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Stress due to Alkali-Silica Reactions in Mortars

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Abstract

Alkali-silica reaction (ASR) deterioration in mortars and concretes is often attribute to the swelling of gel formed by the reaction of alkali hydroxides with reactive silica in aggregates, in the presence of water. The swelling of the gel can generate sufficient tensile stresses resulting in expansion and cracks. Most tests designed for ASR rely on measurements of the length change. A new test, designed to measure the stress generated by the swelling of the gel, has a cylindrical mortar specimen placed in a frame under a load cell. The force required to prevent expansion is measured over time while the specimen and frame are immersed in a solution of 1 N NaOH at 50 °C. The design of the apparatus, together with some early results, are presented. The ASR-induced stress and expansion caused by different aggregates was investigated. Stress measurements showed a strong influence of stress relaxation and self-desiccation/water absorption on the mechanical response of the material subjected to ASR. A preliminary study of the effect of hydration on stress relaxation and self desiccation/water absorption was made, using non-reactive aggregate.

Introduction

Damage of concrete due to alkali-silica reaction (ASR) is a phenomenon that was first recognized in 1940 by Stanton (Stanton, 1940; Frohnsdorff, 1979) in North America. It has since been observed in many other countries. Many studies (Hobbs, 1988; Diamond, 1992; Helmuth, 1993) have been published since Stanton's first paper, but the mechanisms of ASR are not yet clearly understood (Capra, 1995), although the major factors have been identified. In the presence of water, alkalis in the pore solution react with reactive silica, found in certain aggregates. Related factors that play a significant role are the relative humidity, the porosity of the concrete, and the use of mineral admixtures.

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Most methods in use today to determine the extent of ASR in mortars or concretes are based on measurements of the expansion of the specimen. In this paper, we will describe a new technique that measures the expansion stresses generated during the reaction. The main advantage in measuring stresses instead of length changes is the possibility that the results could be used to design a concrete that would resist ASR expansion by having a tensile strength higher than the stress generated by the reaction. Some of these test results have been published (Ferraris, 1996).

Background

Most researchers agree that the main form of ASR is between certain kinds of silica present in the aggregates and the hydroxide ions (OH^-) in the pore water of a concrete. Hydroxide ions from the hydration of portland cement result in a pore solution pH of around 12.5 or higher (Diamond, 1983). The hydroxide ions may attack vulnerable sites exposed in a silica surface. If the silica is well-crystallized the vulnerable sites are few but in the case of poorly-crystallized or amorphous silica, there are many vulnerable sites in the silica structure; in the latter case, alkali attack may lead to extensive conversion of the silica to calcium and alkali silicate gel (Figg 1983; Helmuth 1992).

The formation of the gel *per se* is not deleterious. The deterioration of the concrete structure is due to the water absorption by the gel and its expansion. If the tensile strength of the system is locally exceeded, cracks will form and propagate in radial fashion around the reaction site. The sites of crack initiation are randomly distributed in the specimen, and so there is no overall preferential direction for cracks to propagate. The crack initiation sites are determined by the location of the reactive silica on the aggregates and the local availability of OH^- .

Most tests available for determining the extent of ASR in concrete are based on measurement of the specimen expansion, which comes mainly from crack opening displacement. The mix design and the testing conditions differs among tests. There are three ASTM tests currently used: ASTM C1260 (ASTM, 1994), ASTM C227 (ASTM, 1994b), and ASTM C441 (ASTM, 1995). Other tests described in the literature are usually modifications of the above tests. A German test (Kuhlman, 1975; Lenzner, 1981) was developed to measure the stress generated from ASR but limited data are available. Recently, Sellier et al. (Sellier, 1995) have simulated the stresses and the swelling due to ASR and found reasonable agreement with available measurements.

Experimental Set-up

Figure 1 shows a schematic sketch of the designed apparatus. The specimen, a mortar or concrete cylinder, is placed in the stainless steel frame and attached to a load cell. The load cell is connected to a computer that monitors, at regular intervals, the force generated by the expansion of the specimen. To ensure that the load cell response (voltage) is uniquely related to a force generated by the specimen, the cell was calibrated, using a dead weight set-up, in the same configuration (frame) as was used during the experiment.

