

Contribution to the requalification of Alkali-Silica Reaction (ASR) damaged structures: Assessment of the ASR advancement in aggregates

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Abstract

Methods of requalification of damaged structures are required to help the structure-owners to make decisions on the maintenance, repair or replacement. Several methodologies of requalification have been proposed. One of the problems of requalification is the reliability of the input data of the model. The analysis of the structural behavior of a French dam showed the difficulty of using the residual expansion test (38°C, R.H.> 95%) as input data for structural modeling. Therefore, the LMDC and Electricité De France (EDF) have proposed a global methodology to characterize the expansion kinetics through the assessment of the chemical advancement of the reaction in the aggregates contained in the concrete of the damaged structure. This methodology assumes that alkali content is not the limiting factor in ASR, due to the substitution of alkalis by calcium in ASR gels. Thus it is considered that the limiting factor in the concrete structure is the quantity of silica. Based on this assumption, two parts are highlighted in this method: a laboratory test dealing with the silica consumption kinetics, and a numerical finite element inverse analysis of the affected structure. This paper focuses on introducing the method to assess the chemical advancement of the reaction. The chemical advancement is assumed to be related to the quantity of residual silica remaining in the aggregate, which can be measured indirectly by expansion tests or directly by chemical tests. Laboratory assessment begins with the recovery of the aggregates from damaged structures. Then the reactive silica in damaged aggregates is evaluated by chemical tests. The results of the chemical tests are used to optimize usual expansion tests according to aggregate and specimen sizes. Finally calculations of the chemical advancement of the reaction in the aggregates recovered from the damaged structures are presented.

Key words: Alkali-silica reaction (ASR), requalification, methodology, chemical advancement

1 INTRODUCTION

Alkali-Silica Reaction (ASR) is a deleterious chemical reaction between the alkali hydroxides from the concrete pore solution and the silica of reactive aggregate in concrete. ASR produces expansive gels and causes cracking of aggregate and paste, sometimes resulting in major structural problems which could lead to extensive maintenance, repair and demolition in extreme cases.

In the past two decades, numerous investigations performed on ASR allow these phenomena to be explained. Some models of requalification have been proposed [1-10]. These existing models can describe many phenomena of ASR in micro-scale and macro-scale; however, there are still some problems to predict the service life of the damaged structures. One of these problems is the reliability of the input data of the model, and particularly the residual expansion result which is obtained through the expansion measurement of drilled cores kept at 38°C and R.H.> 95% during 52 weeks [11]. Several

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criticisms arose about this residual expansion test: 1) *Relative humidity*: Bérubé and Frenette [12] showed that the condition of humidity higher than 95% made the results subject to variations among labs, and thus led to bad repeatability and reproducibility. This can be explained by the difficulty of precisely controlling such R.H. during the experiments, and RH variations between 95 and 100% can lead to significant variations of ASR expansions [13]. 2) *the duration of 52 weeks* is not sufficient to obtain a total expansion since for large aggregate size, the time necessary to reach the centre of the aggregate is considerably longer than that for small particle [10,14], 3) *Alkali leaching*: this phenomenon which concerns the loss of alkali of concrete into the external environment was observed on mortar bars tests in air at RH > 95% [17-19] or in water [20]. Due to the alkali leaching from the concrete, the ASR expansions can be stopped by the lack of alkali. 4) *Direction of coring*: the casting direction has an important effect on the expansion since the behaviour of concrete is often anisotropic [21-23]. Thus, cores obtained along different directions can lead to different residual expansions. This difference between the axial and transversal cores leads to large scatter in the results, and leads to difficulties in obtaining a reliable assessment. 5) *The gel obtained in the laboratory is different from the gel found in situ* regarding the nature and chemical composition [10,14]. One explanation attributes this variation of chemical products to the impact of temperature on the chemical equilibrium of gel production. The “residual expansion test” is conducted at a higher temperature (38°C or 60°C) than the average in situ temperature of the attacked structures. Another reason is due to the fact that alkalis can be substituted by calcium [10,14]. This substitution process occurs only over a long period [24-26]. In other words, this substitution takes place mostly in the field cases, and rarely occurs in laboratory tests since the duration of laboratory tests never exceeds one or two years.

