SOME CONSIDERATIONS ON THE EVALUATION OF POTENTIAL RESIDUAL EXPANSION OF AAR AFFECTED HYDROELECTRIC DAMS

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ABSTRACT

This paper examines recent theoretical models of the development of concrete expansion due to the alkali-aggregate reaction and some of the parameters influencing this reaction in an attempt to determine the possibility of using laboratory tests on cores drilled from hydraulic structures to estimate future expansion with a certain degree of confidence. The tests recommended are expansion tests on concrete prisms at 38°C and 100% R.H., immersion in a NaOH solution at 38°C and measurements of the concrete's pore solution alkali content. These tests and theoretical mathematical models combined with field measurements of deformation and stresses, may provide a means of predicting the development of concrete expansion. Three Hydro-Québec dams, Beauharnois, La Tuque and Témiscouata, are analyzed in this light from the point of view of the monitoring instrumentation, the concrete expansion observed there and the various tests conducted.
Keywords: Alkali-silica reaction, finite-element modeling, mathematical model

INTRODUCTION

Assessing the future expansion of concrete at a dam or other hydraulic structures affected by the alkali-aggregate reaction (AAR) calls for a theoretical as well as an experimental investigation if the following two-part questions are to be answered: 1) at any point on a dam, what will the annual expansion rate be for the next few years? and will this rate remain constant? 2) how long will this expansion last? and what will the final expansion be?

The AAR is a complex physicochemical reaction and neither the silica gel formation nor the concrete expansion mechanisms can be fully explained yet. The determining parameters are also not understood in their entirety. In order to develop an efficient mathematical model of concrete expansion, this model will have to be validated with expansion tests in the laboratory as well as field measurements.

The first questions that come to mind concern the modeling of the expansion mechanism. Which model to choose? Can a correlation be established between this model applied to samples of laboratory tested concrete made with reactive aggregate extracted from cores and the model to be developed for an expanding structure for which expansion measurements are available?

AAR EXPANSION MODELS

The AAR reaction model consists basically of three periods: initiation, development, and a rest period. During the initiation period, silica gel is produced by the reactive mineral phases. In the case of the alkali-silica reaction, the quantity of reactive material (opal, chert, flint) can be relatively small whereas in the case of the slow/late alkali-silica reaction (ASSR) the amount of reactive phase (microcrystalline and deformed quartz) is quite high.

In a dam, the onset of cracking, which indicates the end of the initiation period for the alkali-silica reaction (ASR), is generally less than 10 years compared to less than 20 years for the ASSR. The ASR can last 30 ±10 years and the ASSR, over 50 years (Charlwood et al., 1992). On the other hand, the expansion rate and silica production are lower with the ASSR. Note that the values quoted are mean values.

The concrete expansion rate in dams affected by AAR ranges from 20 to 200 microdeformations/year (με/yr) (0.002 to 0.02%/yr). The ASR yearly expansion rate is often between 100 and 200 and the ASSR, between 20 and 100 με. Based on the preceding values, the total expansion of a dam could reach 2,000 to 10,000 με (0.2 to 1%) over its lifetime.

ASSUMPTIONS UNDERLYING AAR DEVELOPMENT

Hobbs (1993) proposes a reaction model in which the volume of gel produced before the development period is controlled by the chemical reaction between the hydroxide ions and the reactive silica (assuming that there is sufficient water in the concrete to maintain the reaction). His mathematical model based on tests on concrete at 100% R.H. at 38°C, 20°C and under outdoor exposure conditions produced two important hypotheses: 1) long-term expansion decreases with longer initiation times; 2) the duration of the initiation time is proportional to the temperature and the exposure condition in a ratio of 1, 4 and 7 for the samples tested at the above exposure conditions respectively.

This study suggests that it should be possible to correlate the expansion of samples tested in laboratory at 38°C with the expansion of in-service structures.