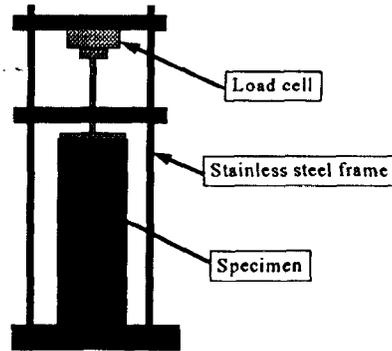


Figure 1: Schematic view of the device used to measure stress due to ASR.

To test for ASR induced stresses, the frame holding the specimen is immersed in a container with a 1N aqueous solution of NaOH which is the test solution used in ASTM C1260 (ASTM, 1994). The container is then placed in a water bath with a controlled temperature of $50\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$. Since the experiment was conducted at constant temperature, the initial differential thermal expansion between frame and specimen must be taken into consideration. By monitoring the inside temperature with a thermocouple in a specially prepared specimen, we found that the middle of the mortar cylinders rose from room temperature to the bath temperature in approximately six minutes. This result agrees very well with calculations using the known thermal diffusivity of mortar ($\approx 0.001\text{ m}^2/\text{h}$) (De Schutter, 1995) and the geometry of the specimen (Crank, 1975).

For stress relaxation measurements, the specimen was placed in the frame and compressed until a stress of about 5 MPa was applied, implying that a different fixed strain was actually applied that depended on the Young's modulus at the time of loading.

In this study, only mortar specimens were tested. We used a mix design that simulated a high performance concrete, with low permeability, low water/cement ratio and high cement content. Table 1 gives the mixture designs used. One sand was selected for its reactivity and one for its lack of reactivity. The specimens were cylinders, 38 mm in diameter and 279 mm long (1.5 in. x 11 in.).

For ASR measurements, three specimens were prepared from each mix; one for measurement of stresses and two for unrestrained expansion measurements either in limewater or in 1 N NaOH solution after 24 h curing. For stress relaxation measurements, specimens were prepared using Mix B and were tested after 1, 3, 7 and 14 days of curing in limewater at $25\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$. All the measurements were done at $50\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$.

Table 1. Mixture design of the mortars

Mixture design	Mix A	Mix B
Water/Cement	0.295 by mass	0.295 by mass
Sand/Cement	1.411 by mass	1.411 by mass
Alkali content of cement	1.2 % Na ₂ O	1.2 % Na ₂ O
Type of sand	Tecosil ^{2,3}	U.S. Silica ³
Sand Gradation	Gradation #1 (Ferraris)	Gradation #2 (Ferraris)
HWRA ⁴	HRWA #1 @ 0.50% by mass of cement	HRWA #2 @ 4% by mass of cement

ASR results

Before examining the data for the measured stress and strain (length changes), it is important to consider what processes can contribute to these phenomena. ASR causes specimens to increase their length, but there are also length changes that come about due to the competition between self-desiccation and water absorption (Miyazawa, 1996), and also those due to thermal changes. In a confined specimen, these length changes will cause the measured stress to change, along with the effect of stress relaxation (Mehta, 1993), which will tend to reduce the measured stress. We can then write the overall time-dependent stress as

$$S(t) = [S_0 + S_A(t) + S_{ASR}(t)] f(t)$$

where S_0 is the initial applied stress, $S_A(t)$ is the stress coming from the competition between self desiccation and water absorption, and which also involves the time-dependent Young's modulus, $S_{ASR}(t)$ is the stress caused by ASR, and $f(t) < 1$ is the stress relaxation function. For these small stresses, well less than half the compressive strength, the stress relaxation function is considered to be independent of stress. These terms must be sorted out in order to be able to measure the actual stress caused by ASR. In this paper, compressive stress is taken to be positive.

The two different aggregates had very different effects on the level of the measured expansion and stress, because of their different reactivity. The total free expansion of Mix A was about 10 times greater than that of Mix B (Figure 2), due mostly to ASR-induced cracking. It should be noted that the baseline length was taken at room temperature, while the length change measurements were taken at 50 ± 3 °C, so part of the measured length change was due to thermal expansion. This will not make much difference to the Mix A data, but will drop the mix B data by about 0.03%. As only the type of aggregates differed between the two mortars, these plots

² Graded sand provided by C-E Minerals⁴, PA USA. The composition is fused silica (amorphous).

³ The name of manufacturers are identified in this report to adequately describe the experimental procedure. Such an identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material identified is necessarily the best available for the purpose.