Considering the imprecision of the “conventional residual expansion test”, especially the notable failure caused by this test to predict the expansion of Temple-sur-Lot dam (in France) [10,14], a new method has been proposed by the Laboratory of Materials and Durability of Constructions (LMDC) and Electricité De France (EDF). First this paper describes this methodology of requalification. It consists of a laboratory test dealing with the silica consumption kinetics and a numerical finite element inverse analysis of the dam. Then the paper highlights the methods used in the laboratory to assess the chemical advancement of the reaction. Finally, some important conclusions are summarized.

2 METHODOLOGY

Knowing that alkali can be substituted by calcium which leads to a regeneration of alkali to the reaction, the method pays attention to the consumption of silica with a sufficient supply of alkalis. A three steps methodology can be proposed (*Figure 1*):

- 1) *In-situ measurement of the affected structure*. This step aims to collect the information necessary for the modelling part. The information should include the surveillance of displacements, temperatures, and moisture of the affected structure. It should also contain the information from the different core samples: the saturation degree, the nature of aggregates and the quantity of cement used in the concrete.
- 2) *Tests in laboratory*. The tests in laboratory are conducted with the aggregates recovered from the damaged structures in order to assess the consumption kinetics of reactive aggregate. Different aggregate size range should be taken into account since the chemical kinetics of the reaction varies along with the aggregate sizes.
- 3) *Finite element inverse analysis of the affected structure*. This step combines the results of steps 1) and 2) to analyze the affected structure. The kinetic coefficient of the model is determined in the laboratory, and the final swelling amplitude is fitted using only one observed structural displacement. The

model prediction capability is validated through the comparison between the displacement of instrumented points predicted by the calculations (not used for the fitting) and the variations measured on the dam. Finally, calculations are performed to predict the future displacements and damage fields of the dam.

2.1 Principle and application of the method

Principle

The principle of the method is based on the assumptions that *the chemical advancement of the reaction can be presented by the degree of silica consumption* (Equation 1). For a given aggregate size, the value of A is in the range of 0-1 (0: the beginning of the reaction, 1: the completion of the reactive silica reaction).

$$A(t) = \frac{Si^{reacted}(t)}{Si^{reactive}(t=0)} \quad (1)$$

$Si^{reacted}$ represents the silica consumed at time t, $Si^{reactive}$ represents the total reactive silica content

The law of kinetics shows that the chemical advancement is a function of the degree of saturation Sr and the temperature T [13-16, 27], thus the derivative of chemical advancement with respect to the reaction time t can be presented in Equation 2. Sr can be obtained from the non-linear equation of mass transfer and solved numerically with the finite element method and boundary conditions imposed from the measurement of in-situ degree of the saturation [10,14].

$$\frac{\partial A}{\partial t} = \alpha_{ref} \exp\left(-\frac{E_a}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right) \times \left(\frac{Sr - Sr^{threshold}}{1 - Sr^{threshold}}\right) (Sr - A) \quad (2)$$

α_{ref} : the constant of the kinetics, E_a : the activation energy of the AAR (~47 kJ/M), R : the gas constant (8.31 J/M/K), T_{ref} : the absolute temperature of the test, T : the current absolute temperature, Sr : the degree of the saturation of concrete porosity, $Sr^{threshold}$: the minimal degree of saturation necessary to allow the evolution of the chemical reaction, equal to 0.2 according to the value given by [14].

