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THE EFFECT OF STRESS RELAXATION, SELF-DESICCATION, AND WATER ABSORPTION ON THE ALKALI-SILICA REACTION IN LOW WATER/CEMENT RATIO MORTARS

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ABSTRACT

A device has been designed and tested for measuring the stress caused by the alkali-silica reaction (ASR) in mortars. Specimens were placed in a frame equipped with a load cell, allowing us to approximately fix the strain at zero and measure the total stress generated over time. The specimens and the frame were immersed in a 1-N NaOH solution at 50°C. Even without ASR, the specimens expanded due to water absorption that relieves the shrinkage caused by self-desiccation. In addition, applied stresses, as well as stresses that were set up in the sample by expansion caused by ASR and/or water absorption, were subject to stress relaxation. By using companion samples having nonreactive aggregates, we were able to distinguish the stress caused by ASR from that caused by water absorption-driven expansion. The effects of stress relaxation could not be removed without further experimentation and theoretical analysis. © *1997 Elsevier Science Ltd*

Introduction

Damage of concrete due to alkali-silica reaction (ASR) was first recognized in 1940 by Stanton (1,2) in North America. It has since been observed in many other countries. Many studies (3,4,5) have been published since Stanton's first paper, but the mechanisms of ASR are not yet clearly understood (6). Nevertheless, the major factors have been identified. In the presence of water, hydroxide ions in the pore solution react with reactive silica, found in certain aggregates. Related factors that can play a significant role are environmental relative humidity (RH), porosity of the concrete, and mineral admixtures in the concrete.

Most methods in use today to detect ASR in mortars or concretes are based on measurements of the expansion of the sample. In this paper, a novel device, described in detail elsewhere (7,8), allowed us to measure stresses generated by the sample. The stresses measured are a combination of any initial applied stress, the ASR gel expansion, and expansion associated with water absorption that contrebalances self-desiccation shrinkage and stress relaxation. To isolate the stresses due to the ASR expansion, we compared nonreactive sand mortars with reactive sand mortars.

Possible applications of this test may be: 1) the design of concrete that has a tensile strength high enough to prevent expansion and cracks, 2) the investigation of the use of reactive aggregates in situations where the externally applied stresses are higher than any possible ASR reaction stresses, and 3) the assessment of the stability of a structure where the parts are exposed to ASR and tend to swell, whereas other parts are not, and may be confining the sweling parts.

Background

Most researchers agree that ASR occurs between certain kinds of silica present in the aggregates and the hydroxide ions (OH^-) in the pore water of a concrete (3,4). Hydroxide ions from the hydration of Portland cement result in a pore solution pH of around 12.5 (9). The pH is influenced by the amount of alkalies present in the pore water, which in turn is related to the amount of soluble alkalies in the concrete. The hydroxide ions may attack sites on a silica surface. If the silica is well crystallized, the most reactive sites are few, but in the case of poorly crystallized or amorphous silica, there are many more such sites in the silica structure; in the latter case, hydroxide attack may lead to complete conversion of the silica to a calcium and alkali silicate gel (10,11).

The formation of the gel per se is not deleterious. The deterioration of the concrete structure is due to water absorption by the gel and its subsequent expansion. If the tensile strength of the matrix is locally exceeded, cracks will form and propagate radially from the reactive aggregate. The sites of crack initiation are often randomly distributed in the specimen, with no preferential direction of crack propagation. The points of crack initiation are determined by the location of the reactive silica in the aggregates and the local availability of hydroxide ions.

Most tests available for detecting ASR in concrete are based on the measurement of specimen expansion using various mixtures and testing conditions. There are three ASTM tests currently used: ASTM C1260 (12), ASTM C227 (13), and ASTM C441 (14). Other tests described in the literature are usually modifications of these. A German test (15,16) was developed to measure the stress generated from ASR, but limited data are available. Recently, Sellier et al. (17) attempted to simulate the stresses and the swelling due to ASR and found reasonably good agreement with available measurements.

