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Normalized age applied to AAR occurring in concretes with or without mineral admixtures

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Abstract

This paper presents a method for assessing the normalized age factors, which allow accelerated alkali–aggregate reaction (AAR) tests performed at various temperatures (20, 40 and 60 °C) to be related to the conditions encountered in situ in concrete structures. The evaluation of normalized age factors is based on the comparison of many experimental results taken from the literature concerning laboratory tests and in situ measurements. The use of these factors permits us to evaluate, from the results of an accelerated test performed at 60 °C, the protection time against AAR that could be expected for in situ concretes containing mineral admixtures (silica fume and fly ashes). The results show that, in addition to the inhibitory action of mineral admixtures leading to a strong decrease in the final AAR-swelling, the protection against abnormal expansion caused by AAR increases significantly when mineral admixtures are used. Abnormal expansion is expected at 2–4 years for plain concrete compared to 7–50 years for concrete with mineral admixtures.

Keywords: Concrete; Alkali–aggregate reaction; Expansion; Accelerated test; Mineral admixtures

1. Introduction

The behavior of concrete mixes potentially affected by alkali–aggregate reaction (AAR) is generally assessed by means of accelerated tests. The objective of the acceleration is to reveal, within a relatively short delay, the potential for reaction by concrete expansion. The most common acceleration method consists of keeping concrete samples at high temperature and high relative humidity (RH>95%).

Currently, many different tests (mortars, concretes, with or without addition of alkalis) using various storage temperatures (the most common being 38, 60 or 80 °C) are carried out. Although they discriminate a reactive aggregate or a concrete mix, in most cases, the use of these accelerated tests is not fully satisfactory. They do not give any information about the real in situ age that corresponds to the laboratory test duration. In other words, what is the relationship between the duration of the accelerated test and the reaction time under normal atmospheric conditions encountered on a real structure? This question leads us to use the concept of normalized age, defined as the correspondence factor between an accelerated test time and in situ concrete.

It is of fundamental importance to answer to this question since the knowledge of a normalized age should allow us to give useful information to engineers and researchers on:

- the initial duration of protection against AAR in a structure;
- the total duration of the reaction, after which the harmful effects of AAR will be negligible.

The aim of this paper is to assess normalized age factors in order to determine a relationship between accelerated tests and in situ environment of structures. These factors have been calculated from many experimental results found in the literature. One of their applications allows us to predict, from the results of an accelerated test performed at 60 °C, the duration of in situ protection towards AAR provided by mineral admixtures (silica fume and fly ash).

2. Normalized age

The normalized age concept refers to the correspondence between the time scale of accelerated tests and the time scale

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Table 1
Multiplying factors proposed in literature to evaluate the normalized age of concrete from accelerated tests

Author/reference	Storage conditions				Calculation method	Multiplying factor			
Carlson [4]		21 °C	43 °C	66 °C	Time ratio to reach the expansion of 10×10^{-4}		8–16	2–3	1
Olafsson [5]		23 °C	38 °C		Comparison of expansion rate		3–5	1	
Connell [6]		20 °C	38 °C		Time ratio to reach the expansion of 10×10^{-4}		4	1	
Hobbs [7–9]	in situ	20 °C	38 °C		Age of abnormal expansion	7–8	4	1	
Lane [10]	in situ		38 °C		n.a.	10		1	
Fournier et al. [11]	in situ		38 °C		Time ratio to reach the expansion of 4×10^{-4}	8–14		1	
Wood [12]	in situ		38 °C		n.a.	5–10		1	

of in situ concrete. There are various theoretical and empirical approaches to assess the expansion acceleration induced by the increase in test temperature.

2.1. Theoretical approach

A way to calculate the thermal acceleration factor is to use an Arrhenius law. This law requires the knowledge of the activation energy of each cement components and an accurate knowledge of internal diffusion conditions and storage conditions (temperature and relative humidity). This approach has been adopted by several authors such as Capra et al. [1] and Francy et al. [2] in the development of mathematical models of AAR.

The use of this kind of law does not seem suitable to represent the temperature effect on AAR for two reasons. The first one is that it is not appropriate to consider all AAR reactions (including silica dissolution, diffusion phenomena and gel formation) as a single reaction characterized by a single activation energy. The use of a mean value could lead to significant calculation uncertainty. The second reason is that it is also inaccurate to suppose that this activation energy remains constant during the reaction, while the chemical mechanisms vary strongly with time. This is in accordance with the conclusions of Larive [3], who did not succeed in calculating a single activation energy between the beginning and the end of the reaction.

These are the reasons why, instead of searching for laws combining the effects of temperature, relative humidity, diffusion, etc. on expansion, it seemed to us more appropriate to calculate equivalent time factors by an experimental approach using the literature.

2.2. Bibliographic approach

This approach consisted of using the abundant results available in the literature concerning tests on the same concretes stored in different conditions. Some authors propose multiplying factors connecting two or three storage conditions from their own results (Table 1). The most common method consists of comparing the time, for two concretes stored at different temperatures, to reach the same expansion level. Carlson [4], who was one of the first to perform this kind of test, evaluated the acceleration effect of temperature on AAR swelling. His tests, performed at 21, 43 and 66 °C on mortars containing 22 different aggregates, led to the conclusion that an expansion of 10×10^{-4}, reached over more than 2 years at 21 °C, occurred in 6 months at 43 °C and only 3 months at 66 °C. These lengths of time were reduced to 32, 6 and 2 weeks, respectively, for the same mortars doped with alkalis.

Afterwards, other authors used this same approach, changing only the absolute value of the reference expansion to be reached. For instance, Fournier et al. [11] "compare the time to reach 0.04% expansion for various test specimens subjected to laboratory and field testing."

