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Development of a remote monitoring strategy for building foundations affected by AAR

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ABSTRACT: Alkali-aggregate reaction (AAR) is one of the most serious problems that can adversely affect the durability and the integrity of concrete structures. Corrective actions are usually very costly. Although this problem is known to affect large concrete structures, severe cases of AAR were recently observed in building foundations of small size concrete structures. The main objective of this study is to develop of a sensor-based remote monitoring strategy for AAR-affected building foundations that is both reliable and cost effective. Different commercially available sensors were reviewed and selected for this application. The results and findings of this study will then be used to develop a monitoring strategy, which will be helpful to assess the progress of AAR in small size concrete structures or the effectiveness of corrective actions, and to assist the owners of these structures in prioritizing future repairs or replacement.

1 INTRODUCTION

Alkali-aggregate reaction (AAR) in concrete is a deleterious reaction between the alkali in cement and silicon dioxide found in many common aggregates. It produces a gel that expands when in contact with the moisture in concrete, and can lead to the development of high tensile stresses and cracking of concrete. AAR is a serious problem that adversely affects the durability and integrity of concrete structures. This problem was first reported in the USA in 1940 after it was observed in road transportation structures (Stanton 1940). Since then, large-size concrete structures, such as dams, received considerable attention due to their importance and their aggressive environment, which can promote the development of AAR and the resulting deterioration. This led to the general belief that AAR would only occur in dams or other large-size civil structures. However, some severe cases of AAR were observed in smaller concrete structures in Europe (Swamy 1992), and more recently in foundations of buildings, as reported by Andrade (2006) who presented eight confirmed cases of AAR in Recife-PE, Brazil. It was emphasized that this problem of AAR in small size concrete structures could be more common than what is actually identified in the literature.

The rehabilitation of AAR-affected structures still represents a considerable engineering challenge and the corrective actions are usually very costly, especially for building foundations that are not easily accessible, often requiring the demolition of the concrete slab and excavation to gain access to the buried foundation (Fig. 1). The repair of AAR-affected structures is also problematic since the reactants in the concrete cannot be removed. In order to extend the service life of the affected structures and to keep the life cycle costs down, Newman & Choo (2003) emphasized the necessity of conducting particular corrective actions in cases (i) when the AAR expansion is still progressing; (ii) when the AAR has significantly impaired other concrete structural properties; or (iii) when the AAR damage has rendered the concrete structure potentially vulnerable to other deleterious physico-chemical agents.

Figure 1. Building foundation with AAR-induced cracks under repair by epoxy injection (Andrade 2006).

Depending on the degree of expansion, exposure conditions and reinforcing details, Doran (1992) indicated that the affected structures can usually remain in service, subject to structural health monitoring and/or remedial action. In order to control the AAR problem, it is necessary for the structure owner to rely on a reliable source of information to effectively assess parameters such as rate of expansion, crack opening, and aggressiveness of the microenvironment. This will ensure a more accurate assessment of the condition and will prevent the use of unnecessary costly interventions or ineffective solutions.

One of the possible ways to manage the AAR problem is the use of a surface treatment to reduce the moisture content in the affected concrete, which is one of the prerequisites for the reaction to develop in concrete. Eskridge et al. (2009) evaluated different surface mitigation techniques for large structures affected by AAR and concluded that the best treatment method is one that prevents moisture ingress while allowing vapor to escape the concrete. In order for this treatment to be effective, the affected area of the structure needs to be exposed to wet/dry cycles, and this is usually not the case for concrete foundations because they are either under water or buried. Another possible solution is to confine the concrete foundation with external reinforcement in order to restrain the expansion of concrete (Newman & Choo 2003). This is also a costly solution of which the effectiveness needs to be verified periodically. However, if the reaction does not have a severe impact on the structure, the AAR problem can be managed by conducting periodical inspections to assess the serviceability and safety of the affected structure.