In a low water/cement (w/c) ratio system, there is another source of linear expansion when a specimen is immersed in water: relief of the shrinkage that was caused by self-desiccation via absorption of water (18). Miyazawa and Monteiro (18) showed that there is a tradeoff between water coming in to relieve the self-desiccation shrinkage stresses and the rate at which self-desiccation proceeds. This tradeoff is controlled by the size and water sorptivity of the samples. For specimens of the size we have used, only increases in length were seen over time (18). Larger specimens could possibly show some shrinkage, followed by length increases, because the larger sample size may slow down the process by which external water relieves the internal self-desiccation shrinkage. Lower w/c ratios will accentuate this effect because self-desiccation increases with w/c ratios below about 0.4. The w/c ratio used by Miyazawa and Monteiro was 0.3, almost identical to the value we used in the present study.

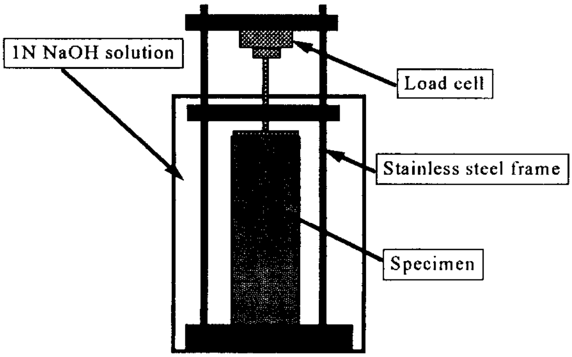

FIG. 1.
Schematic of the device used to measure stress due to ASR.

Experiment

Measurements

To measure the stresses generated by the expansion of a specimen, the following test was developed. A detailed description of this test was published previously (7,8). Figure 1 shows a sketch of the apparatus. The specimen, a mortar or concrete cylinder, is placed in the stainless steel frame and connected to a load cell. Usually some small load is initially placed on the specimen by screwing down bolts set in the frame. The load cell, connected to a computer, monitors at regular intervals the expansive force generated by the specimen.

If the load cell were infinitely stiff, then the sample would be constrained to stay at the prescribed initial strain, which is determined by the load that is initially placed on the sample. This experiment would then be a pure stress relaxation experiment at a fixed strain level. Because, the load cell is not of infinite stiffness, this test is not a pure stress relaxation test. It does allow some deformation to take place.

The frame holding the specimen is immersed in a container with a 1-N aqueous solution of NaOH, which is the test solution used in ASTM C1260 (12). The container is then placed in a water bath with a controlled temperature of 50°C ± 3°C. All length and stress measurements reported in this paper were made at this controlled temperature so that the effects of thermal expansion stresses were eliminated (7,8).

To extract the stresses due to ASR from stresses generated by other phenomena (water absorption, autogenous shrinkage, etc.), the expansions and stresses generated in companion samples with no reactive aggregates were measured. All expansions were measured using a digital comparator with a resolution of 0.002 mm (0.0001 in.). For the samples used (see below) the uncertainty in the measured strain was then approximately 0.001%.

Specimen preparation

The samples studied in this work were mortar samples. The mixture used simulates high-performance concrete having a low w/c ratio and high cement content. All specimens had a w/c ratio of 0.295 and a sand/cement ratio of 1.411. A melamine-based superplasticizer (4%

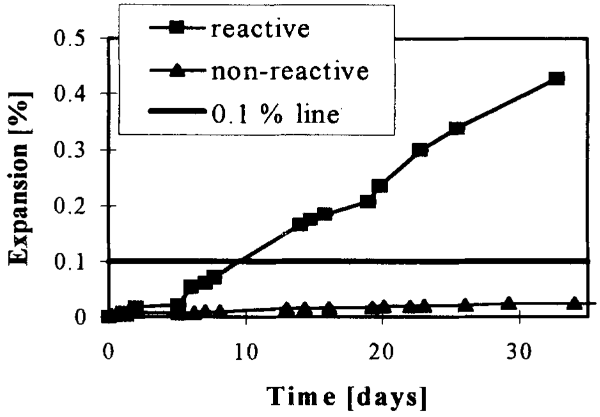

FIG. 2.
Expansion of specimens in 1-N aqueous NaOH at 50°C.

solid by mass of cement) was used to obtain a desirable flow. The sand gradation was prepared by grinding coarse aggregate as described in ASTM C1260 (12). Both sets of aggregates were ground similarly, and identical aggregate size distributions, selected using identical sieve analyses, were obtained. The only difference between the two sets of samples was in the aggregates' reactivity: one was very reactive (Spratt from Canada (siliceous dolomitic limestone), with more than 0.1% expansion at 14 days (ASTM C1260 (12)), the other was a nonreactive limestone (0.01% expansion at 14 days (ASTM C1260 (12)).