This procedure seems incorrect to us since the raw expansion curves are not affine. In other words, the final expansions obtained for tests performed at different temperatures do not reach the same absolute value, as shown on Fig. 1, which has been plotted using experimental results (final expansions) from many literature references. In these conditions, comparing the different periods needed to reach the same critical expansion ε_i (e.g., $\varepsilon_i = 2 \times 10^{-4}$ in the French performance test) in order to evaluate an acceleration factor (defined as the ratio for obtaining ε_i for two temperatures of test) will certainly lead to an incorrect

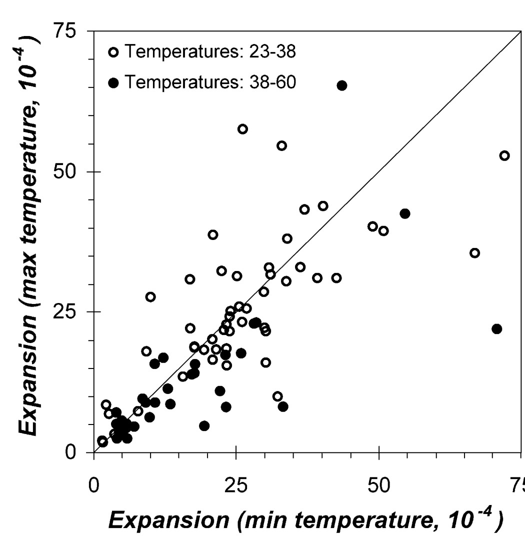


Fig. 1. Final AAR expansions of concrete prisms for tests performed at two temperatures (min: 23 or 38 °C, max: 38 or 60 °C), after Refs. [3,5,8,9,13–27].

result because this approach does not take into account the fact that the expansion value ε_i represents different fractions of the final expansion depending on the test temperature applied.

To avoid this problem, we propose to evaluate an affine factor between two expansion curves obtained in different storage conditions (e.g., in situ − 38 or 38–60 °C) after having brought the final expansion values to the same relative level. Thus, this approach consists of comparing the times to obtain the same fraction of the final expansion.

2.2.1. Processing of experimental curves

The processing steps for calculation of equivalent time scales were performed on expansion curves published in the literature for concretes stored at different temperatures.

(1) Evaluation of the parameters of the expansion curves for each experimental result given in literature by means of least square analysis.

Many types of expansion curves were observed (Fig. 2a) and, in order to use them, we decided to adopt a formal mathematical expression taken from Larive [3] then modified by Carles-Gibergues and Cyr [28] (Eq. (1)).

$$\varepsilon_{tot} = a + b\ (1) \text{ where a is the primary expansion } \varepsilon'(t)\ (\text{non} - \text{AAR})[28] \text{ and b is the AAR expansion } \varepsilon^{\infty}_{AAR}\frac{1-e^{-\tau/\tau_c}}{1+e^{-(\tau-\tau_l)/\tau_c}}\ [3] \quad (1)$$

The modification proposed led us to consider that the swelling measured in an AAR test (ε_{tot}) could be divided in two parts.

- One part due to AAR; this was confirmed by visual and SEM observations of reaction products (gel, dark reaction rim on the periphery of aggregates). This expansion is modeled by part b of Eq. (1) and by Fig. 2b, in which are defined a latent time (τ_l), a characteristic time (τ_c) and a maximum swelling ($\varepsilon^{\infty}_{AAR}$), corresponding to the maximum value observed on an expansion curve, which ends by a constant plateau.
- One part independent of AAR (part a of Eq. (1)), which is characterized, on expansion curves, by a final constant expansion rate different from zero; this part is called primary expansion (ε') and is often observed on experimental expansion curves. More details can be found in our previous paper [28].

(2) Presentation of the curves as fractions of total expansion due to AAR ($\varepsilon_{\%,AAR}$), according to Eq. (2) and illustrated on Fig. 3:

$$\varepsilon_{\%,AAR} = \frac{\varepsilon_{tot} - \varepsilon'}{\varepsilon^{\infty}_{AAR}} 100 \quad (2)$$

where ε_{tot} is the raw expansion, ε' is the primary expansion [28], modeled in this example by a straight line of slope K, equal to the final slope observed after 500 days, and $\varepsilon^{\infty}_{AAR}$ is

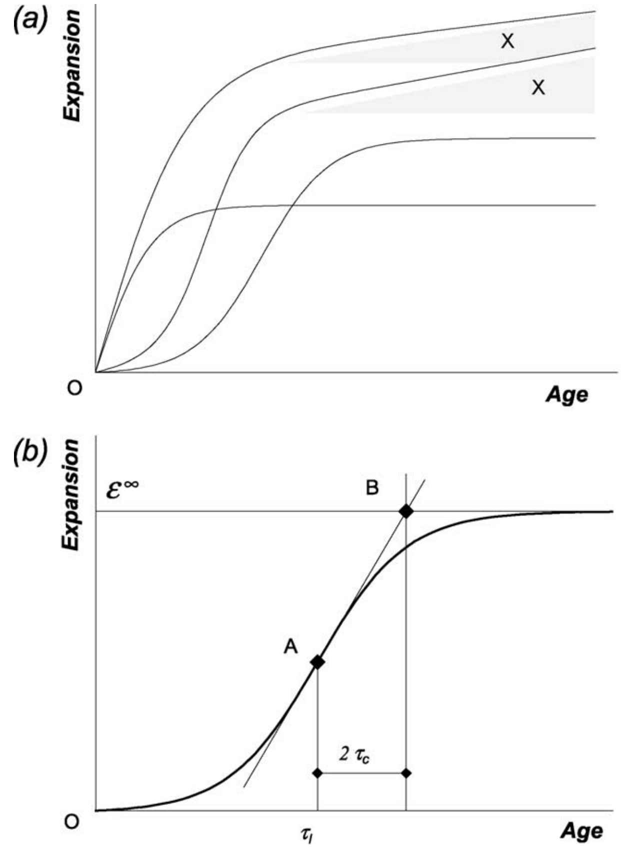


Fig. 2. (a) Typical expansion curves of concretes affected by AAR. X: visible part of expansion characterized by phenomenon independent of AAR [28]. (b) AAR expansion modeled according to Eq. (1).

the maximum AAR expansion, calculated by fitting Eq. (1) by least square analysis.