Once the repair work is complete and the area back in service, it is very difficult for the structure owner to evaluate the long-term effectiveness of the corrective action and the possible reoccurrence of the problem. Predicting the growth of AAR-induced damage is difficult, as different deterioration rates can be observed in structures made of similar concretes, because the deterioration rates are strongly dependent on the various exposure conditions to which these structures can be subjected (Fournier et al. 2009).

Due to the importance of dams and other large concrete structures, and the potentially large impact of their failure on public safety, structural health monitoring of these structures is already well established and often used to monitor the progress of AAR (e.g. Sellier *et. al.* 2009). However, monitoring strategies for smaller concrete structures with specific needs are not common. Two important criteria for the design of a structural health monitoring system for small size AAR-affected concrete structures, is reliability and affordability, as most of these structures are often owned by small enterprises or individuals with limited resources. The ability to monitor AAR-affected building foundations with sufficient accuracy will enable the structure owner to make informed and timely decisions regarding future possible corrective actions.

The main goal of this study is to test a variety of selected sensors for the monitoring of this type of problem and to highlight the weaknesses and strengths of each sensor type in the context of monitoring small size concrete structures. The monitoring strategy developed in this study will be used to determine the development rate of the AAR problem and the need for a corrective action, and/or to evaluate the effectiveness of the rehabilitation.

2 EXPERIMENTAL PROGRAM

2.1 *Test specimen*

In order to test a monitoring strategy for AAR in small size concrete structures, it was necessary to simulate the AAR expansion and cracking within reasonable laboratory timescale. A new approach has been developed to simulate AAR-like expansion and random surface cracking in a few days without the need for a controlled environment. The approach consisted of casting a pervious concrete prism, and coating its lateral and bottom surfaces with regular mortar. After curing, expansive cement paste was then poured into the prism to fill the large voids of the pervious concrete contained by the outer mortar shell. The development of the material formulations and the detailed specimen construction procedure for achieving the desired expansion and crack pattern are presented in a companion paper (Nery et al. 2010). The present paper will focus on the health monitoring aspects of AAR-affected structures.

The prismatic shape of the concrete specimen used for this study was chosen to be representative of small size 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. 2).

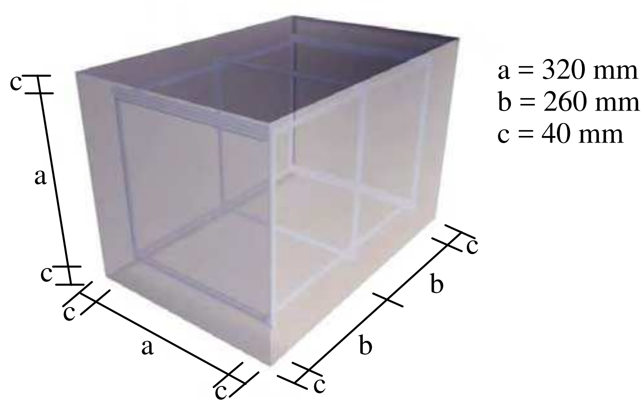

Figure 2. Three-dimensional view of the reinforced concrete prism.

2.2 *Selected sensors*

The AAR foundation problem occurs mostly in residential buildings, for which the engineering expertise and available budget for maintenance are usually limited. With this in mind, one of the main concerns of this research was to find a simple and affordable monitoring strategy. Advanced fiber-optic systems were disregarded because they are typically more expensive and more complex to operate than conventional electric-based monitoring systems. Also, techniques such as strain relief, seismic tomography, ultrasonic pulse velocity (on drilled cores) and petrographic examination (Rivard et al. 2009) were not considered since they require periodic access to the affected concrete structures.

For their simplicity, low cost and known accuracy, electrical strain gauges, linear variable displacement transducers (LVDT) and an analog data logger were selected for the experiments.