⁴ by mass of cement; HWRA #1 was supplied by W.R Grace and Co.³. while HRWA #2 was supplied by Masters Builders³

indicate that sand #1 is more reactive than sand #2, as was expected. The amount of gel produced in the two specimens will be measured in the scanning electron microscope to help determine the actual difference in reactivity between the two aggregates. It should be noted that the same length change results were found for Mix B while immersed in saturated lime water, indicating that the NaOH solution had no effect on the Mix B aggregate. The Mix B aggregate can truly be considered non-reactive, at least with respect to NaOH.

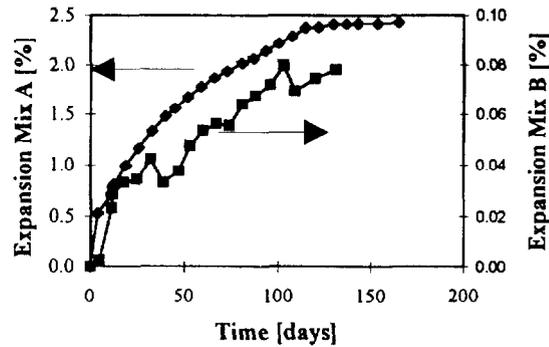


Figure 2: expansion measurements on the tested mortar.

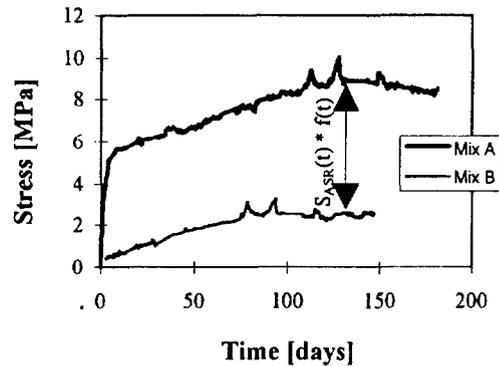


Figure 3: Change of stress with time for the constrained specimens.

Figure 3 shows the measured stress, $S(t)$, as a function of time in the confined specimens, where $S_0 = 0$. The stresses in Mix A built up very rapidly, and then increased slowly over time, while the stress in Mix B increased more gradually, although still at a higher rate at earlier times. The stress in Mix B shows the effect of stress relaxation and the competition between self-desiccation and water absorption. Clearly, the water absorption is winning, since a compressive stress developing means that the specimen wants to grow bigger. Unconfined specimens of this size do indeed display length increases over time (Miyazawa, 1996). As in the length change measurements, the specimens were put into the frame at room temperature, with $S_0 = 0$. Upon placement into the water bath at 50°C, the differential thermal expansion

between the frame and the specimen would cause a small gap to open up between the frame and the top of the specimen. This will cause the measured stress to be somewhat smaller than it really is, since the specimen could undergo unrestrained growth until the top of the specimen ran into the frame and load cell.

Without this thermal expansion effect, and if both specimens had the same gradation of aggregate, since all other aspects of the mix design and curing schedule were identical, then the difference between the two curves in Figure 3, as shown by the arrow, would just be the quantity $S_{ASR}(t) \cdot f(t)$, the actual stress caused by ASR times the stress relaxation function.

Stress relaxation measurements

To help to clearly see the effect of self-desiccation, water absorption, hydration, and stress relaxation on the measured stresses, several experiments were carried out using non-reactive aggregates at different ages, where S_0 was non-zero.

Approximately a 5 MPa compressive stress was applied at room temperature to each specimen. Upon placement in the 50°C water bath, there was an immediate drop in stress, which was different for each specimen (Table 2). The amount of stress lost is equal to the initial Young's modulus of the specimen multiplied by the difference in thermal expansion between the stainless steel frame and the mortar specimen. The frame expands more than the mortar cylinder, so that compressive strain is lost. The thermal expansion coefficient of the (304 stainless steel) frame is approximately $20 \cdot 10^{-6} / ^\circ\text{C}$ (CRC Handbook, 1978), while that of the mortar is approximately $10 \cdot 10^{-6} / ^\circ\text{C}$ for the younger age specimens, but increases with hydration (Klieger, 1994). The Young's modulus, $E(t)$, is also increasing with hydration, so that the initial stress lost is a product between an increasing function, the modulus, and a decreasing function, the difference in thermal expansion strain between specimen and frame. Therefore we expect to see the stress lost to be a function with a minimum, which can be clearly seen in Table 2. This thermal expansion phase is over by the time the specimen comes up to the bath temperature, which is complete in six minutes or so, as was previously discussed. In this short of time, the effect of stress relaxation is negligible. After this point, each specimen was held at a fixed strain, and the stress measured as a function of time.