The mechanical consequences of the ASR advancement are the concrete expansion in damaged structures. This expansion can be measured only when the volume of ASR gel formed by the reaction is upper than the volume of porosity in which ASR gel can permeate. For large aggregate (larger than 1 mm), this effect can be neglected. When the cement paste is cracked and does not restrain the aggregate any more, the ASR expansion can be approximated by the increase of the aggregate volume. The expansion at a time step t can be deduced from the advancement and from the final increase of the aggregate volume

ϕ_{ASR} :

$$\varepsilon^{ASR} \approx A(t)\phi_{ASR} \quad (3)$$

Therefore, the expansion kinetics and the final expansion can be assessed separately. Since laboratory tests appear to affect the measured final expansion, the methodology uses these results only to obtain indirectly the in situ expansion kinetics.

Application

The application of the method is based on the testing of aggregates extracted from two types of cores drilled from the affected structure, which have been called sound aggregates and affected aggregates.

- 1) Silica consumption kinetics with sound aggregate

The sound aggregates come from central zones of large aggregates or can be taken in dry zones of the structure where ASR is little advanced. This type of aggregate is used in order to quantify the total reactive silica in the aggregate (S_i^{reactive}).

2) Requalification of the structure with affected aggregate

The affected aggregates can be extracted from wet zones or zones affected by ASR. With the tests of this aggregate, the residual reactive silica ($S_i^{\text{residual}} = S_i^{\text{reactive}} - S_i^{\text{reacted}}$) can be obtained. Supposing that the time of drilling cores is t_1 , which is relative to the time from the construction of the structure to the time of drilling core, the chemical advancement $A(t_1)$ can be calculated from Equation 4:

$$A(t_1) = \frac{S_i^{\text{reacted}}}{S_i^{\text{reactive}}} = 1 - \frac{S_i^{\text{residual}}}{S_i^{\text{reactive}}} \quad (4)$$

Since the chemical advancement is independent of the absolute expansion of the structures, this $A(t_1)$ value, deduced from the laboratory condition, can also represent the chemical advancement of silica consumption in the field. Thus, the kinetics constant of the expansion can be deduced from Equation 5:

$$\frac{1}{\alpha_{\text{ref}}} = \frac{\int_{t=0}^{t=t_1} \exp\left(-\frac{Ea}{R}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right) \times \left(\frac{S_r - S_r^{\text{threshold}}}{(1 - S_r^{\text{threshold}})}\right) (S_r - A) dt}{A(t_1)} \quad (5)$$

Once the kinetic constant is known, the chemical advancement can be rebuilt through Equation 2. And then, the finite element method (including the mechanical aspect – *creep and damage effects*) can be used. Since the swelling is assumed to be proportional to the advancement rate and proportional to the amplitude ϕ^{ASR} (Equation 3), the kinetics of swelling can be deduced from Equation 6. The only unknown parameter is ϕ^{ASR} . This value can be obtained through curve fitting with the measurements of in-situ displacement (Figure 2).

$$\varepsilon^{\text{ASR}}(t) \approx \frac{\partial A(t)}{\partial t} \phi_{\text{ASR}} = \left(\alpha_{\text{ref}} \exp\left(-\frac{Ea}{R}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right) \times \left(\frac{S_r - S_r^{\text{threshold}}}{(1 - S_r^{\text{threshold}})}\right) (S_r - A) \right) \phi^{\text{ASR}} \quad (6)$$

3 METHOD TO ASSESS THE CHEMICAL ADVANCEMENT OF THE REACTION

The chemical advancement differs according to the size of the aggregate in the structure concrete. Four steps (shown in Figure 3) were proposed to determine the different chemical advancement according to the size of the recovered aggregate. Each of the steps is introduced in detail in the following parts.

3.1 Recovery of the aggregate from damaged concrete

As stated earlier, two types of aggregates must be recovered:

- Sound aggregates to evaluate the reactivity potential of the aggregate. These aggregates can be taken from sound zones of large aggregates (not attacked yet) or from dry zones of the structure.
- Attacked aggregates to evaluate the advancement of ASR. They can be extracted from wet zones or zones affected by ASR.