The strain gauges used in this study had an electrical resistance of 350 ohms. They were bonded to the reinforcement of the concrete prism to monitor the longitudinal strain of 4 reinforcing bars (i.e. 2 horizontal and 2 vertical) as shown in Figure 3. The strain gauges were installed in pairs on opposite sides to compensate the bar bending interference, sealed and protected with rubber coating and aluminum foil (Fig. 3). In order to monitor long lengths of concrete surfaces, long gauges (LG) with gauge lengths of 30 cm and 40 cm were designed and built using thin aluminum plates (thicknesses of 1 mm and 2 mm) with strain gauges bonded to both sides at mid-length (Fig. 4). Each long gauge was anchored to the concrete surface using 2 pairs of short aluminum plates bonded with 24-hour epoxy and 2 concrete screws (Fig. 4). The long gauges were preliminary tested in tension in a hydraulic testing machine, and excellent correlation was found between the strain gauge readings and the imposed displacements (Fig. 5).

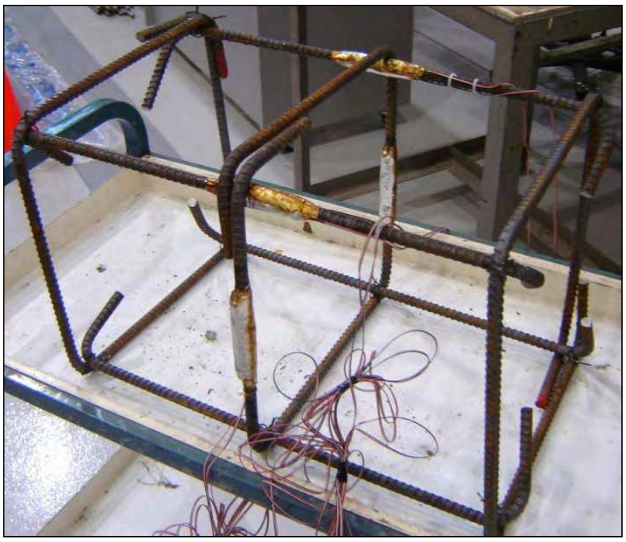

Figure 3. Electrical strain gauges applied on reinforcing bars (with protection).

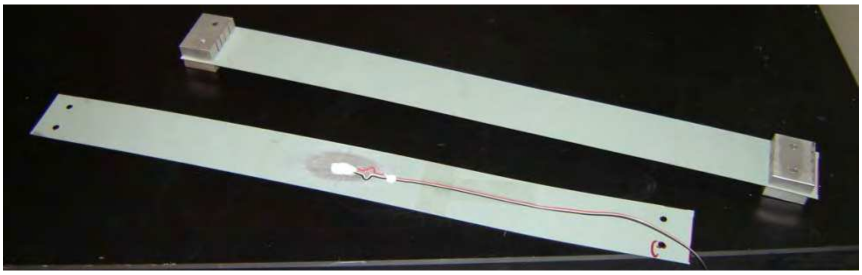

Figure 4. Custom-made long gauges.

