation of the expansion and random surface cracking typically found in concrete structures affected by alkali aggregate reaction. This accelerated laboratory simulation will be eventually used to develop a structural health monitoring strategy for AAR-affected concrete building foundations, with the aim to provide timely information for maintenance and rehabilitation planning and to ensure the safety of AAR-affected structures and their occupants.

Different simulation approaches were evaluated and, from the obtained results, the following conclusions can be drawn:

- The expansive concrete specimens made with blends of OPC and CSA additive produced considerable expansion, but did not form large cracks (only fine microcracks), even for large CSA additive dosage rates.
- The OPC concrete specimens with drilled holes filled with expansive paste displayed severe expansion and cracking, but the crack pattern was different from AAR-induced cracks.
- The proposed approach consists of casting a pervious concrete specimen, in a first step, and filling the large voids with expansive cement paste, in a second step. This approach was found successful when tested on small cylindrical specimens and large-size prismatic reinforced concrete specimens, with crack openings and patterns that are very similar to those found in existing AAR-affected reinforced concrete building foundations.
- The proposed approach, however, does not simulate or accelerate any internal chemical reaction of AAR. It is designed to simulate the resulting surface deterioration.

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