Furusawa et al. (1994) also tried to model the expansion of mortar samples mathematically, based on the ASTM C277 mortar prism test. Their model assumes that the main reaction mechanism depends on the hydroxide and alkaline ion diffusion rate in the reactive aggregate. The reaction development period does not begin until a porous zone surrounding the aggregate, a zone which depends on the specific surface area of the aggregate, is filled with the reaction product (gel). Interestingly, their model suggests that the reaction initiation period depends on the diffusion coefficient of the aggregate and that the final expansion of the mortar mixes is not proportional to the duration of the initiation period but depends, among other things, on the values of these coefficients. This final expansion seems to reach the same limit value for a certain type of aggregate and for the same initial quantity of alkalis. If the diffusion coefficient of the aggregate is reduced, the same final expansion is attained but it takes longer.

The reaction rest period depends on the depletion of one of the three basic reactive components, namely the reactive silica, the alkalis or the water.

On the basis of the models described above, it appears to the authors of this paper that, from a practical point of view, it is important to determine whether in fact the concrete expansion rate of a dam can be related to the final expansion. If so, it should be possible to estimate the final expansion from the mean expansion rate.

It seems idealistic, a priori, to hope that such a simple relation between the expansion rate and the final expansion could be developed, considering all the many factors influencing the reaction. But, if all these factors together with their effect on the reaction are known, there should be a means of incorporating them into a mathematical model relating the expansion of structures to that of laboratory-tested samples.

FACTORS INFLUENCING THE AAR

The major factors influencing the AAR are listed below together with the way each is handled in order to integrate it into a mathematical model:

- Quantity of reactive silica: this value can be evaluated by expansion tests or other suitable methods (petrography, SEM, etc.)
- Quantity of alkalis in the concrete that come from the cement and, possibly, from the aggregate and the environment. In the case of dams, it is sometimes possible to assess the quantity of original alkalis if the dam construction date is known and the amount of cement can be determined by microscope analysis. The amount of alkalis contributed by the aggregate could be assessed by alkali extraction methods. For instance, Grattan-Bellew (1994) estimated that at the Sanders Generating Station (Ontario, Canada), the limestone aggregate contributed to the alkali content of the concrete pore solution by 1.2 kg/m^3.
- Confinement pressure due to the weight of the dam and to the reinforcing effect and pressure generated by the AAR. Generally, the confinement pressure in a gravity dam is such that the longitudinal expansion is less than the lateral expansion, which in turn is less than the vertical expansion. The latter is in fact similar to free expansion because it is due only to the weight of the concrete in the dam. Rogers et al. (1994) observed that the confinement pressure needed to prevent concrete expansion is around 4.1 MPa. Stark et al. (1993) performed tests on triaxially confined concrete cylinders and, on the basis of their findings, suggested that 2.07 MPa suffice to stop concrete expansion. Durand et al. (1992) performed laboratory measurements of the pressures generated by the AAR and found values of up to 7 MPa. The internal stresses caused by concrete expansion will increase over time. Charlwood et al. (1992) have modeled the expansion of concrete as a function of the variations in stress with time and found that the variation of the concrete expansion with the log of the stress offers a strong correlation with field observations.
- Adequate amount of water to sustain the reaction. In a dam, it is assumed that, for all practical purposes, there is sufficient water in the concrete for the AAR to take place. The water can come from that excess of the cement hydration water (in a mass concrete the W/C ratio is high) and from infiltrations.
- The geometric configuration of the structure influences the state of the internal stresses and expansion. Geometric discontinuities will increase expansion at the junctions. Finite-element modeling in these specific cases is an essential tool for monitoring developments (Charlwood et al., 1992, and Léger et al., 1995). For example, in the event of a saw cut in a dam, it is becoming standard practice to use finite-element analysis.
- Concrete quality and the physical/mechanical properties of the structure. Microcracks associated with the thermal shrinkage of concrete, the construction joints, and construction defects contribute to the nonhomogeneity of the structure, which makes it more difficult to predict how expansion will develop at any specific location on the dam.
- Thermal shrinkage of the concrete will conteract the expansion due to the AAR in dams.
- Temperature. The temperature distribution inside a dam can be estimated by analyzing the heat transfer. Léger et al. (1995) propose the use of a monthly temperature distribution during the year and a weighted average of these 12 values to obtain an average for the entire year.