(3) Determination of the corresponding time for the different storage conditions as a function of the fraction of the total expansion. Then, calculation of the variation of the normalized age factor (β) with the fraction of the total expansion (Fig. 4).

2.2.2. Results

Results published by many authors (Table 2) allowed us to calculate the β factors linking expansion times at 23, 38 and 60 °C under laboratory and in situ (i.s.) conditions. The following conventions are used:

$$\beta_1 = \frac{t_{23\ °C}}{t_{38\ °C}}; \quad \beta_2 = \frac{t_{38\ °C}}{t_{60\ °C}}; \quad \beta_3 = \frac{t_{i.s.}}{t_{38\ °C}}; \quad \beta_4 = \frac{t_{i.s.}}{t_{60\ °C}}$$

Since no result was found in the literature for the calculation of factor β_4, this factor was evaluated according to the following hypothesis: $\beta_4 = \left(\frac{t_{i.s.}}{t_{38\ °C}}\right)\left(\frac{t_{38\ °C}}{t_{60\ °C}}\right) = \beta_2\beta_3$.

The calculated factors β_1, β_2 and β_3 (after removal of aberrant values, Student test) followed normal distributions,

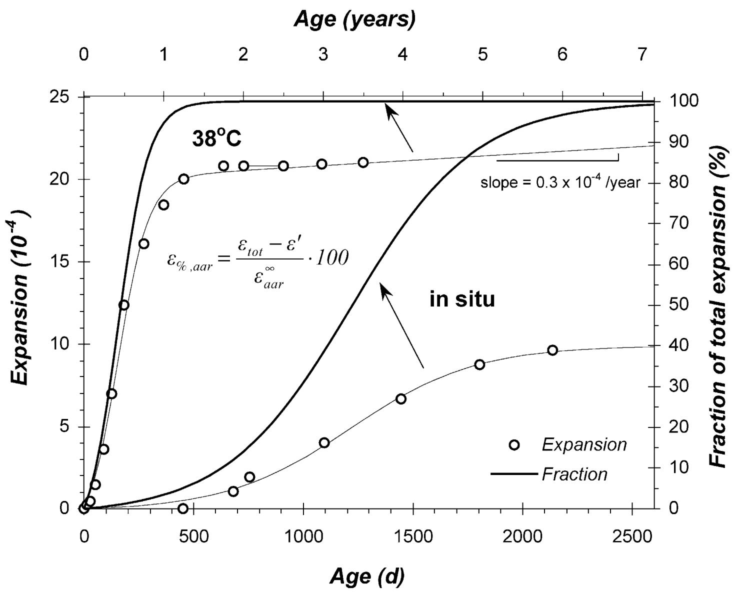


Fig. 3. Treatment of raw experimental curves from literature, which consists in presenting the curves as fractions of the total expansion (Step 2). The results presented on this figure are from Fournier et al. [11].

as confirmed by Chi-square tests. These factors are illustrated in Fig. 5. The analysis of this figure leads us to make some remarks.

• The use of β factors leads one to suppose that the final expansion is known, since the calculations are made for fractions of the total expansion.

• The β factors vary from one author to another. This variation explains the uncertainty on the values of β, especially for initial (0–10%) and final (90–100%) expansions. Then, for this reason, we decided to use three values of β corresponding to three levels of expansion progress (10%, 50% and 90% of final expansion) and having a confidence interval with a probability level of .90. Table 3 shows the calculated values of the factors β. It can be seen that the mean values of factors β_1 and β_2, obtained from many experimental results, are close to 4. These results are not in contradiction with the common assumption that the chemical reaction rate doubles for each 10 °C rise in temperature.

• Then, the results given in Table 3 must be used in this way: for example, a concrete stored at 23 °C takes between 3.7 and 4.7 ($\beta_{1,\ 10\%} = 4.2 \pm 0.5$) more of time to reach 10% of its total expansion than a concrete stored at 38 °C. Thus, if 10% of the total expansion is reached in 1 month at 38 °C,

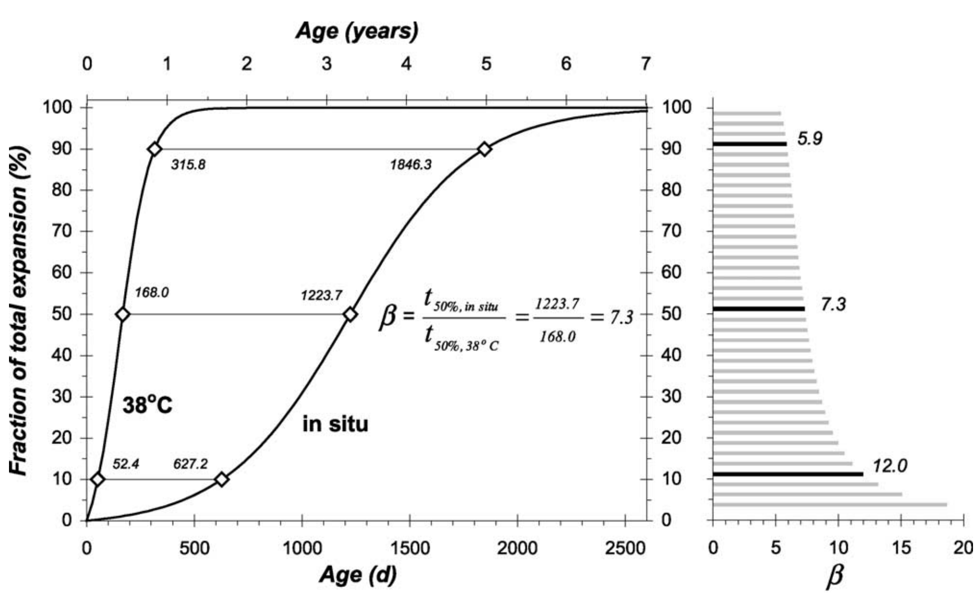


Fig. 4. Treatment of modified experimental curves, which consists in calculating the normalized age factor (β) as a function of the total expansion (Step 3). The results presented on this figure are from Fournier et al. [11].

