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Influence of water on Alkali-Silica Reaction: experimental study and numerical simulations

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Abstract: Alkali-Silica Reaction (ASR) is a concrete pathology due to chemical reactions involving reactive silica from reactive aggregates and the inner solution of concrete. Main effects are swelling, cracking and the reduction in the mechanical properties of affected concretes. Water is very important for ASR, the more available water the more expansion and degradation. This article presents new laws for the modelling of the influence of water upon ASR. They are based on experimental results and then used to simulate results taken out of scientific literature.

Keywords: concrete durability, Alkali-Silica Reaction, swelling, water, modelling, numeric simulations.

Introduction

Alkali silica reaction (ASR) is a world wide known concrete pathology. It is due to chemical reactions between amorphous or badly crystallized silica and ions from the interstitial solution (hydroxyls, alkalis and calcium ions). It leads to progressive destruction of reactive aggregates, precipitation of reaction products called “gels” which composition may vary a lot. It creates local variations in dimension.

ASR affected concrete structures have to cope with displacements, structural deformations, decrease of rigidity and sometimes pull-outs and collapse of mechanical resistance. Service of the structure may be severely affected.

After more than 60 years of research, the knowledge gained on reaction mechanisms did allow researchers and recommendation committees to edit rules to prevent new ASR cases (Ministère de l'Équipement 1994, Mather 1994). Unfortunately, from now on there has been no way to stop the reaction or to cure an affected structure. There are many ASR affected structures around the world for which periodical repairs and preventive maintenance policies cost a lot of money. Their managers need predictive tools to determine rate and end value of swelling in order to determine frequency, effectiveness of maintenance operations and effective economic life of structure.

The aim of our work is to provide a robust and safety modeling able to take account for the influence of hydric history on free ASR swelling. In a first part of this paper we present a non exhaustive literature review, afterward our experimental program is presented, the proposed modeling is then presented fitted on a the first part of the experimental program and tested on a second part and on literature data.

Literature review

Experimental approach

To initiate and develop Alkali-Silica-Reaction, soluble alkalis (sodium or potassium), reactive silica from aggregates and sufficient water must come into contact. Water plays two roles in this reaction:

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- transport medium of ionic species involved in ASR,
- reactant (water is included in the amorphous gel formed).

Influence of water is therefore a matter of concern in ASR research. H. E. Vivian (1981) observed that expansion measured on mortar samples affected by ASR decreases with the available water quantity. He therefore stated that drying affected mortar samples could stop ASR reaction. This was confirmed by several researchers working with different mix compositions and specific tests protocols to accelerate ASR reaction, Olafsson (1986), Tomosawa et al. (1989) and Kurihara et al. (1989). Table 1 and Fig. 1 sum up their respective test conditions and results.

Fig. 1 does not show a straight correlation between external relative humidity and ASR expansion. This may be due to the duration of Olafsson (for 23°C) and Kurihara 40°C tests which are too short to reach the maximal ASR expansion (Table 1). The computed deformations percentage being therefore not representative of ASR development. For a given cementitious material, ASR swelling is directly correlated with mass variations. The higher the mass gain, the more expansion (Tomosawa et al. 1989, Kurihara et al. 1989 and Larive et al. 2000). Moreover, water intake history is very important for ASR (Vivian 1981, Larive et al. 2000). Irregular external water supplies seem to irreversibly affect concrete expansion. Larive et al. (1998, 2000) submitted two series of specimens to different water supplies. The first ones were dried (561 days) and then immersed into water; the final expansion was about 0.45%. The second ones were kept without significant water exchange (447 days) and then immersed into water; the final expansion was about 0.15%.

In addition, Tomosawa et al. (1989) and Kurihara et al. (1989) have shown that below a water content threshold (water content within the sample with respect to the dry weight of the sample) ASR expansion is inhibited. Unfortunately the value of this water content threshold (4% of the dry mass for Tomosawa et al., 8% of the dry mass for Kurihara et al. and 0.15% of weight loss for Larive et al.) depends on the affected material, the initial water content within the samples.

According to Nilsson (1983) there is no ASR degradation when the external relative humidity drops below 80%. Ludwig (1989) defines this RH (Relative Humidity) threshold between 80% and 85% for a temperature equal to 20°C. The value of this threshold depends on temperature. According to Olafsson (1986) it falls from about 80% at 23°C to 75% at 38°C. According to Tomosawa et al. (1989) and Kurihara et al. (1989), it is below 75% at 40°C (see Fig. 2). Fig. 2 shows that there is no linear relation between temperature and relative humidity threshold.

Moreover, variations of external relative humidity and temperature induce transport of ionic species and local differences of concentration within the material (Xu and Hooton 1993, Rivard et al. 2003). These phenomena may modify the evolution of ASR swelling (Nishibayashi et al. 2003).

Review of existing modelings

Water has a great influence on kinetics of ASR as well on swelling value. A few models are able to take into account the role of water. The model proposed by Nielsen et al. (1993) relates the value of ASR swelling to the relative humidity within pores of the material. The law used is empirical (Fig. 3). It is based on the observations of L. O. Nilsson (1983).