Obtaining these two kinds of aggregate properly and entirely determines the accuracy of the following steps, thus the recovery method should be chosen carefully. A two-steps process was chosen: 1) the first step involved a thermal treatment by “*immersing the samples into Na_2SO_4 solution, and then*

freezing and thawing the solution in five cycles (minimal)” to separate roughly the aggregate and the cement paste. After the treatment, the attached mortar was easily removed by scratching the surface of aggregates. However, this step was effective only for the coarse aggregate (>4mm). 2) For recovering the fine aggregate, a second step of treatment with *organic chemical attack “salicylic acid”* was carried out to dissolve the rest of the attached cement paste. The salicylic acid solution (1.3M/l with methanol as solvent) dissolved selectively the cement paste, and was considered better than inorganic acid (eg. HCl solution used in [14-16]) since HCl acid attacks reactive silica in the aggregate and can modify the reactivity of aggregate.

3.2 Chemical test for reactive silica content

The second step aims to use a chemical test to quantify the potential of reactive silica contained in the recovered aggregate. A test with diluted HF solution was proposed in [28]. The principle of the method is based on the fact that the amorphous silica dissolves rapidly in diluted HF solution, and the rate of dissolution can be distinguished from the dissolution of crystalline phases. A typical curve of dissolution kinetics of aggregates in HF is given in Figure 4. Two different phases are observed: a rapid dissolution (phase I) followed by a constant rate of dissolution characterized by a linear evolution (phase II). In phase I, the high reaction rate is mainly due to the quick dissolution of the reactive phase. In phase II, the reaction rate slows down, but the reaction still keeps an upward trend. This phase is usually considered to be representative of the attack of crystallised minerals such as quartz. The reactive phase is estimated by extrapolating the linear trend to $t=0$, since it can be assumed that the crystallised phases are also dissolved from the beginning.

The results of this method obtained from several different aggregates showed a high correlation with expansion tests [28], which approves that this method seems to be the best compromise to quantify the active fraction of silica. However, some doubt arises about the sensitivity of the method to the small differences of residual silica between the attacked aggregates. At present, a complementary expansion test has to be conducted when evaluating the chemical advancement.

3.3 Choice of the best size of aggregate and specimen for fast and relevant expansion test

The expansion tests were carried out in NaOH solutions so that there was enough alkali to consume all the reactive silica, and at 60°C to accelerate the reaction. This condition of conservation guarantees that all the residual reactive silica is consumed in a short period of time. In order to use expansion tests in predictive calculations, it is necessary to clarify all the complex and coupled phenomena and quantify all the parameters involved during expansion. In particular, the scale effect “Prism size/ aggregate size ” used to perform the expansion test (as shown in Figure 5) could make the expansion results vary wildly [28-29] due to the process of gel accommodation by cracks and the non-linearity of expansion with the reactive silica content of the aggregate. This effect should be carefully considered. The consideration can be partly taken into account through two equations (Equations 7 and 8). In order to decrease the influence of this effect, the constants D_1 and D_2 in (Equations 7 and 8) should be fixed. Once D_1 and D_2 are fixed, the aggregate size and the specimen size can be deduced from these two equations [29].

$$\frac{4}{3} \pi R_a^3 s V_{gel}^{mol} - \varphi \frac{4}{3} \pi [(R_a + t_c)^3 - R_a^3] = D_1 \quad (7)$$

$$\frac{R_a}{L} = D_2 \quad (8)$$

R_a : the radius of the aggregate, L : the dimension of the specimen, s : the reactive silica content, V_{gel}^{mol} : the molar volume of the gel, ϕ : the concrete porosity, t_c the thickness along which the gel can migrate from the aggregate to the cement paste.

For example, in the case of the expansion tests on siliceous limestone and opal aggregates, the reactive silica content was 3000 mol/m³ for the siliceous limestone and 21900 mol/m³ for opal. For mortars of siliceous limestone, if aggregate class C₂ (315-630 μm) and specimen size 20x20x160 mm are chosen, which means that R_a and L were equal to 472.5μm (a mean diameter) and 20 mm (the smallest dimension), then D_1 and D_2 can be deduced as 6.8×10^{-11} m³ and 0.012, respectively, from Equations 7 and 8. In order to have the mechanical conditions for opal as for siliceous limestone (the same D_1 and D_2), the aggregate size calculated for opal should be about 240 μm and the specimen size should be about 10 mm. With such experimental conditions, the ASR-expansions for these two aggregates can be compared with more accuracy [29].