Table 2
References of literature experimental results used for the calculation of factors β

Reference	Number of mixes analyzed	Mortar or concrete	Temperatures (°C)	Duration of test (years)
23–38 °C (β_1)	Total: 51 mixes			
Hobbs [8,9]	15	Concrete	20–38	1–6.5
Nakajima et al. [22]	13	Concrete	20–40	2
Shayan and Diggins [13] and Shayan et al. [14]	4	Concrete	23–40	1–6
Swamy [17] and Swamy and Al-Asali [20]	2+2	Concrete	20–38	1
Alasali et al. [15]	3	Concrete	23–38	0.75
Thomas et al. [16]	3	Concrete	20–38	2
Larive [3]	1	Concrete	23–38	1.1–1.6
Nixon et al. [29]	1	Concrete	20–38	2
Sideris [21]	1	Concrete	20–40	0.6
Wood et al. [18]	1	Concrete	20–38	0.6
Olafsson [5]	3	Mortar	23–38	1.8
Herr and Wieker [19]	1	Mortar	20–40	1.1
Diamond et al. [30]	1	Mortar	20–40	1.3
38–60 °C (β_2)	Total: 34 mixes			
Murdock and Blanchette [27]	9	Concrete	38–60	1
Bollotte [23]	5	Concrete	38–60	0.25–2
Larive [3]	2	Concrete	38–60	0.5–0.8
Sideris [21]	1	Concrete	40–60	0.6
Kobayashi et al. [24]	3	Concrete/mortar	38–60	0.4–0.5
Hooton and Rogers [25]	8	Mortar	38–64	0.5–1.5
Rodrigues et al. [26]	4	Mortar	38–60	2
Herr and Wieker [19]	2	Mortar	40–60	1.1
i.s.–38 °C (β_3)	Total: 28 mixes			
Hobbs [8,9]	10	Concrete	U.K.—38	1–6.5
Fournier et al. [11]	7	Concrete	Can—38	3.5
Kawamura et al. [31]	6	Concrete	Jap—38	1–3.3
Rogers et al. [32]	5	Concrete	Can—38	8

the same relative level of expansion will be reached in between 3.7 and 4.7 months at 23 °C.

• The factors β are not constant with the degree of expansion. This means that elapsed times (on the mean value of all data used) between the results of tests performed at two different temperatures vary between the beginning and end phases of the expansion phenomenon. This situation is due to an insufficient number of data that have been analyzed (lack of literature results). Consequently, we recommend to limit the use of factors β to discrete points of an expansion curve (e.g., at 10%, 50% or 90% of the total expansion), otherwise, the calculation could lead, for some extreme cases, to a paradox (simultaneous beginning and completion of AAR swelling). It represents probably the weakness of our method.

• The great variation observed on factor β_3 is probably due to the uncontrolled variability of the environmental conditions in field tests. The calculation of this factor, linking laboratory and in situ tests, should be refined by using supplementary experimental data. The only ones used until now concern the results of four authors and are all related to relatively cold storage conditions (UK, Canada

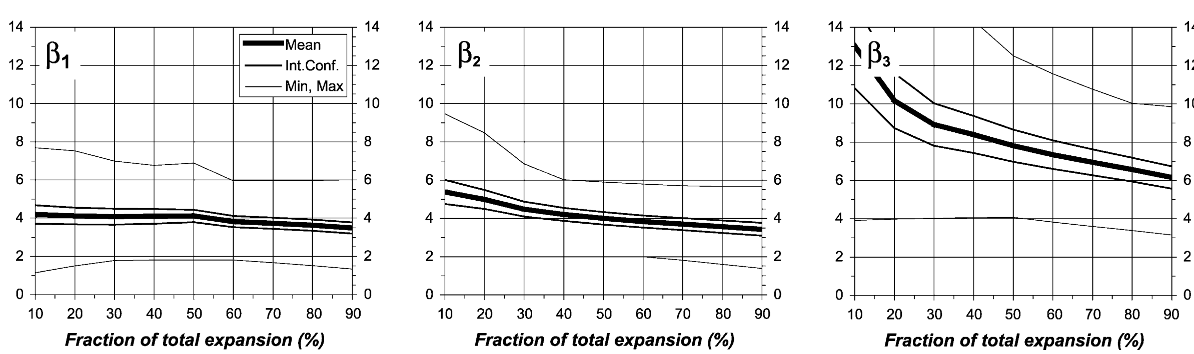


Fig. 5. Factors β connecting the tests performed at different temperatures, for 10%, 50% and 90% of the total expansion.

Table 3
Factors β connecting the tests performed at different temperatures, for 10%, 50% and 90% of the total expansion

Fraction of total expansion	23–38 °C		38–60 °C		i.s.–38 °C	
	Mean value of β_1	Confidence interval α=.10	Mean value of β_2	Confidence interval α=.10	Mean value of β_3	Confidence interval α=.10
10	4.2	±0.5	5.4	±0.6	13.0	±2.2
50	4.1	±0.3	4.0	±0.3	7.8	±0.8
90	3.5	±0.3	3.4	±0.3	6.2	±0.6

and Japan). On the other hand, it would be interesting to perform the calculation on experimental results from temperate and hot climates.

3. An application of normalized age factors: calculation of the protection time of mineral admixtures against AAR

The use of the β factors calculated previously should lead to an improvement in knowledge about the protective role of mineral admixtures against AAR. At the present time, it is commonly assumed that the use of mineral admixtures in concrete is one of the most effective solutions to limit the deleterious effects of swelling due to AAR. Works showing this beneficial effect are abundant (general books on durability of concrete, many international congresses on AAR) and it would be too long to cite all authors who have demonstrated the preventive effect of mineral admixtures towards AARs.