Capra and Bournazel (1998) compute ASR swelling using the following equation:

$$\varepsilon^{asr}(t, h, T, \sigma) = \varepsilon^{100\%}(t) f(h) g(T, \sigma) \quad (1)$$

- $\varepsilon^{100\%}(t)$ is the free swelling observed on sample at 100% RH,
- h is the relative humidity in the material pores,
- $g(T, \sigma)$ and $f(h)$ are two functions, that describe the influence of temperature, stress and relative humidity on ASR swelling. The setting of the last function is made using values issued from literature (see Fig. 3).

$$f(h) = \left(\frac{h}{100} \right)^8 \quad (2)$$

According to the two models proposed by Bažant and Steffens (2000) and Li et al. (2000, 2002), ASR does firstly result in a dry gel that matures with time. This maturation (imbibition of the dry gel in order to create a fluid) is described by a first order kinetic. Bažant and Steffens (1999) state that the capture of some water by the gel may only occur above a relative humidity threshold in the pores. This threshold value is supposed to be equal to 85% (Fig. 3, this curve is theoretical and does not stand represent experiment results). Li et al. (2000, 2002) do not define any threshold value. In their model, the ASR gel incorporates water in a continuous way depending on water availability. All the authors consider that the amount of water which influences ASR is the available water within affected material near to reaction sites. To use a model for extrapolation purposes, i.e. for prediction of ASR swelling, one must therefore know quite exactly the water distribution within the material.

Our purpose is to develop a modeling that relates the amount of available water within affected materials to the kinetics and the value of the free swelling induced by ASR. A first experimental program is designed to calibrate the

modeling constitutive laws. A second experimental program and some experimental works issued from a literature review are used to check whether the model is sound and consistent.

Experimental campaign

The experimental campaign aims at studying the evolution of kinetics and maximal expansion induced by ASR on mortar samples kept at different relative humidities (Poyet, 2003). Two series of experiments are undertaken. In the first one (subsequent called RH_constant) the external relative humidity remains constant. In the second one (called RH_variable) the specimens undergo cyclic changes in relative humidities. Moreover, two types of cycles are studied short ones and long ones (see Fig. 4).

The specimens are cylindrical (16 cm height with a diameter of 2 cm). They are cast and kept vertically. ASR expansion is measured vertically as well. Two compositions are cast including different aggregates: a reactive limestone sand (the same as the one studied by Guédon-Dubied et al. 2000), and an innocuous limestone one, (Table 2). The two sand particle size distributions are corrected in order to be similar. An ordinary Portland cement is used. The mixing water is de-ionized water at ambient temperature. The alkali level is adjusted by adding sodium hydroxide pellets into the mixing water. More data about these experiments can be found in (Poyet, 2003).

The specimens are removed from their mould after 10 days at 20°C wrapped in a sealing film. Afterwards, they are kept at 60°C and submitted to the desired external relative humidity. Mass and length of sample are measured up to 200 days. The presented results (mean value) are computed using four identical specimens (the standard deviation is mostly less than 0.04%). Target relative humidity in each chamber is obtained by a saturated saline solution. The chambers are agitated every day in order to be sure that the humidity is uniform within the whole chamber. This method has already been used by other authors and recently by the followings Baroghel-Bouny et al. (2000), Raouf (1998) and Delage et al. (1998). The external relative humidities imposed to the first series are between 59% RH and 100% RH. Six levels are used (Table 3).

The external relative humidity history for cyclic experiments are pictured in Fig. 4. The 28 day cycles are long enough to dry the material at each cycle, whereas the 14 day ones are short enough to remain in an intermediate state: partial saturation. Cycles are calculated so that a 59 day old sample has spent in both cases the same time in 98% RH chamber (28 days for the long cycles, 2*14 days for the short one).

RH_constant experiments

Relative mass variations of specimens are presented on Fig. 5. The mass variations are ranged between a loss about 2.5 % for 59% RH to a gain 2.4% for 100% RH (Table 4). The mean mass of 82% RH samples remains constant over the test. It means that the initial relative humidity within pores of the specimens is 82%.

Expansion generated by ASR is calculated by deducting the expansion of inert specimens (including non-reactive sand) from the expansion of reactive specimens (Fig. 6). The higher the external relative humidity, the more and the faster ASR expansion. These results confirm the observations of previous experiments (Olafsson 1986, Tomosawa et al. 1989 and Kurihara et al. 1989). Moreover, they clearly show that there is a correlation between water intake and ASR expansion (Table 4) as it has already been pointed out by Vivian (1981) and Larive et al. (2000).

Nevertheless, the expansion generated by ASR for the specimens submitted to RH=100% is inferior to the one for RH=96% whereas water intake is superior (Fig. 6:). This is due to the leaching of alkalis in consequence to the condensation of pure water on the external surface of the samples which leads to the reduction of ASR expansion. This fact has already been pointed out (Rogers and Hooton 1991 and Wiecker et al. 2000). The results for RH=76% are not reproduced because they are irrelevant (alkaline pollution of the specimens because of contact with the solution).

In addition, for a temperature equal to 60°C, the RH threshold under which ASR swelling is inhibited seems to be less than 59% since the ASR expansion of specimens submitted to RH=59% is about 0.06% after 100 days.

RH_variable experiments

Fig. 7 presents the mean mass variations of the specimens for 14 and 28 day cycle. As expected samples that undergo the 28 day cycle reach a mass equilibrium while the ones that undergo the 14 days cycle remains partially saturated. Cyclic RH mass variation are included in a [-5.0%;0.0%] range that differ from the [-2.5%;2.4%] range found for constant RH specimens. The width is the same but the mean values are distinct. The specimens from both series were not cast the same day. They were respectively cast in summer and in winter for RH_constant and RH_variable series. This could explain the difference on the initial water content.