It is obvious from the foregoing considerations that finite-element analysis using the factors given above represents the best method that has been developed so far for modeling the distribution of stresses and deformations in a dam. Léger et al. (1995), for example, have already developed a finite-element analysis model of the behavior of a dam which takes account of confinement, temperature, humidity and aggregate reactivity.

The expansions and deformations estimated by the models currently in use will be compared to those measured on dams in service. In this way, an expansion monitoring program in the field combined with a suitable model will allow real-time follow up of the dam. However, it will not offer a short-term estimate of future variations in the concrete expansion of the dam, for which we suggest that different tests be performed on cores. The most suitable tests seem to be expansion tests on cores and on a concrete made with aggregates extracted from drilling cores and, also, measurements of the alkali concentration in the concrete's pore solution.

LABORATORY TESTS ON CORES FROM A DAM

Effects of drilling on the core samples

The first effect to be considered is that of the drilling operation on the concrete of the samples. In addition to the fact that the sample will be broken into several pieces, the action of the drill introduces cracks in the pieces of the cores to be used for the tests. As soon as the samples are removed, the stresses will be relieved and the sample will expand which may further crack the concrete in the sample. Another important point to consider is the handling of the cores. If they are not sealed immediately to prevent humidity loss, the drying action can fix part of the hydroxide alkalis in the pore solution. According to Stark et al., 1993, those alkalis will no longer be available when rehydration occurs later. Their laboratory tests suggested that carbonation was somehow involved in the effect.

The most appropriate tests to be conducted on the concrete core samples seem to be the expansion tests at 38°C and 100% R.H., those at 38°C in a 1M NaOH solution, and measurements of the concrete's pore solution alkali content.

Test at 38°C and 100% R.H. (CSA A23.2-14A, concrete prism expansion) (CSA, 1994) on cores

It is suggested that the test be performed at a temperature of 38°C so that expansion results will be obtained within two years. Although, expansion tests may be performed at different temperatures within the range that the structure may experience during its lifetime, the present authors consider that 38°C is reasonable. The only information missing is the factor linking the expansion rate at this temperature to the in situ dam concrete expansion.

The mass and length of each sample are measured periodically until each reaches equilibrium, which may take a few days if the samples are kept damp and anywhere between 2 and 20 weeks if kept in the laboratory in a dry environment. Equilibrium is considered reached when the expansion rate starts to change and, also, when the mass of the sample becomes more stable (Bérubé et al., 1993). Once equilibrium is attained, the time counter is reset to zero and the expansion is measured at regular intervals.

On the basis of a long series of tests, Bérubé et al. (1994) established limit values for the potential expansion. At one year, an expansion of 0.015% is considered being on the average while a value of 0.02% and over indicates some high expansion potential.

Expansion test on concretes immersed in a 1M NaOH solution at 38°C

The aim of this test is to determine whether the concrete of an in-service structure is showing any signs of expansion in an environment where there is a suitable quantity of available alkalis. In a way, it represents a measurement of the amount of reactive silica still present in the concrete.

The method is identical to that of accelerated test CSA A23.2-25A (Canadian Standards Association, 1994) which consists of immersing concrete samples in an alkaline solution of 1M NaOH. However, the temperature of this solution is set at 38°C instead of the 80°C specified for the CSA test because the authors, like Bérubé et al. (1993) consider that it is more realistic to test at a lower temperature for a longer period of time. Shayan et al. (1988) have shown that testing concrete in 1M NaOH at 80°C produces erratic results too.

Bérubé et al. (1994) suggest some expansion limits at one year on samples of in-service concrete to evaluate their reactivity. They offer four possible explanations in the case of low expansion : 1) the aggregate is not reactive and the concrete expansion is due to other mechanisms 2) the aggregate was, but no longer is, reactive because the reactive phases have been consumed 3) the concrete was so cracked that the reaction product fills the cracks 4) the concrete is so impervious that the alkaline solution can barely penetrate it. The present authors also believe that, if the reaction products are sufficiently fluid — or conversely, the concrete is permeable enough — they may pass into the immersion solution.