The test specimens were cylinders, 38 mm in diameter and 279 mm long (1.5 in. x 11 in.). The ASTM Type I Portland cement had a high alkali content (about 1.2% Na_2O equivalent). As the high alkali content of the cement should have resulted in a high alkali concentration and pH in the pore solution, this cement should have promoted ASR with reactive siliceous aggregates. The NaOH bath and the high temperature, 50°C ± 3°C, should also have promoted the alkali-silica reaction. After casting, the specimens were cured for 24 h in 100% RH at 20°C ± 5°C. Then, the specimens were cured at 50°C ± 3°C until testing. Stress vs. time measurements were initiated at 1, 3, 7, and 14 days after casting.

Results and Discussion

Figure 2 shows the results obtained for the linear expansion of the two mortars with the different sands. The expansions of the specimens showed, as expected, that the reactive aggregate elongation was over 0.1% at 14 days whereas the nonreactive aggregate had a 14-day expansion of only 0.02%. The same specimens used for the expansion measurements were weighed. Figure 3 shows the measured mass increases vs. time. There is no significant difference between the two sets, nonreactive and reactive aggregates. The mortars with nonreactive aggregates also had approximately the same mass gain and linear expansion when immersed in a saturated solution of $Ca(OH)_2$. Therefore, the origin of the mass gain is identical for both samples and is not dependent on the formation and expansion of the gel due to the ASR. It is believed that self-desiccation causes regions of the pore space to become dry and that capillary sorption pulls in water from the surrounding bath. This phenomenon is identical in both specimens because the same cement, mixture proportions, and curing

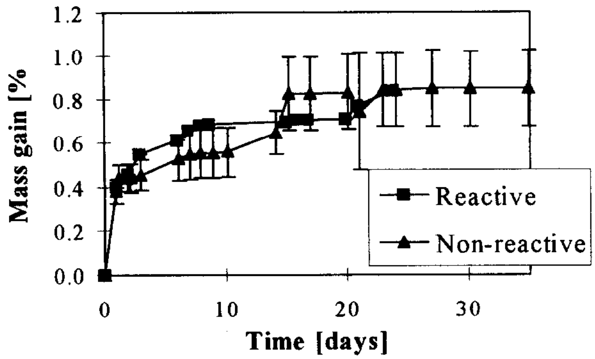

FIG. 3.
Mass gain for the mortar specimens with reactive and nonreactive aggregates in 1 N aqueous NaOH at 50°C.

conditions were used. Also, the samples were of the same overall dimensions. Therefore, the hydration characteristics and pore structure are believed to have been similar and that the expansion due to the ASR alone is the difference between the expansion for the nonreactive mortar and the reactive mortar. From Figure 2, it can be seen that, at 14 days, this value is 0.150% (reactive 0.166%; nonreactive 0.016%), and not 0.166% (reactive) as would be the case if the water absorption effect was not considered.

This is an important effect to keep in mind if lower w/c ratios are ever used to determine aggregate reactivity. If the cutoff for reactivity in most of the tests is >0.1%, and water absorption can contribute up to 0.02%, then an aggregate may be incorrectly classified as reactive.

Figure 4 shows the stress measurements obtained when the specimens were placed in the frame. The following equation summarize the various factors that make up the actual stress measured, $S(t)$:

$$S(t) = S_0(t) + S_a(t) + S_{ASR}(t)$$

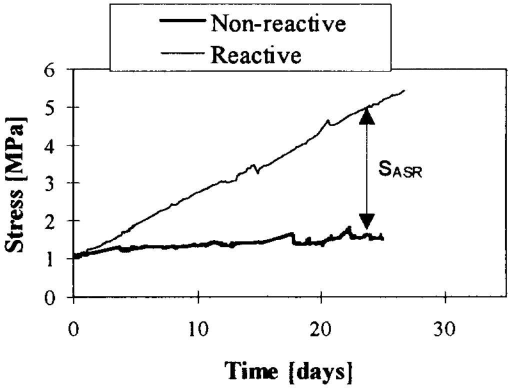

FIG. 4.
Stresses measured in the mortars with reactive and nonreactive aggregates in 1 N aqueous NaOH at 50°C.