One can notice that the first drying cycle always differs from the others. For short cycles, a 4.0% mass loss is associated to the dry end of the first cycle. This value becomes higher for all the following cycle: 4.8%. For long

cycle, a 5.0% mass loss is associated to the first cycle. This first value is a maximum and is not reached again in the following cycle. The mass variation goes only down than to 4.3%. This might be explained by precipitation reaction or maturity evolution that modifies porosity.

Fig. 8 shows the ASR expansions. They are quite similar for both cycles up to 80 days. Afterwards expansion for short cycles seems to stop whereas expansion for long ones seems to keep on increasing. This should be confirmed by longer test duration.

For each drying part (short and long cycles), an extra shrinkage about 0.04% is recorded. Its origin is unknown. It might be that those ASR samples undergo two kinds of shrinkage:

- A shrinkage due to cement paste drying. This part does not appear here as the curves plotted are expansion generated by ASR only (deformations of a reactive sample minus deformations of a non reactive sample),
- A shrinkage due to water loss by the ASR gel. As the sample dries, ASR gels lose water. It comes that the ASR gel takes less volume. The pressure exerted on pore walls is relieved and the recorded deformation decreases.

Fig. 9 compares the expansion generated by ASR for cyclic RH and relevant constant RH. Given a date of test, ASR deformations for cyclic samples are always higher than the one for constant 59% RH and lower than that of constant 96% RH.

At 20 days, deformations values are 0.01% for 28 days cycles, 0.04% for 14 days cycles, 0.05% for constant RH. This shows that for the same formulation, several specimens give different experimental results. Comparing those deformation values with the mass variation values, one can notice that those small expansion differences are only due to differences in water loss. This confirms that comparison between some expansion curves can not be done as a separate task. To analyze an ASR expansion curve, the mass variation curve and the initial water state of the sample are necessary.

Conclusion about the experimental campaign

Fig. 10 compares our results with the ones found in the literature. The new values obtained are within “the literature range”. Nevertheless, the range of values found is too wide to state a law that relates ASR expansion to the relative humidity (external RH or within pores). Moreover, the available water content within the affected material is neither constant nor uniform versus time. It is thus compulsory to take it into account in order to propose a hydro-chemo-mechanical method to estimate the swelling generated by ASR.

Presentation of the modeling

In the modeling proposed herein, we have chosen to describe the available water within affected concrete by the means of the Saturation Ratio “ Sr ”. It represents the pore water filling percentage. We define a dimensionless variable A to monitor the progress of ASR. The values of A are ranged between 0 and 1. A only depends on time t and saturation ratio Sr . We suppose that for any given value of Sr below 1, A cannot reach its maximum value. Corresponding ASR swelling thus depends on external relative humidity and water intake as it has already been observed experimentally. The ASR advancement A and the free expansion induced by ASR ϵ^{ASR} are supposed to follow the following original laws:

$$\dot{A}(Sr, t) = \frac{\partial A}{\partial t}(Sr, t) = \alpha_0 \alpha(Sr) [\beta(Sr) - A(Sr, t)] \quad (3)$$

- α_0 is a constant which characterizes the kinetics of ASR,
- β is a function which gives the maximal advancement that the ASR can reach. It is a function of the saturation ratio Sr . It only depends on Sr . Its values are ranged between 0 (for $Sr=0$) and 1 (for $Sr=1$). Its form has to be fitted on experimental data. The physic meaning of β is that the involved chemical phenomena are limited around residual saturated zones of concrete.
- α is another function which alters the kinetics of ASR as a function of the saturation ratio Sr . Its value are always between 0 (for $Sr=0$) and 1 (for $Sr=1$). Its mathematical expression has also to be defined. The physic meaning of α is that necessary chemical species for ASR diffuse towards reactive sites and that drying slows diffusion.

The ASR free swelling ϵ^{ASR} is linked to the advancement A by the following:

$$\begin{cases} \text{if } A(Sr, t) < A_0 & \text{then } \dot{\epsilon}^{ASR}(Sr, t) = 0 \\ \text{if } A(Sr, t) \geq A_0 & \text{then } \dot{\epsilon}^{ASR}(Sr, t) = K \dot{A}(Sr, t) \end{cases} \quad (4)$$

- K is a parameter that relates the expansion to the advancement. It depends on the mechanical properties of the affected material, the quantity and the reactivity of the reactive aggregates used, the amount of available alkalis, ... etc.
- A_0 stands for the minimal ASR advancement necessary to initiate swelling (i.e. it represents the quantity of gel to fill the available porous volume around reactive aggregates).

When the saturation ratio Sr is a function of time t , one cannot solve analytically the equations (3) and (4). An incremental process is necessary to integrate these expressions. For example, we can assume that Sr is constant between two close times t and $t + \delta t$:

$$A(\overline{Sr}, t_1) = \beta(\overline{Sr}) - [\beta(\overline{Sr}) - A(\overline{Sr}, t)] \exp[-\alpha_0 \alpha(\overline{Sr})(t_1 - t)] \quad (5)$$

- δt is the time increment ($\delta t < t$),
- \overline{Sr} is the mean value of Sr within the range $[t; t + \delta t]$,
- t_1 is a time included in the domain $[t; t + \delta t]$.