It is clear that interpretation of the results on the basis of just one test may be complex and should really be based on judgment and confirmed by other tests. For example, if aggregate is extracted from drilled cores and the two tests just described are repeated (100% R.H. and immersion), we would have confidence in determining whether or not it contained reactive phases. These two tests and the previous one with concrete cores in an immersed solution of 1M NaOH at 38°C should show about the same expansions because concrete made with extracted aggregates will have a high alkali content of 5.3 kg/m^3 (CSA A232-14A-1994).

Alkali concentration measurement of the pore solution of concrete cores

Grattan-Bellew (1994) and other researchers have observed that the extent of concrete degradation (cracking and expansion) due to the AAR depends, among other things, on the amount of alkalis in the concrete's pore solution. Below a certain minimum quantity of alkalis, the reaction cannot continue. Since the AAR consumes alkalis, measurement of the alkali concentration in the pore solution at different times could reveal whether any variation occurs in the reaction rate with time and, ultimately, if there is any deceleration in the reaction (if the alkali concentration decreases).

The most promising method developed so far is to extract the pore solution from a concrete sample using a high pressure steel die apparatus. Barneyback and Diamond (1981) further developed the Longuet method (Longuet et al., 1973) and have used it on various samples of cement and mortar pastes. If the high-pressure method is not readily available, a useful alternative is the hot-water alkali extraction method developed by the Ontario Ministry of Transport (Rogers and Hooton, 1989). Bérubé et al. (1994) suggest a number of criteria that could be applied to assess the concrete's expansion potential according to its alkali content by the hot-water leaching method. According to those criteria, an amount of over 3.0 kg/m^3 Na_2O eq. shows a high expansion potential.

It should be remembered, as pointed out by Bérubé et al. (1994), that the alkali content measured by the hot-water leaching method is liable to be an overestimate if earlier formed silica gels are also dissolved.

The foregoing remarks indicate that measurements of concrete expansion and alkali content performed on core samples provide a useful means of obtaining an impressive volume of data which, as far as we know, remains the only short-term way of predicting variations in the behavior of a dam.

FIELD MONITORING OF CONCRETE DEFORMATION IN A DAM

In any program of field monitoring of concrete deformation in a hydraulic structure, the choice of measuring instruments and their location are two major factors to be considered if the dam expansion due to the AAR is to be modeled correctly. Each instrument will be selected on the basis of its cost, usefulness, accuracy and long-term performance. The location of the measuring instruments is dictated by two different needs, namely, to establish a definition of the dam behavior as a whole and, also, to asses the behavior of the dam at some precise location (e.g. geometric discontinuity) where the accumulation of deformations and stresses may disturb the operation of mechanical parts or even jeopardize the structural integrity of the dam itself. Furthermore, new components can be added to an existing measuring system should major repair works such as dam cuts be undertaken.

Three case studies of Hydro-Québec dams will now be used to illustrate the approach the utility has adopted for assessing the residual expansion of concrete based on laboratory tests and field measurements of dam deformation.

HYDRO-QUÉBEC CASE STUDIES

Beauharnois dam

The Beauharnois dam is located at the end of the Beauharnois canal 40 km southwest of Montreal, Québec. It is 865 m long and comprises three power plants with a total of 37 generating units with one concrete gravity dam to the right and one to the left. The structures were built in three stages over the years from 1928 to 1961. The aggregate is reactive Potsdam sandstone excavated from the canal.

Measurements of the vertical displacements showed 60, 27 and 53 $\mu\varepsilon$/yr for the gravity dams, power plants and water intakes respectively (Gocevski and Rivest, 1993). In addition, all three plants are shifting slowly upstream, plants #1 and #2 at a rate of 1 mm/year, and plant #3 at a rate of 0.5 mm/year. Tests at 38°C and 100% R.H. on cores revealed an expansion rate of 77 $\mu\varepsilon$/yr.