On the other hand, questions about the long-term protection of mineral admixtures against AAR have not yet received an unanimous answer in spite of being long under debate [33]. Thus, while Thomas et al. [34] mention that, in a 30-year-old concrete dam, only the parts containing fly ash did not exhibit disorders due to AAR, Shayan and Diggins [13] and Shayan et al. [14] show that, after 6 months, concretes with high alkali content are not protected by fly ashes. Moreover, Bérubé and Duchesne [35] show, for concrete prisms containing 5% or 10% of silica fume, that the protection apparently provided for a few months only results from a start delay and that afterwards the expansion rate is not reduced by this mineral admixture.

The practical application developed here aims to provide a part of the answer regarding the duration of the protection against AAR granted by mineral admixtures. We use results from our own tests performed at 60 °C and 100% RH and pursued for up to 7 years. β factors have been applied in order to determine the normalized age in situ.

3.1. Materials and experimental procedure

High performance concretes were tested with a mix designed by our laboratory for the construction of highway bridge piles. These concretes had 475 kg/m^3 of binder and some of them contained mineral admixtures: silica fume, raw fly ash or micronized fly ashes [36].

The aggregates consisted of a nonreactive fluvial natural siliceous sand (0–5 mm) and a reactive crushed limestone gravel (5–20 mm). The coarse aggregate is used as a reactive reference (R) by the AAR AFREM group. It is obtained from Tournaisis black limestone, which is slightly dolomitic with a fine siliceous network that reacts easily with alkalis.

The cement used was an ordinary Portland cement (CPA HPR, according to French standard P15-301 in use in 1992); its properties are given in Table 4. The mineral additives used were a silica fume (SF) and a class F fly ash (FA) (Table 4) and their replacement rates were respectively 10%

Table 4
Physical and chemical properties of cement, silica fume and fly ashes

	Cement	Silica fume	Fly ash	FA-S22	FA-B12	FA-S11
Specific area (m^2/kg)	430	n.a.	310	569	680	667
SiO_2	20.2%	90.8	56.6	57.2	56.6	56.7
Al_2O_3	5.0	0.5	31.3	32.6	31.3	32.7
Fe_2O_3	2.7	0.1	5.8	4.5	5.8	4.7
CaO	64.4	tr	2.9	2.8	2.9	2.8
MgO	1.3	0.3	0.7	0.7	0.7	0.8
K_2O	0.9	0.5	1.8	1.8	1.8	1.9
Na_2O	0.06	0.4	0.1	0.1	0.1	0.2
Na_2O eq.	0.7	0.7	1.3	1.3	1.3	1.4
SO_3	3.3	–	0.6	0.5	0.6	0.4
< OI	2.1	3.3	2.6	2.7	2.6	3.0
Minerals	C_3S: 61% C_2S: 8% C_3A: 9% C_4AF: 8%	Glass	Glass, mullite, quartz, magnetite, hematite			

Table 5
Concrete mix design (1 m^3)

Concretes	OPC	SF	FA	FA-B12	FA-S22	FA-S11
Cement (kg)	475	430	356	356	356	356
Mineral admixture (kg)	0	45	119	119	119	119
Sand (kg)	776	773	759	767	764	765
Coarse aggregate (kg)	1071	1067	1047	1058	1056	1056
Water (l)	162	171	166	157	162	152
Superplasticizer (kg)	15.7	15.7	15.7	15.7	15.7	15.7
Water/binder	0.34	0.36	0.35	0.33	0.34	0.32
Water/cement	0.34	0.40	0.47	0.44	0.46	0.43
Slump (cm)	16	17	17	17	17	14

and 25% of the cement mass. Physical treatments on raw fly ash (FA) allowed us to use three other additives (Table 4): fly ash FA-G12, which was obtained by grinding (maximum size of particles: 12 μm) and fly ashes FA-S22 and FA-S11, which were air-selected (particles < 22 and 11 μm).

High performance concretes were made with a constant slump of 16 cm, a water/binder ratio ranging from 0.30 to 0.35, and a superplasticizer content of 1.15% (dry). The details of the design of the concrete mixes, which were not adjusted for alkali content, are given in Table 5.

Concretes were made, conserved and tested according to the directions given by the document «Test de performance d'une formulation de béton vis-à-vis de l'alcali-réaction», in «Recommandations pour la prévention des désordres dus à l'alcali-réaction» [37]. This test consists in evaluating the performance of a concrete against AAR by measuring its expansion on 7 × 7 × 28 cm prisms stored at 60 °C and 100% RH.

Table 6
Content of active alkalis in concrete mixes

	Concrete	OPC	SF	FA	FA-B12	FA-S22	FA-S11
Active alkalis	(%)	0.7	0.65	0.6	0.6	0.6	0.6
	(kg/m^3)	3.3	3.1	2.7	2.7	2.7	2.7

After mixing, the samples were stored in a moist room at 20 °C for 24 h. Then, the concrete prisms were placed vertically on grids in waterproof containers containing 35 mm of water (the concrete was not in contact with the water). Each concrete was tested with three prisms, so the expansion data are means of three measurements. The containers were placed in a reactor generating a controlled atmosphere of 60 °C and 100% RH.

Expansion measurements were made after the containers and their prisms had been cooled for 24 h at 20 °C. Immediately after each measurement, the prisms were put back into their containers and kept in the reactor at 60 °C until the next measurement. Concrete mixtures were considered as reactive (or not) if they exceeded (or not) the expansion value of $2 \cdot 10^{-4}$ at 3 months.

3.2. Results after 6 months

The expansion curves of all six concretes (Fig. 6) show that the swelling was relatively weak. This result could be related, in a first analysis, to the low content of active alkalis in the concretes (Table 6).