α and β laws are supposed to follow:

$$\alpha(Sr) = \left(\frac{\langle Sr - Sr_0^\alpha \rangle^+}{1 - Sr_0^\alpha} \right)^{m_\alpha} \quad \text{and} \quad \beta(Sr) = \left(\frac{\langle Sr - Sr_0^\beta \rangle^+}{1 - Sr_0^\beta} \right)^{m_\beta} \quad (6)$$

- $\langle X \rangle^+$ represents the positive part of X ,
- Sr_0^α and Sr_0^β are thresholds below which the functions are zero,
- m_α et m_β stand for possible non linearity.

A goal of the experimental program is then to characterize both functions α and β . This implies in the one hand the determination of the two thresholds Sr_0^α and Sr_0^β , and in the other hand the determination of both exponents m_α and m_β .

Application of the modeling

Determination of the saturation ratio Sr and corresponding ASR expansion

The input data of the model to predict both kinetics and maximal ASR induced expansion is the saturation ratio Sr and the swelling parameters α_0 , A_0 and K . The main goal of this work is to fit the laws α and β , so we need to know the more accurately possible the saturation ratio Sr . It could be estimated using a water transport calculation.

In our case (with available mass variations) the determination of the values of Sr in every point of the sample is based on some previous works by Benboudjema et al. (2003) and Torrenti et al. (1999). The fields of saturation ratio Sr are estimated thanks to a finite element calculus (French code CAST3M). The variation of the diffusivity with the hydric state of the material are included (Xi et al. 1994).

Once the fields of saturation ratio Sr are determined in every location in the sample, the fields of reaction advancement A and ASR free swelling ε^{asr} are computed by the means of the formulas (3) and (4). The supplementary drying shrinkage observed experimentally (Fig. 8) is supposed to be proportional to ASR expansion and capillary pressure Pc :

$$\varepsilon_{shr}^{asr}(Sr, t) = -c \varepsilon^{asr}(Sr, t) \left\langle \frac{Pc - Pc_0}{Pc_0} \right\rangle^+ \quad (7)$$

The capillary pressure Pc within pores depends on the saturation ratio Sr (Van Genuchten 1980 and BaroghelBouny et al. 2000):

$$Pc(Sr) = -a(Sr^{-b} - 1)^{\frac{1}{b}} \quad (8)$$

The swelling (ASR and supplementary shrinkage) of each specimen is then computed thanks to an elastic approach:

$$\varepsilon = \varepsilon^e + \varepsilon^{asr} + \varepsilon_{shr}^{asr} \quad \sigma = \lambda tr(\varepsilon^e) I + \mu \varepsilon^e \quad (9)$$

This elastic approach neglect induced damage and lead to a slight overestimation of K .

Simulation of RH_constant experiments

The saturation ratio Sr is estimated on the basis of experimental mass variations (Fig. 11). The ASR swelling parameters (α_0 , A_0 and K) are identified thanks to experimental expansions (Table 5). The thresholds Sr_0^α , Sr_0^β and

the exponents m_α et m_β for the laws α and β are determined thanks to a parametric study in order to fit in the best way possible the experimental ASR expansions (see the comparison between experimental and predicted ASR expansions on Fig. 12). The laws α and β thus obtained are linear without threshold (Table 6).

Validation of the modeling

The laws α and β have been fitted thanks to the results of RH_constant experiments. They are supposed to be characteristic of alkali-silica reaction. They are assumed neither to depend on affected concrete, reactive aggregates nor temperature. In order to verify this assumption, the model thus obtained ($\alpha(Sr)=Sr$ and $\beta(Sr)=Sr$) is used to reproduce the results of different experiments: RH_variable, Tomosawa 1989, Kurihara 1989 and Larive 2000 (mortar and concrete, different reactive aggregates and different temperatures). Full results can be found in (Poyet, 2003), only the simulations for RH_variable, Tomosawa et al. (1989) and Larive et al. (2000) are presented here.

Simulation of RH_variable experiments

The modeling is applied in order to reproduce the results of the second experimental campaign: RH_variable experiments. Like before, the saturation ratio is estimated on the basis of experimental mass variations (Fig. 13). Corresponding ASR expansion is then computed using the incremental process described above (Fig. 14). Once fitted, the proposed modeling is able to correctly predict both ASR expansion rate and maximal value. The swelling parameters (α_0 , A_0 and K) are the same as for RH_constant simulations (Table 5).

Simulation of experiments taken out of literature

Several authors have published experimental results on influence of water on ASR expansion. The experimental results of Tomosawa et al. (1989), Kurihara et al. (1989) and Larive et al. (1998, 2000) were successfully used to validate our model (Poyet 2003). The results of the simulations of Tomosawa and Larive experiments are presented in this paper. Reactive specimens undergo different water intakes. Their length and mass variations are measured. As before, the saturation ratio Sr is estimated on the basis of the experimental mass data (see Fig. 15 and Fig. 16). Expansion generated by ASR is then computed and compared to the experimental data (see Fig. 15 and Fig. 16). The swelling data used to simulate the results of the experiments of Tomosawa et al. (1989) and Larive et al. (2000) are presented in the Table 7.

More simulations have been made; they are presented in Poyet (2003). The model gives satisfactory results according to the precision on the description/prediction of the saturation ratio Sr .

Conclusions

A new modeling of Alkali-Silica Reaction is presented in this paper. It allows to take into account the amount of available water within affected material to estimate the free expansion generated by ASR. The saturation ratio Sr is chosen as parameter. The modeling allows predicting rate of swelling and end value of swelling generated by ASR on any structure.