The instrumentation at this dam comprises 16 pendulums, two in the gravity dam on the right-hand bank, four in the intakes and ten in the power plants, together with various monitoring benchmarks. Also ten instrumented cylinders from Université de Sherbrooke were installed, three two-dimensional units in 1987 and seven three-dimensional units in 1992. The former were interpreted by Bois (1994) who reported that the instruments at plant #1 indicated a compression of 2 MPa in the longitudinal axis and 4 MPa in the vertical direction since they were installed at the dam. The two cylinders at plant #3 show an isotropic compression of 3 MPa since their installation.

La Tuque dam

Built in 1938-40, La Tuque dam is located on the Saint-Maurice River, 405 km northeast of Montréal. It comprises two gravity dams, one on each bank, a spillway and an intake abutting the plant. The total length is 424.5 m and the maximum height, 53.3 m.

The concrete is affected by the ASSR. The coarse aggregate is composed of granite and granitic gneiss which is slightly reactive to the alkalis in the cement.

The dam is fitted with various instruments, including a topographic monitoring system with 19 measuring points and three inverted pendulums, jointmeters and boreholes extensometers (Buffex type) near the saw cut made in the dam in 1993.

The monitoring data show that over the last ten years the structures have been slowly moving upstream, except at the junction between the water intake and the gravity dam on the left-hand bank, which are at an angle of 141° to each other, where the displacement is downstream. In both cases, the maximum displacements are around 1.3 mm/year. Uplift is approximately 1 mm/yr for the dams and the water intake, and about 2 mm/yr at the joint, which represents 33 and 66 $\mu\varepsilon$/yr respectively (Veilleux, 1992).

Three instrumented cylinders were installed in 1995-96, namely two near the cut, at the junction between the intake and the gravity dam on the left bank, and one in the gravity dam on the right bank. The core samples collected are currently used for potential-expansion tests, as discussed earlier.

Témiscouata dam

Témiscouata dam is a retaining structure built on the Madawaska River in 1930 about 100 km south of Rivière-Du-Loup, Québec. It was in 1952 that workers first observed that the apron slab had expanded. In 1993 and 1994, the deterioration of the AAR affected dam was such that it was demolished and rebuilt. The coarse aggregate used in the new concrete mix was considered to be slightly reactive but it was employed nevertheless because it was the only one available. To improve the concrete quality and prevent the risk of future expansion, 7.5% silica fume was added to the mix.

Samples of the concrete were taken from the new dam at the end of 1993 and expansion tests at 38°C and 100% R.H. are now under way to determine whether expansion will occur even with the use of silica fume. Also, upstream of the dam, on the right-hand bank, two test columns have been poured using different types of concrete. The first mixture is identical to the one used for the original dam, the second is that used for the new dam but without any silica fume. An instrumented cylinder has been installed in each column. The columns are exposed to the same conditions as the dam. Samples of each concrete have been taken and tests at 38°C and 100% R.H. are currently being performed so that expansions measured in the laboratory can be compared to those recorded in the field.

CONCLUSION

Theoretical mathematical models for the development of the alkali-aggregate reaction, such as those of Hobbs and Furusawa, will become more and more essential if we are ever to correlate the expansion of samples, including cores subjected to laboratory tests, with real expansion in a structure affected by AAR.

In the last few years, several dams have been the subject of a drilling program to determine the physical state of the concrete together with microscope studies to identify the extent or presence of the AAR. This work was completely separate from other drilling operations done to install instruments, drains or other items. In the authors' opinion, it would be wise to use cores from all drilling operations for the expansion tests and measurements of the alkali content. The expansion tests most strongly recommended are the 38°C and 100% R.H., the immersion test in alkaline solution at 38°C, and measurement of the alkali concentration of the concrete's pore solution.

The last point concerns the field measurements of concrete expansion in dams. Knowing these, it is then possible to correlate between free expansion determined in the laboratory tests and real expansion in the field. If eventually, a finite-element-based numerical simulation of the dam behavior is required, the information gathered— laboratory and field expansions, alkali content in the pore solution— could be used to complete the model.

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