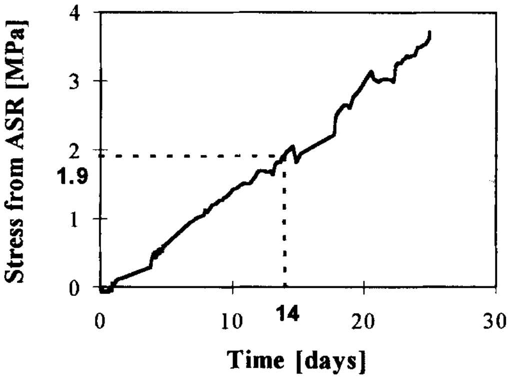

FIG. 5.
Stresses due to ASR, i.e., the difference between the reactive aggregate mortar and the nonreactive aggregate mortar.

where S_o (t) is the applied stress, S_a is the stress due to the competition between the self-desiccation and water absorption, S_{ASR} is the stress caused by the ASR, and t is the time. At $t = 0$, S_a $(0) = S_{ASR}$ $(0) = 0$ and S_o (0) is the initial stress applied, in our case about 0.9 MPa ± 0.1 MPa. Therefore, to measure the stresses due to the ASR only, the stresses measured with a nonreactive samples should be subtracted. Figure 5 shows the results obtained.

These stresses are all time-dependent because of the time-dependence of the water absorption effect, the time-dependence of the ASR, and the time-dependence of stresses in a material like concrete due to its viscoelasticity. The analysis of this time-dependence, in the complicated non-fixed-strain of our frame and load cell setup, is a difficult procedure. A further complication is the changing water content and degree of hydration of the mortars, which will change their viscoelastic properties. A proper theoretical analysis of this experiment would need to take all these factors into account, along with the actual moisture profile of the specimen in the bath. This analysis will be considered at a later stage of this project, and is not treated further in this paper.

It can be deduced from these results that if an external stress larger than the stress generated by the reaction is applied, the sample will not expand in the direction of the loading and therefore no transverse cracks will appear, but longitudinal cracks may occur. This fact can explain why ASR-induced cracks are usually not seen at the bottom of a dam or in the lower stories of a building. Therefore, we could imagine that this test might someday be used to estimate if a specific aggregate could be used for a desired application.

For example, if we calculate the pressure existing at the bottom of a dam or column 100 m high, the result will be roughly (2600 kg/m3)(9.8 m2/s)(100 m) = 2.5 mpa. In our test, the stresses due to ASR alone at 14 days are 1.9 MPa in the case of the Spratt aggregate (Fig. 5), for a 0.295-w/c ratio mortar. The two values are of the same order of magnitude. Therefore, the stresses generated by the ASR should and could be considered in the design of the dam to limit the deleterious cracking. This approach could allow the usage of deleterious aggregates if needed or give the engineer the means to take into account the stresses generated by ASR in the design of the dam or column. Of course, as the stresses are constantly increasing as shown on Figure 5, at least up to the time limit that we investigated (about 25 days), this could imply that eventually the stresses due to ASR may be higher than the dead load of the dam or column. Also, in our experiment the supply of alkalies is very large because the samples are in a NaOH solution. In the field, the only alkalies available are usually contained in the cement, therefore the reaction should slow down with time and eventually stop. This could protect the concrete from further damage. The compressive stresses in prestressed and post-tensioned concrete may also be large enough to overcome the expansive ASR stress.

Conclusions

Using a newly-designed device, we were able to determine that the stresses measured on a specimen of concrete are the combination of the external load applied, the expansion due to moisture absorption that relieves the shrinkage stresses caused by self-desiccation, and the expansion due to ASR. To correctly measure the stresses and expansion that are only caused by ASR, it is necessary to measure the other components of the total stress. Comparing two samples that differed only in the type of aggregates (reactive or nonreactive) allowed us to show how the stresses and expansion due to ASR could be calculated. Further testing and interpretation of the results are necessary to render this method fully applicable for the selection of potentially reactive aggregates for their possible use in construction.

Acknowledgments

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