These expansions can be compared to the limit value of $2 \cdot 10^{-4}$ at 3 months, which, in the French test, divides concrete mixes into two classes: nonreactive or reactive. The OPC mix was qualified as reactive since swelling almost

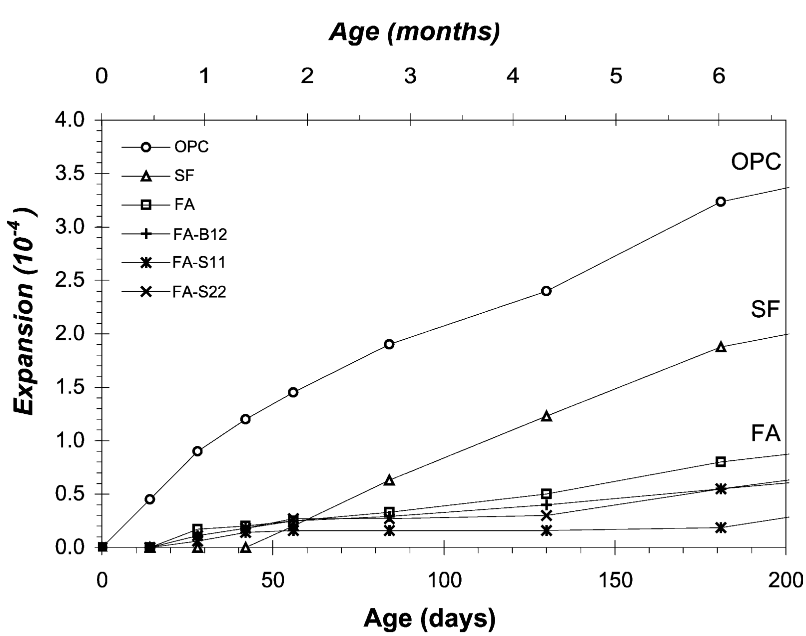


Fig. 6. Expansion of concrete prisms up to 6 months [36].

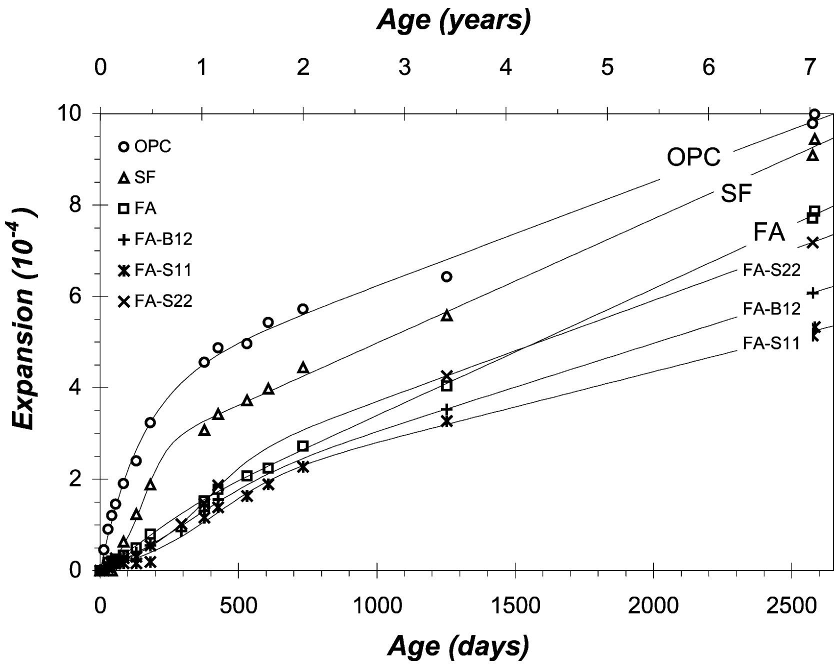


Fig. 7. Expansion of concrete prisms up to 7 years.

reached the limit value at 3 months and had increased at 4 and 6 months. On the other hand, the expansion values at 3 months for concretes with mineral admixtures were largely below the limit value of $2 \cdot 10^{-4}$. Thus, we concluded that silica fume (SF), fly ash (FA) and micronized fly ashes (FA-B12, FA-S11, FA-S22) fulfilled their expected function of restraining AAR.

3.3. Results after 7 years

Fig. 7, which illustrates raw experimental data, shows without any doubt that swelling continued for all concretes until the last measurement, i.e., for 7 years. A microscopic analysis of concrete prisms confirmed the presence of typical silica–calcium–alkali gels, which allowed us to

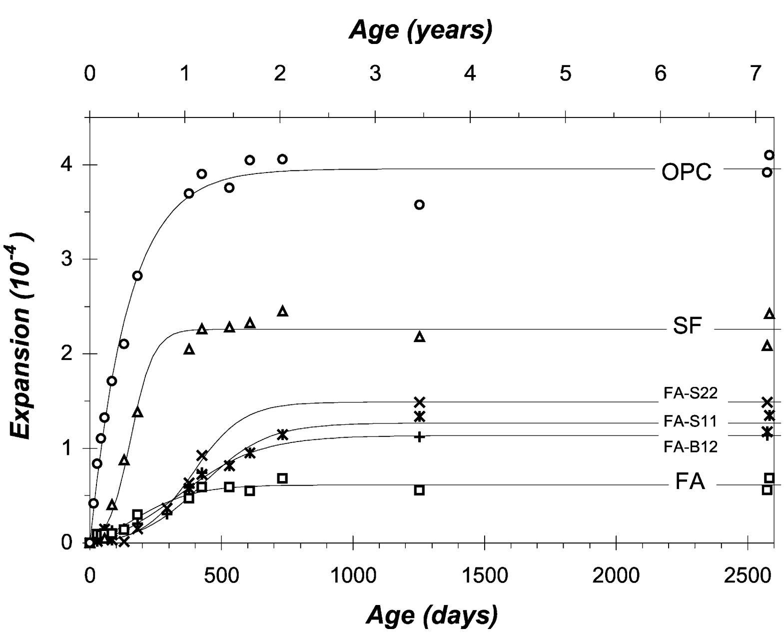


Fig. 8. Net expansion due to AAR of concrete prisms up to 7 years.