Table 2: Stress loss due to temperature

Curing Time [days]	Initial Stress drop [MPa]
1	1.0
3	0.6
7	0.8
14	1.5

Consider a specimen held at fixed compressive strain. As discussed above, there are two competing processes occurring that can cause changes in the strain when no ASR is present. The first is stress relaxation, which causes the stress carried to be

reduced. The amount that the stress is reduced for a given amount of time decreases with age, so that younger specimens (less degree of hydration) will have more stress relaxation than older specimens (greater degree of hydration) (Mehta, 1993). A typical stress relaxation curve, $f(t)$ vs. t , shows a sharp drop over a period of a few days, followed by a much more gradual decrease over tens of days and longer.

The second process is the competition between self-desiccation, which causes a specimen to shrink, and water absorption, which relieves the internal capillary stresses caused by the self-desiccation and so causes expansion (Miyazama, 1996). The kinetics of this process are quite interesting. At earlier times, the faster hydration causes a high rate of self-desiccation, but also the permeability is higher and so water can flow into the specimen more quickly. At later times, as hydration slows so does the rate of self desiccation, but at this point the specimen's permeability is lower, so water ingresses at a slower rate. For the size of specimen we are considering here, along with the w/c ratio used, we should only see expansion over time and so an increase in compressive stress over time (Miyazawa, 1996). Figure 1 shows just this effect for the non-reactive specimen.

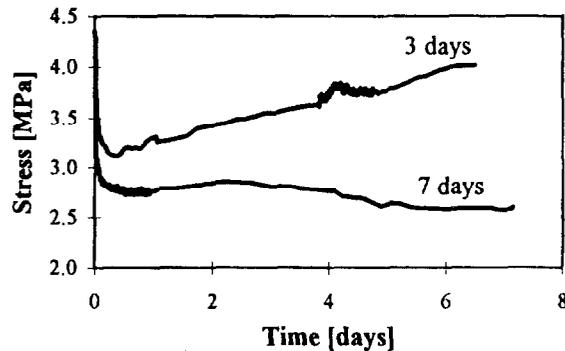


Figure 4: Stress relaxation curves. Fluctuations in the curves are due to temperature fluctuations in the bath. From the magnitude of the initial thermal drop in stress, every degree change in the bath temperature will result in a stress change of roughly 0.05 MPa, so that the nominal $\pm 3^{\circ}\text{C}$ on the bath will give fluctuations of ± 0.15 MPa, of the order seen.

Now add both processes together. These two processes have different rates at different times, and so one or the other process will tend to dominate at different times. Figure 4 shows stress vs. time, after the first six minute temperature-induced drop, for a 3 and a 7 day old specimen. It seems clear from their behavior that initially, the sharply dropping part of the stress relaxation function $f(t)$ dominates, as both measured stresses fall sharply over the first 1/2 day or so. From that point, for the 3-day specimen, which has a higher hydration rate, the product $[S_0 + S_A(t)] f(t)$ has a slope greater than zero. In the 7-day old specimen, it would seem that the slope of the product $[S_0 + S_A(t)] f(t)$ is approximately zero, resulting in a curve that is roughly

flat in time. Further work is planned to study the behavior of these curves for different age specimens. Measurements are planned of degree of hydration, mass gain, length change, and stresses which will aid in extracting the true value of S_{ASR} (Garboczi, 1996).

Conclusions

It has been shown, using the new apparatus, that substantial forces can be exerted by ASR. However, along with ASR-induced compressive stress there are also changes in stress caused by the changes in length caused by the competition between self-desiccation and water absorption, along with stress relaxation, which decreases the stress. Some preliminary measurements on nominally non-ASR-susceptible-aggregate mortars show that when stress was applied and measured starting at shorter times (≤ 3 days), water absorption dominates, so that the measured stress increased with time. When stress was applied and measured at longer times (7 days), stress relaxation gradually came to dominate, so that the measured stress decreased with time. When ASR was active, the measured stress always increased with time. More measurements on the competing role of these various processes must be made in order to be able to clarify the actual stress that is caused by ASR.

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