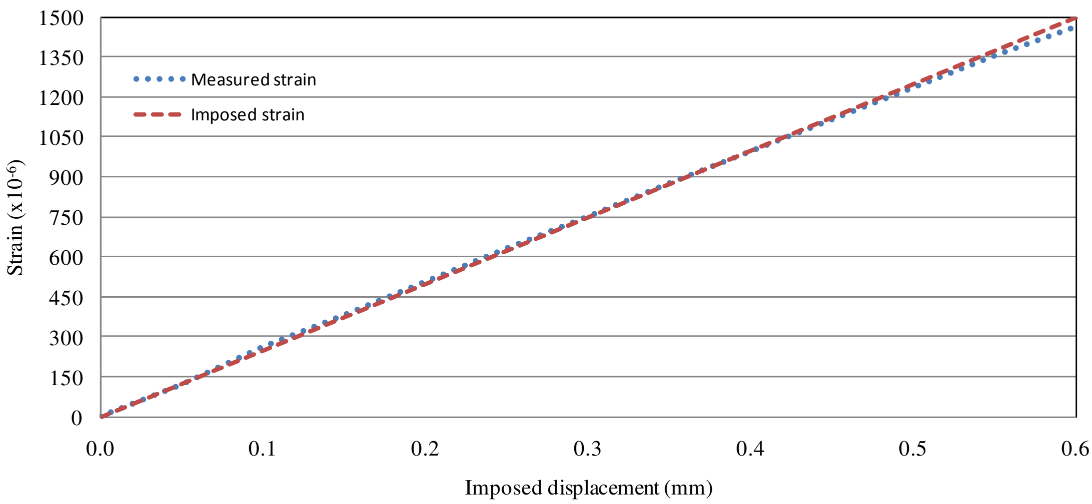

Figure 5. Correlation between imposed displacement and measured strain from long gauge (LG).

The LVDTs used for this study were direct-current transducers with a rugged construction and a stroke length of 5 cm. They were used on the surfaces of the concrete prism to monitor the gradual opening of cracks, in general, and beside the long gauges to confirm their readings.

A crack scope with an accuracy of 0.05 mm was used to obtain direct measurements of surface crack openings in the direction perpendicular to the axis of the nearby sensor. Such measurements are considered to be the reference measurements.

A 30-channel data acquisition system was used in this study. Type T thermocouples monitored the temperature close to each pair of strain gauges (on the reinforcement), in the center of the concrete prism, and in the room.

To evaluate the effect of sensor distribution on measurement accuracy, more sensors than necessary were used to monitor the expansion and cracking of the concrete surfaces. Three faces of the prism were instrumented as follows: the north face (N) with 5 LVDTs (2 horizontal and 3 vertical, Fig 6a), the east face (E) with 4 LVDTs (2 horizontal and 2 vertical, Fig. 6b) and the south face (S) with 2 long gauges (horizontal and vertical) and 3 companion LVDTs to confirm their readings (Fig. 6c). Each sensor is identified by sensor type (LVDT or LG), prism face orientation (N, E or S), sensor direction (H or V) and number (e.g. LVDT-N-H1; LG-S-H1).

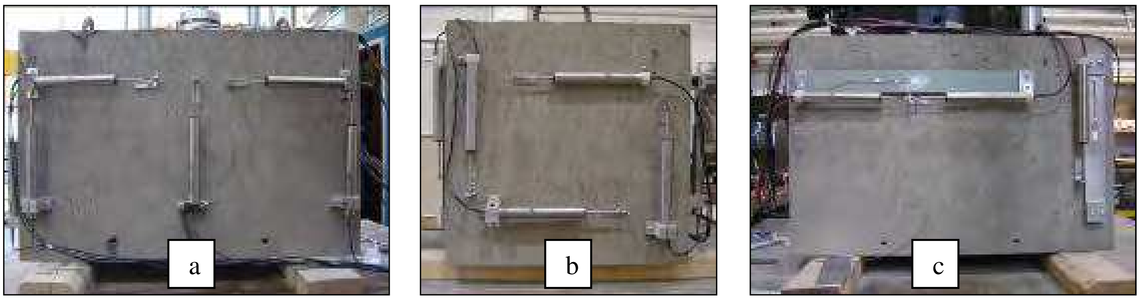

Figure 6. Sensor distribution on each instrumented face.

2.3 *Monitoring program*

The acquisition of data was initiated 24 hours before filling the pervious concrete prism with expansive paste in order to confirm the stabilized values of temperature and displacement before the onset of concrete expansion. Automatic readings were taken every 5 minutes, photographs of concrete surfaces were taken every 12 hours, and the main cracks were identified and measured with the crack scope regularly until an opening of up to 3 mm was reached, which was the maximum measurable value of the scope.