3.4 Determination of chemical advancement

The principle of the determination of chemical advancement A_i of aggregate of size i is to compare the residual reactive silica obtained on recovered aggregate with the reactive silica obtained on sound aggregate [10,14]. The value of A_i is calculated using Equation 9.

$$A_i(t) = \frac{RRS_i(t)}{RS} \quad (9)$$

$RRS_i(t)$: residual reactive silica of aggregate size i , RS : reactive silica of sound aggregate

In Equation 9, RRS_i and RS can be obtained in two complementary ways: 1) directly by chemical measurements, 2) indirectly by the expansion test and the use of a micro modelling. For the second way, the results of expansion tests cannot be used directly to represent the chemical advancement. The chemical advancement is defined as the degree of silica consumption or as the volume of produced gels (as shown in Equation 10).

$$A(t) = \frac{V_g(t)}{V_{g_max}} \quad (10)$$

V_g : volume of gel created as a function of time (according to the diffusion phenomenon in aggregate), V_{g_max} : maximum value of the volume of gel. It stands for the consumption of all the reactive silica.

However, not all of the ASR gels are available for the expansion since, a part of the gels fills in the connected porous and cracks. In order to evaluate the chemical advancement with the expansion results, the loss of gels should be taken into account. Thus, a microscopic model which is based on the ions diffusion into the aggregate and the mechanical damage theory to predict the expansion of a Representative Elementary Volume (REV) of concrete was developed in [6, 28] to evaluate the volume of gel necessary to develop the expansion measured during the expansion test and thus calculated the advancement.

Finally, under the condition $T_{ref} = T$ of the structure, the kinetic constant of the expansion induced by the aggregate of size i needed for the requalification calculation can be evaluated from equation 2, it reads:

$$\alpha_0^i = \frac{1}{\tau_i \frac{Sr_i - Sr^{threshold}}{1 - Sr^{threshold}}} \quad (11)$$

$$\text{with } \tau_i = \frac{\Delta t}{\ln(1 - A_i)} \quad (12)$$

Δt : time between the building of the structure and the drilling of the core samples, Sr : mean degree of saturation of the concrete in the structure.

The value of the kinetic constant is influenced by the aggregate size. Relevant structural calculations should take into account different values of kinetic constant according to the size of the aggregates contained in the concrete structure [10,14].

4 CONCLUSIONS

This work presents a methodology originally created by LMDC and EDF to evaluate the ASR damaged structures. This method can determine the chemical kinetics of aggregate consumption of the structure in the field (with the parameters of saturation degree and temperature) through the laboratory experimental analysis of the sound aggregate extracted from the sound zone of the affected structure. It can also evaluate the damage degree of the concrete and predict the future deterioration by analyzing the chemical kinetics of the aggregates extracted from the damaged zone of the affected structure. As a part of the method, the laboratory tests of four-steps were introduced to assess the chemical advancement of the reaction. This four-steps process consist of recovering aggregates from the damaged structures, carrying out chemical test and expansion test with the recovered aggregate, at last determining the chemical advancement with the above results.