To use this modeling, one has first to fit three swelling parameters (A_0 , α_0 and K). They are material parameters that define the swelling properties of the studied reactive material (ASR kinetics, maximal expansion and latency time). Moreover the overall water distribution within the sample must be known at each stage of the reaction. This implies to define and compute water diffusion within the affected sample/structure versus time. As a consequence, for any affected structure and reactive material, the expansion generated by ASR is governed by the evolution of the saturation ratio Sr .

The results of a first series of experiments, (cylindrical samples maintained within constant RH -6 different levels), are used to fit the modeling constitutive laws (laws α and β which describe the influence of water on ASR kinetics and maximal value of swelling as functions of Sr). These functions do not depend on the studied material.

The modeling is then used to reproduce the results of other experiments (specimens submitted to cyclic water intake and experiments taken out from literature). Experimental results and numerical simulations are in good accordance.

This modeling will also be used to simulate ASR affected beams submitted to an external moisture gradient (Multon et al. 2003, 2004). Full results will be presented in a following article.

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Table 1: test conditions and main measurements for several authors

Authors	Olafsson	Tomosawa et al.	Kurihara et al.
Temperature	23 and 38°C	40°C	40°C
Sample shape	Prismatic	Prismatic	Unknown
Dimensions	Unknown	7.5*7.5*40 cm	Unknown
Material	Mortar	Concrete	Mortar
Duration	22 months	52 weeks	12 weeks
Results	Expansion	Expansion and mass	Expansion and Water content

Table 2: composition of the mortar

Materials	Quantity		Units
	Non reactive	Reactive	
Cement	537.8	537.6	kg/m ³
De-ionized water	268.8	268.8	l/m ³
Non reactive sand [0-5mm]	1612.8	806.4	kg/m ³
Reactive sand [0-5mm]	-	806.4	kg/m ³
NaOH	9.9	9.9	kg/m ³

Table 3: soluble salt used and relative humidity reached

Soluble salt	Formula	Relative Humidity (60°C)
De-ionized water	H ₂ O	100%
Potassium sulfate	K ₂ SO ₄	96%
Potassium nitrate	KNO ₃	82%
Potassium chloride	KCl	80%
Sodium chloride	NaCl	76%
Sodium nitrite	NaNO ₂	59%

Table 4: mass variation and ASR expansion for different external Relative Humidities

External RH	100%	96%	82%	80%	76%	59%
Mass variation	2.40%	2.10%	0.00%	-0.98%	-1.27%	-2.51%
ASR expansion	0.24%	0.28%	0.19%	0.14%	0.11%	0.03%

Table 5: swelling data used for the numerical simulations

Data	A_0	α_0	K
Value	0.00	0.04 day ⁻¹	0.35%

Table 6: definition of α (kinetics) and β laws (expansion induced)

Law α (Sr)		Law β (Sr)	
Sr_0^α	m_α	Sr_0^β	m_β
0	1	0	1

Table 7: swelling data for the simulations of the experiments of Tomosawa et al. (1989) and Larive et al. (2000)

Data	Tomosawa et al.	Larive et al.	Unity
α_0	0.011	0.02	day ⁻¹
A_0	0.25	0.35	-
K	0.265	0.35	%

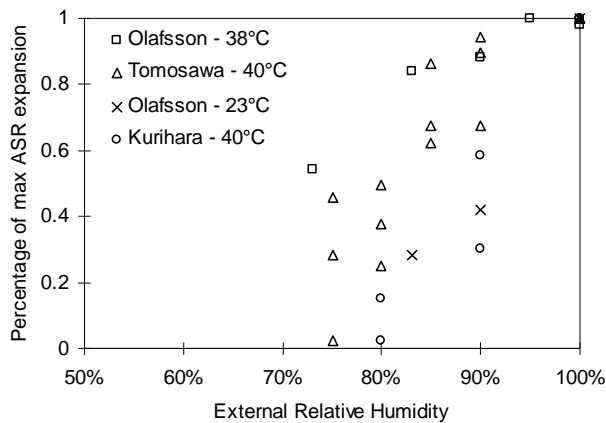


Fig. 1: evolution of maximal ASR expansion versus external relative humidity for several authors.

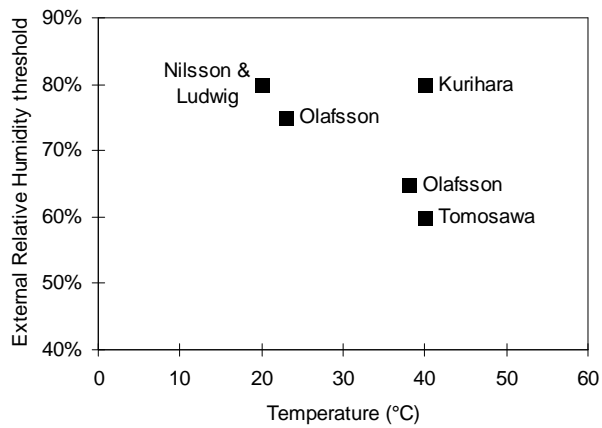


Fig. 2: evolution of the external relative humidity threshold as a function of temperature (from several authors).