3 RESULTS, ANALYSES AND DISCUSSIONS

3.1 *Long gauges*

Visual observations made during the measurement period revealed that the anchors used to secure the long gauges to the concrete surface were not stable enough to measure large displacements with accuracy. For this reason, the long gauges lost adherence to the concrete surface after some small expansion. At the same time, the LVDTs located beside the long gauges on Face S (Fig. 6c) also lost their alignment because they shared the same anchors with the LGs. This instability problem prevented any readings to be taken after the first few hours of accelerated expansion. In the future a new anchoring system for this type of gauge will need to be developed in order to ensure accurate measurements.

3.2 *Embedded strain gauges*

In order to compare the measured values from the strain gauges to the measured cumulative crack opening or to the measured displacement from the LVDTs, the strain readings were multiplied by the bar length on which the gauges were installed. In general, the strain gauge readings showed good response to the expansion, but were always proportionally smaller than the cumulative opening of the cracks that developed perpendicularly to the sensor measuring path (Fig. 7). This effect could be due to the gradual debonding of the reinforcement from the surrounding concrete when the deterioration level became relatively high in the expanding concrete. The outward bending of the reinforcing bars also caused the failure of some strain gauges, after which time it was difficult to cancel out the bending effect of the bar on the strain measurement. The use of supplementary (redundant) pairs of strain gauges on the reinforcing bars with additional mechanical protection would minimize the impact of gauge failure on the measurements.

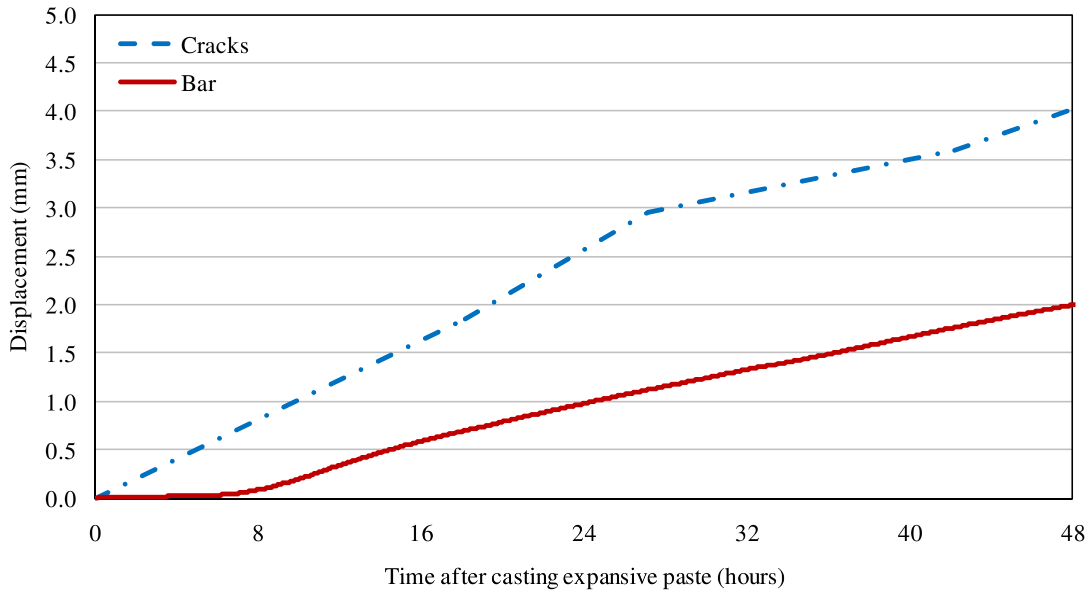

Figure 7. Horizontal expansion measured on Face S.