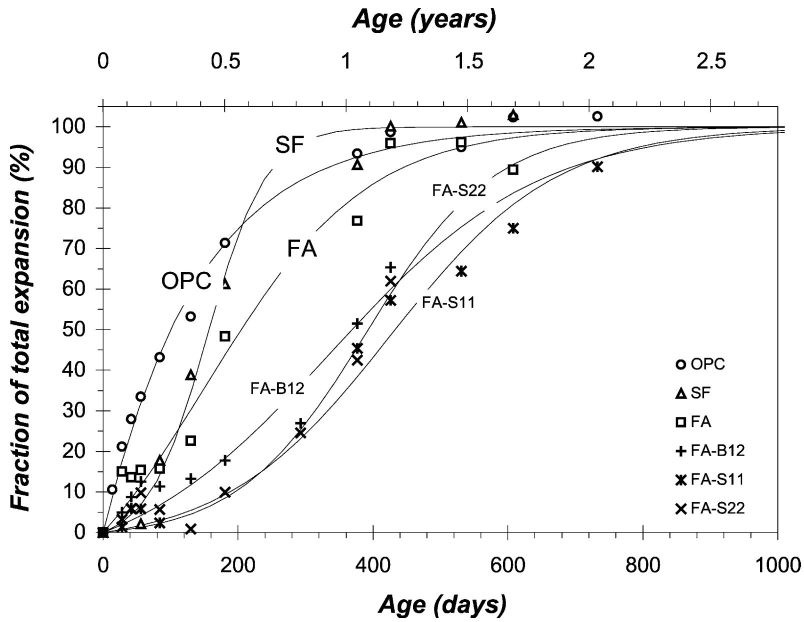


Fig. 9. Relative expansion due to AAR (60 °C test).

suppose that at least a part of the swelling was caused by AAR [28].

The analysis of the expansion curves suggests a separation of the total swelling into two phases [28]: a first phase due to AAR (Fig. 8) and a second phase due to a non-AAR phenomenon called primary expansion. Since little information is available about its evolution in the first few days of hydration of these concretes, the primary expansion (ε' in Eq. (1)) will be modeled by a straight line of slope K, equal to the final slope observed after 500 days.

Fig. 8 illustrates the net expansion curves due to AAR, after subtraction of the primary expansion. This figure shows that:

- the final expansion was reached in less than 2 years;
- the use of mineral additives led to a significant reduction of swelling, in the region of 50% for silica fume and 75% for fly ashes; these results are in accordance with those usually found in the literature.

In order to use β factors to predict the in situ behavior of concretes from the 60 °C tests, it is necessary to present the curves as fractions of the total expansion. Fig. 9 shows the time necessary to reach the different fractions of total expansion in the 60 °C tests.

In the next step of processing of experimental data, the values of factor β_4, linking in situ behavior to 60 °C tests, were obtained by multiplying factors β_2 and β_3 together (Table 7). With these calculated values of β_4, it was possible to transform the data of Fig. 9 into a normalized age, which could be expected for the in situ structure. The results are presented in Fig. 10 for the six concretes studied here.

Fig. 10 requires the following remarks (if we consider that the beginning and completion of AAR, expansion are assimilated to the values of 10% and 90%):

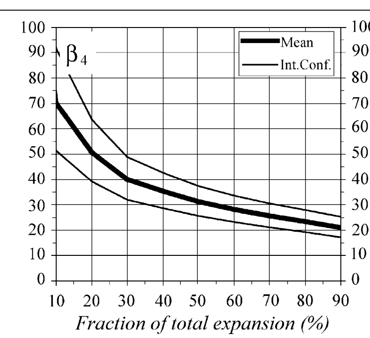
(i) The duration of the in situ AAR expansion of OPC concrete (without admixture) should be between 2 (10% of $\varepsilon_{AAR}^{\infty}$) and 23 years (90% of $\varepsilon_{AAR}^{\infty}$).

(ii) For the concretes studied, the use of silica fume or fly ashes strongly delays the beginning of swelling.

(iii) Silica fume, although it decreases the total AAR swelling, does not seem to delay the end of the reaction whereas all fly ashes both decrease final expansion and delay the end of the reaction. Moreover, the treatments for selection (FA-S11 and FA-S22) and grinding (FA-G12) of fly ashes enhance their retarding effect.

Table 7
Calculation of factor β_4 from factors β_2 and β_3 (confidence interval α=.10)

Fraction of total expansion (%)	38 °C–60 °C β_2	x	i.s.–38 °C β_3	=	i.s.–60 °C β_4
10	5.4 ± 0.6		13.0 ± 2.2		70.2 ± 19.7
50	4.0 ± 0.3		7.8 ± 0.8		31.2 ± 5.5
90	3.4 ± 0.3		6.2 ± 0.6		21.1 ± 3.9