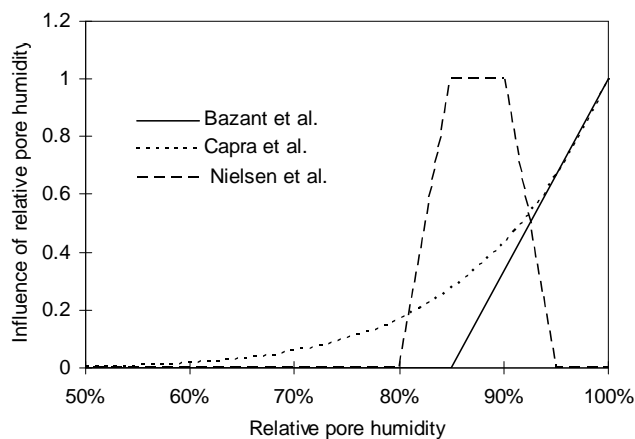


Fig. 3: influence of computed pore relative humidity on predicted expansion generated by alkali-silica reaction from Nielsen et al. (1993), Capra et al. (1998) and Bazant et al. (2000).

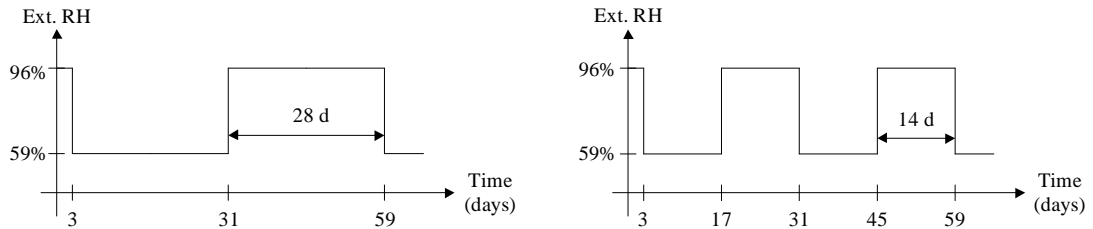


Fig. 4: long cycle (on the left) and short cycle (on the right)

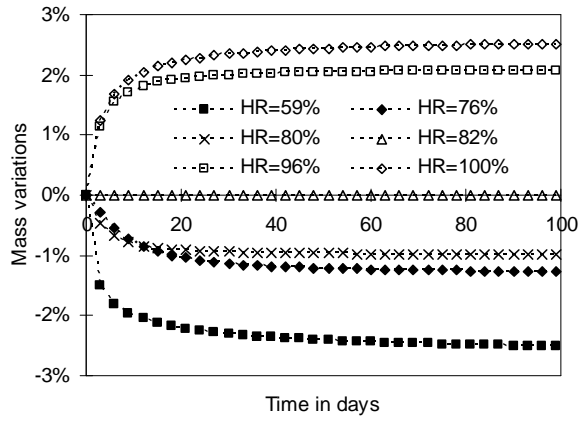


Fig. 5: mass variations for RH_constant specimens as a function of time and external relative humidity.

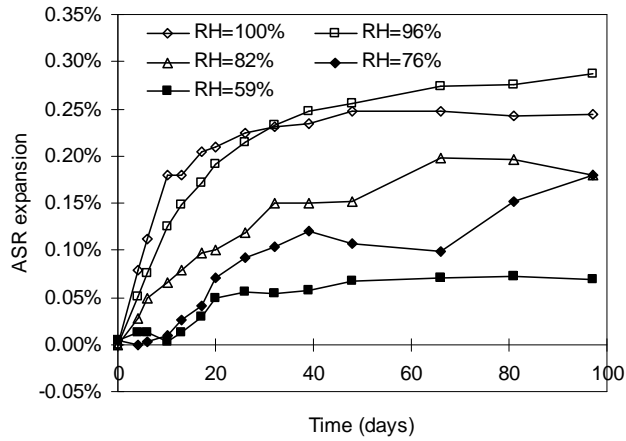


Fig. 6: ASR swelling versus time for different constant external relative humidities.

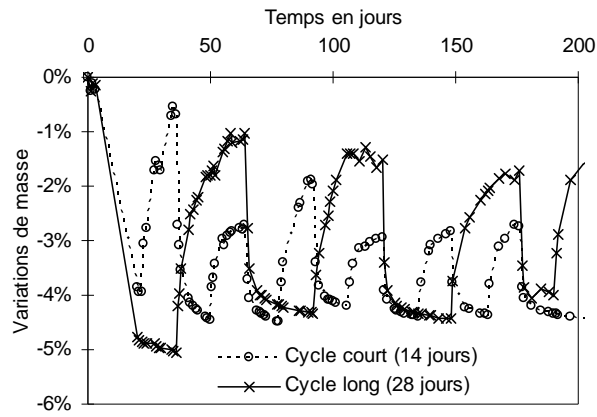


Fig. 7: mass variations for cyclic external relative humidity.

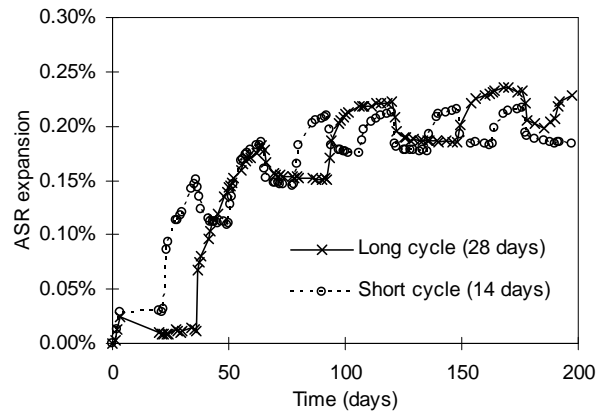


Fig. 8: ASR swelling versus time for cyclic relative humidity.