3.3 *LVDTs*

The LVDTs showed good correlation with the measured cumulative crack opening (Fig. 8). In an advanced stage of accelerated expansion and deterioration, the cracked surfaces of the concrete prism moved in all directions, which affected the alignments of the LDVTs, as expected. The LVDT-H1 on Face E provides an example of the misalignment problem when the cumulative crack opening exceeded 3 mm, as shown in Figure 8.

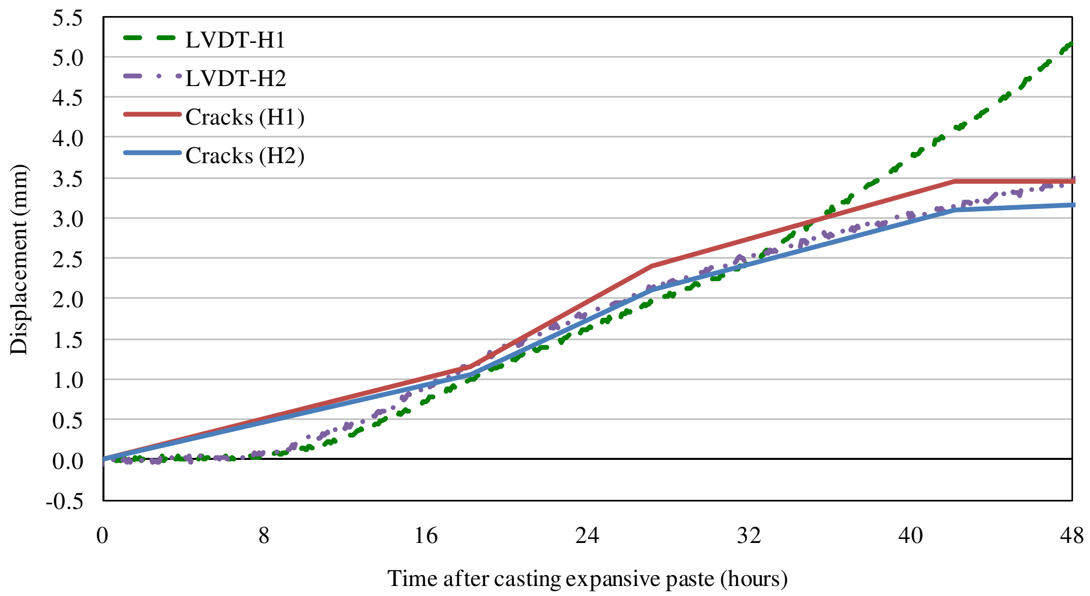

Figure 8. Horizontal expansion measured on Face E.

The monitoring of random surface cracks showed that LVDTs may not capture the effect of nearby cracks that are outside the measuring length. This problem may be compounded by the closing of older cracks induced by the opening of newer cracks, as well as by the angle of the cracks relative to the measuring line. Figure 9 shows the horizontal expansion measured on Face N, and Figure 10 illustrates Face N after 24 hours of accelerated expansion. It can be seen that a large crack developed between the 2 horizontal LVDTs, explaining the results in Figure 9.