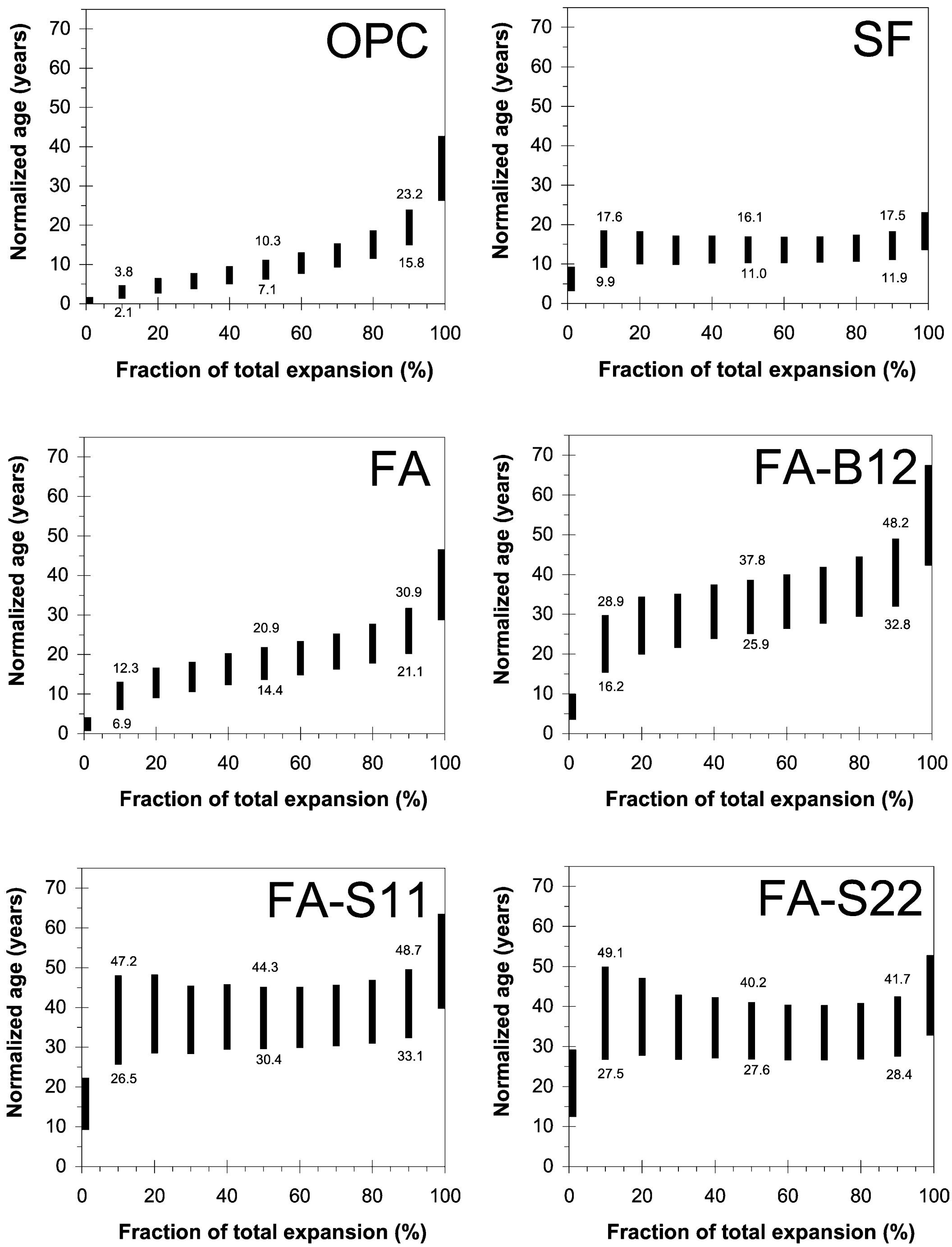


Fig. 10. Normalized age concept (equivalent time for field concrete) applied to our experimental results (tests performed at 60 °C).

(iv) The significant ranges obtained for some concrete mixes is related to the high uncertainty on factor β_4. This uncertainty is caused by the lack of experimental results connecting in situ to 60 °C storage conditions (this situation leads to the addition of the relative errors on β_2 and β_3) and by the strong variability of the in situ test results (as discussed earlier).

(v) The evaluation of the delay to reach the end of swelling could be of practical interest in the following case: at a real age t_{real}, it can be observed that a structure is affected by disorders due to AAR and it would be useful to know the approximate time (T) for which AAR will progress. If t_{final} is the real age for which the end of reaction will be reached, then this time can be calculated from a 60 °C test with the time corresponding to 90% ($t_{90\%}$) of the total expansion: $t_{final} = t_{90\%} \cdot \beta_4$ and $T = t_{final} - t_{real}$.

In order to avoid abusive use of β factors, which could lead to significant errors of interpretation, it is necessary to set some limits on their utilization.

• In some cases, the transformation of the whole expansion curve (laboratory) into an equivalent in situ curve leads to a contradiction (simultaneous beginning and completion of AAR swelling), caused by the uncertainty on β factors. In these cases, it is better to use the factors punctually, either to determine a protection delay ($\beta_{10\%}$) or to find the time remaining before the end of swelling ($\beta_{90\%}$). However, in the latter case, it is not possible to obtain the final value of the absolute expansion since the calculations are made for fractions of total expansion.

• β factors are not to be used without prior reflection on absolute time scales. In other words, it is impossible to affirm that a time X at 60 °C (e.g., 3 months, the standard time of the French test) corresponds in all cases to the same age $\beta \cdot X$ for in situ conditions ($\beta \times 3$ months for the example). Thus, for a given term at 60 °C, several normalized ages can be calculated, depending on the shape of the expansion curve analyzed. In our cases, the 3-month's test duration corresponds, for the OPC concrete, to 6–9 years in situ (at 3 months, 40% of the total expansion has been reached, which represents 6–9 years in normalized age, as shown in Fig. 10). For other concretes, different values are obtained: SF (11–18 years), FA (9–14 years), FA-S11 (14–27 years), FA-S22 (20–38 years) and FA-G12 (17–29 years).

4. Conclusion

This paper exposes a method for assessing normalized age factors, which relate accelerated tests performed at various temperatures (20, 40 and 60 °C) to in situ conditions encountered in real structures.

This concept of normalized age is not intended to provide better knowledge of the AAR phenomenon. Its aim is simply to give useful information to engineers and researchers wishing to evaluate the correspondence between the time scales of laboratory tests and the in situ behavior of concrete.

The evaluation of normalized age factors that we propose is based on the comparison of many experimental results concerning laboratory tests and in situ measurements. In order to increase the degree of confidence in these factors, more experimental results are needed, especially for in situ conditions. Moreover, it would be interesting to obtain experimental results for temperate and hot climates.

These factors are used to evaluate, from the results of an accelerated test performed at 60 °C, the protection time against AAR that could be expected for in situ concretes containing mineral admixtures (silica fume and fly ashes). This evaluation allows us to complete the traditional conclusions generally obtained from expansion curves for concrete containing mineral admixtures, i.e., their use strongly decreases the final value obtained for swelling caused by AAR. In the present case, the decrease reaches up to 50% for silica fume and 75% for fly ashes. The results also show that the duration of protection against abnormal expansion caused by AAR is significantly prolonged when mineral admixtures are used since the abnormal expansion (related to a swelling of 10% of the total expansion) is expected at 2–4 years for plain concrete compared to 7–50 years for concrete with mineral admixtures.

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