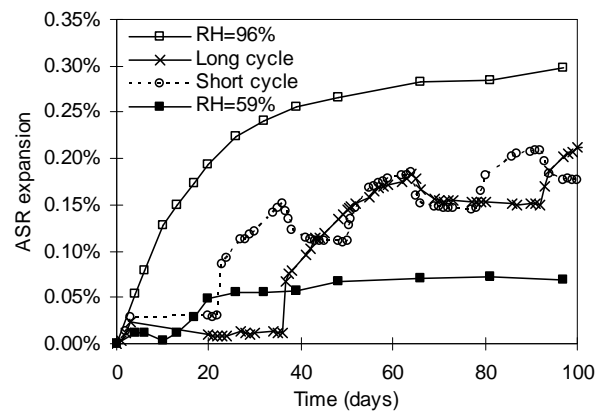


Fig. 9: ASR swelling comparison between constant and cyclic relative humidity.

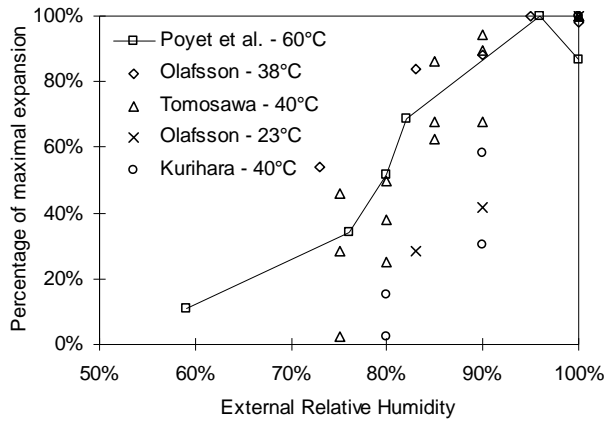


Fig. 10: evolution of maximal ASR expansion versus external relative humidity for several authors.

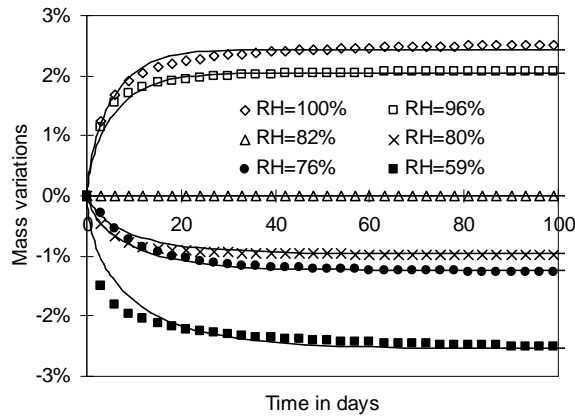


Fig. 11: comparison between simulated and experimental mass variations for constant RH experiments.

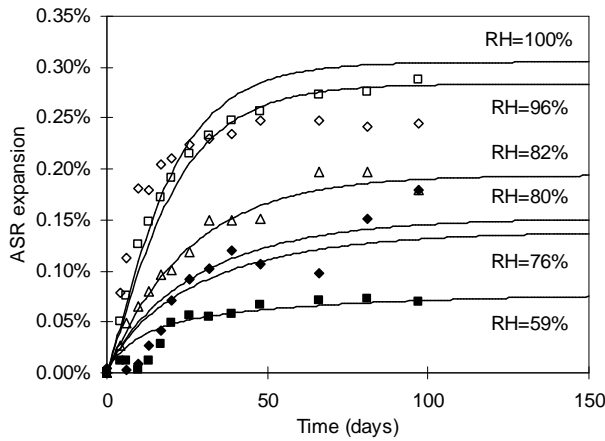


Fig. 12: comparison between predicted and experimental ASR swellings (irrelevant experimental results for RH=76% are not reproduced).

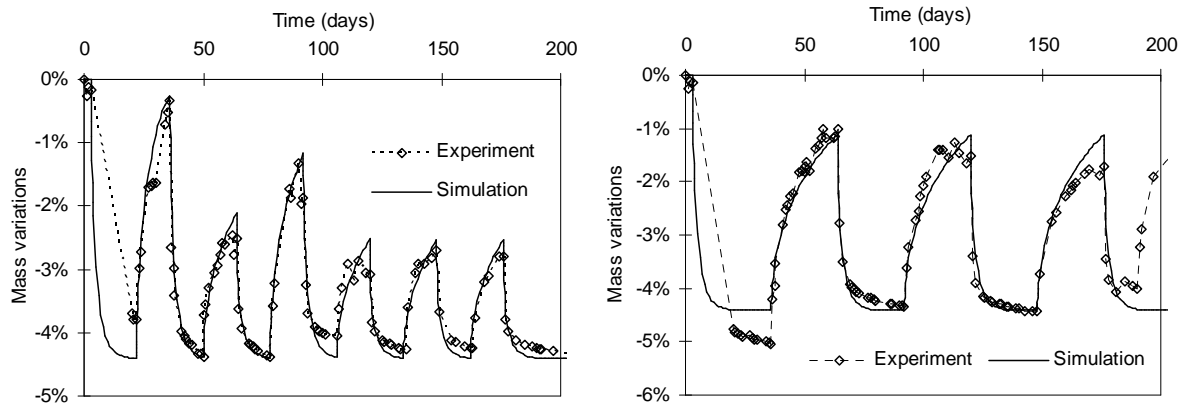


Fig. 13: comparison between experimental and simulated mass variations.