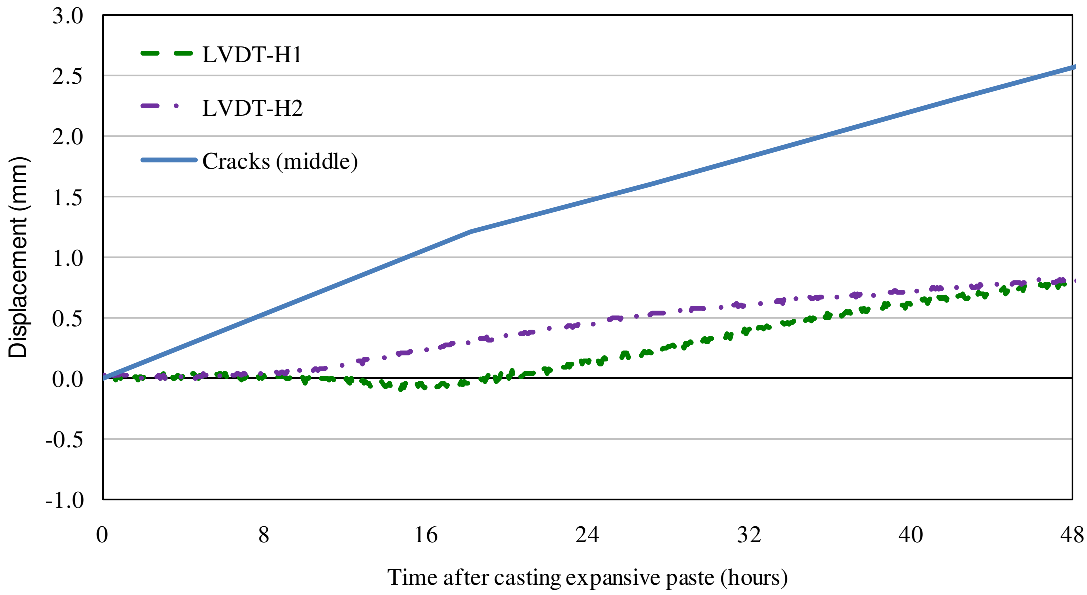

Figure 9. Horizontal expansion measured on Face N.

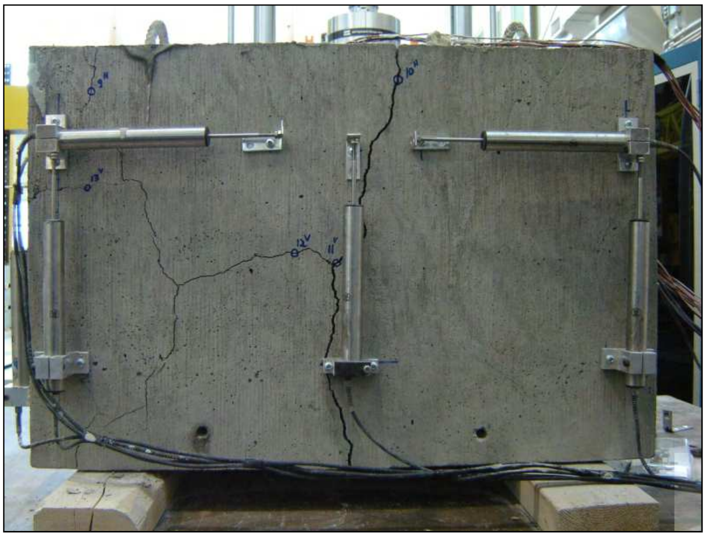

Figure 10. Face N shown 24 hours after the onset of accelerated expansion.

3.4 *Next steps*

In order to complete the study, a second large-size reinforced concrete prism will be made and instrumented considering the improvements required to address the issues identified in this initial test. A complete monitoring strategy will then be developed for small size AAR-affected concrete structures, with possible field testing on an existing affected structure.

4 CONCLUSIONS

The main objective of this study was to develop of a sensor-based remote monitoring strategy for AAR-affected building foundations that is both simple and cost effective. Different commercially available sensors were selected for this application. From the obtained results, the following conclusions are drawn:

- The custom-made long gauges showed good potential for monitoring displacement when expansion and deterioration levels were relatively small. The anchoring system of the long gauges to the concrete surface requires improvement for better measurement accuracy under large expansion.
- The electrical strain gauges installed on the embedded reinforcement proved to be a good way to monitor the AAR expansion of building foundations when strengthening or confinement becomes necessary as a corrective action. This method can indicate when the reinforcement undergoes additional tensile stresses due to AAR-induced expansion, and possibly when the expansion stops.
- The LVDTs proved to monitor the opening of cracks with sufficient accuracy as long as their individual alignment is not affected by the instability of the underlying concrete surface. They seem to provide reliable monitoring of cracks on prismatic foundations.

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