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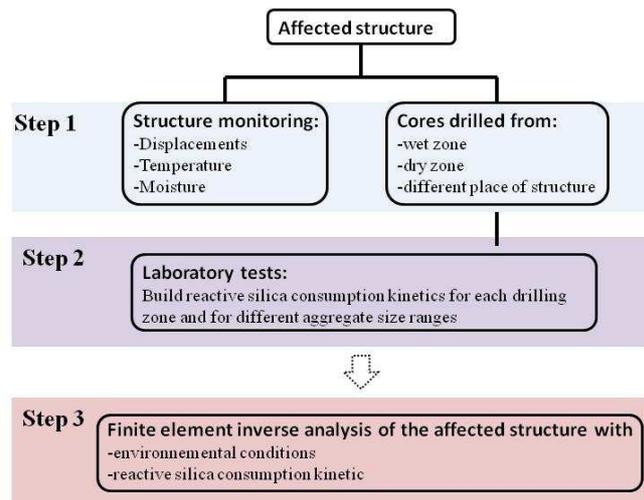


FIGURE 1. Schema of the LMDC method [10]

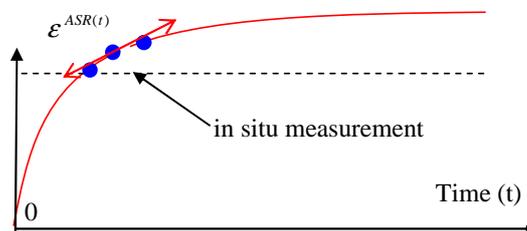


FIGURE 2. Determination of ϕ^{ASR} (volume of gels) through curve fitting with the measurements of in-situ displacements

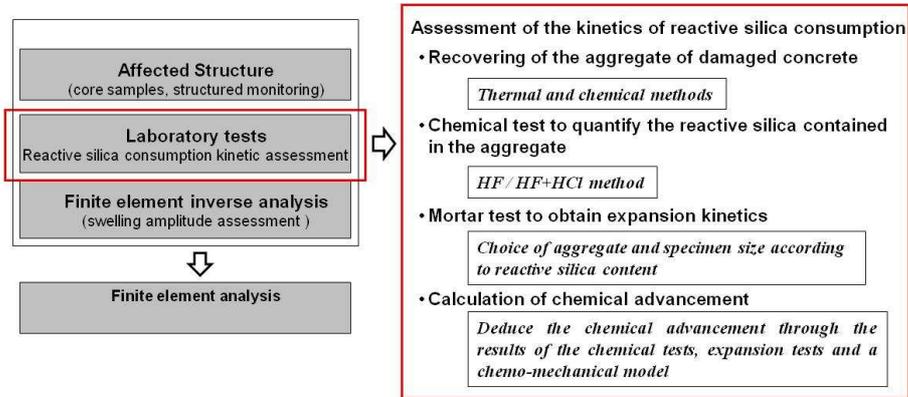


FIGURE 3. Proposed method to assess the chemical advancement

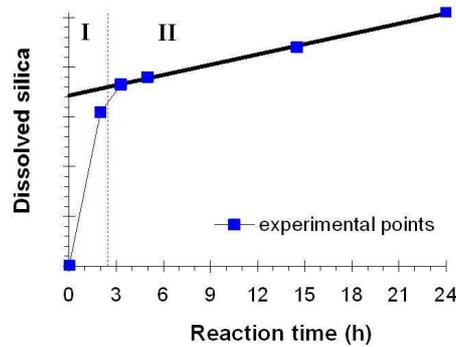


FIGURE 4. Typical dissolution kinetics of aggregate in HF

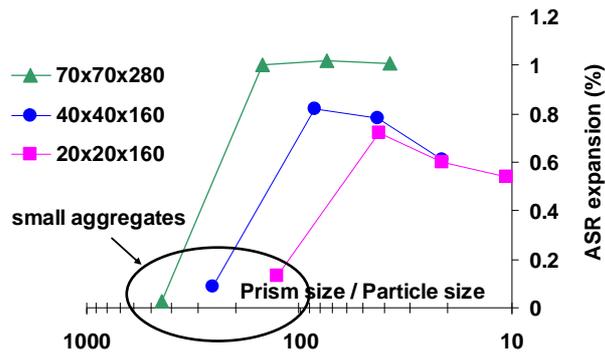


FIGURE 5. ASR expansions according to the 'Specimen size / Particle Size' ratio used to perform the expansion test