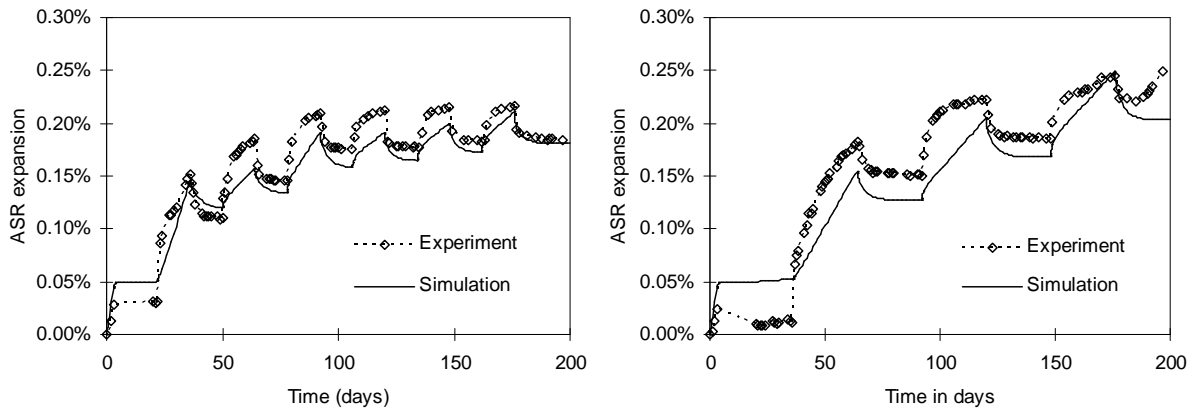


Fig. 14: Cyclic RH swelling simulations compared to experiments.

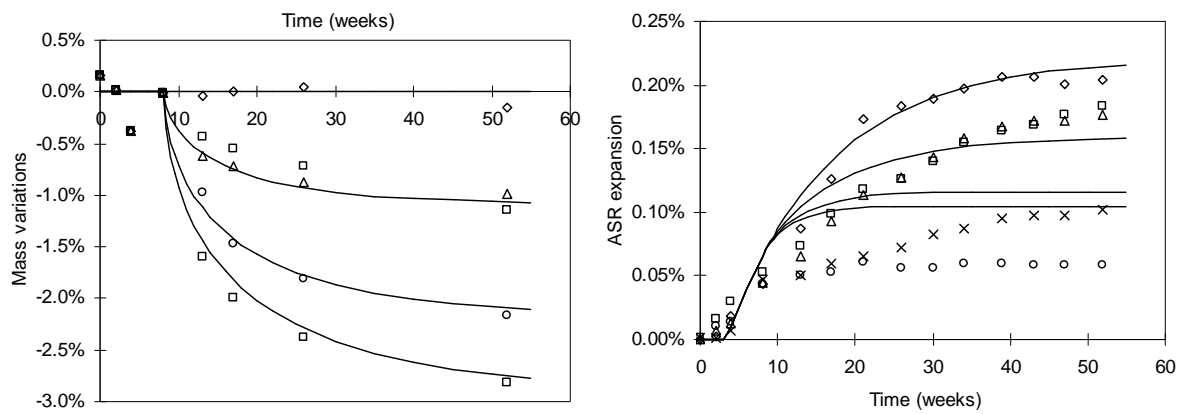


Fig. 15: Simulation of the experiments of Tomosawa et al. (1989).

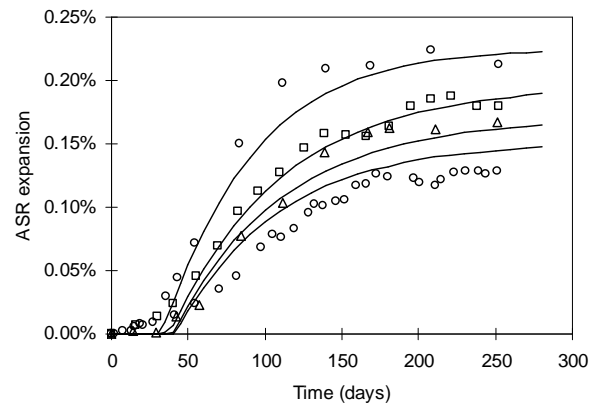
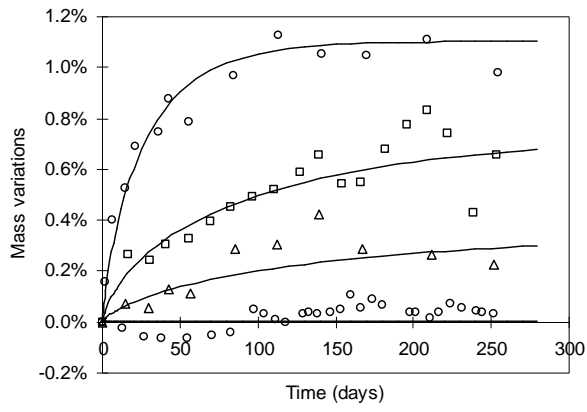


Fig. 16: simulation of the experiments of Larive et al. (2000).