Pergamon

Cement and Concrete Research 32 (2002) 691–700

CEMENT AND CONCRETE RESEARCH

Interpretation of expansion curves of concrete subjected to accelerated alkali–aggregate reaction (AAR) tests

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Received 25 June 2001; accepted 16 November 2001

Abstract

The examination of several long-term expansion results for concretes subjected to accelerated alkali–aggregate reaction (AAR) tests shows that, in some cases, the expansion continues for a long time after AAR has stopped. For these cases, all the concrete swelling is certainly not only caused by AAR, and the continuation of the expansion probably reveals the swelling behavior of concrete when it is conserved in saturated moisture conditions. Considering that this swelling is not negligible compared to the limit expansions fixed by standard AAR tests (2×10^{-4} at 90 days for the French performance test), it becomes important to evaluate it in order to avoid the inappropriate rejection of an aggregate. © 2002 Elsevier Science Ltd. All rights reserved.

Résumé

L'exploitation de plusieurs résultats à longue durée de gonflement des bétons soumis à des tests accélérés d'alcali-réaction montre que, dans certains cas, l'expansion continue bien après que l'alcali-réaction ait stoppé. Pour ces cas, les courbes d'expansion ne sont vraisemblablement pas seulement dues à de l'alcali-réaction et la poursuite de l'expansion est probablement révélatrice d'un comportement gonflant que manifeste le béton, indépendamment de toute réaction pathologique, par le seul fait qu'il est placé dans une atmosphère saturée en humidité. Dans la mesure où cette composante n'est pas négligeable par rapport à la valeur seuil de gonflement d'un essai réglementaire d'alcali-réaction (2×10^{-4} à 90 jours dans le cas de l'essai performance béton français), il devient alors important de l'évaluer afin d'éviter le rejet inapproprié d'un granulat. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Concrete; Alkali–aggregates reaction; Expansion; Accelerated tests

Mots-clés: Béton; Réaction alcali–granulats; Expansion; Essais accélérés

1. Introduction

For many years, potential disorders due to alkali–aggregate reaction (AAR) in concretes have been evaluated by measuring longitudinal expansion of concrete prisms stored in environmental conditions favoring the acceleration of the reactions. This is particularly the case for many concrete tests performed at 38 °C or 60 °C and 100% relative humidity (RH) (CAN/CSA A23.2-14A in Canada, P18-587 and P18-454 in France).

These accelerated tests, carried out in several countries, differ in many ways: specimen shapes, temperature and duration of the test, maximum expansion limit for a given age, etc. On the other hand, they all have in common the idea that the expansions measured on concrete prisms are only related to AAR.

This paper originated from questions arising during the interpretation of accelerated AAR tests for concretes made with reactive aggregates and containing a mineral admixture. These tests were performed for much longer than the period recommended by the French standard (3 or 5 months). The tests notably showed residual expansions in concretes, while some signs led us to suppose that AAR was completed. Since the analysis of our own experimental curves was not sufficient to provide an understanding of the origin of this

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PII: S0008-8846(01)00747-5

residual expansion, many results from the literature, presenting similar curve shapes, were used.

This paper does not claim to explain the physical mechanisms of all types of expansion occurring in concretes; its scope is to demonstrate, with the help of our experimental results and of abundant literature results, that expansion is not only due to AAR. Moreover, it could be unwise to neglect the non-AAR part of expansion in accelerated tests since it is probably caused by well-known phenomena that, like AAR, also lead to dimensional changes in concrete.

2. Experimental conditions

2.1. Materials

The cement used was an ordinary Portland cement (CPA HPR, according to French standard P15-301 in use in 1992), the properties of which are given in Table 1. The mineral additive used was a silica fume (Table 1) and its replacement rate was 10% of the cement mass.

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

High-performance concretes were made with a constant slump of 16 cm, a water/binder ratio of 0.36 (reference: Ref-R) and 0.38 (silica fume: SF-R), 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 2.

2.2. Experimental procedure

Concretes were made, stored, and tested according to the specifications 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» [1]. This test consists in evaluating the performance of a concrete with respect to AAR by measuring its expansion on 7 × 7 × 28 cm prisms, stored at 60 °C and 100% RH.

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

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, which were kept in the reactor at 60 °C until the next measurement.

Table 1
Physical and chemical properties of cement and silica fume

	Cement	Silica fume
Specific area (m^2/kg)	430	–
SiO_2	20.2%	90.8
Al_2O_3	5.0	0.5
Fe_2O_3	2.7	0.1
CaO	64.4	tr
MgO	1.3	0.3
K_2O	0.9	0.5
Na_2O	0.06	0.4
Na_2O eq	0.65	0.73
SO_3	3.3	–
LOI	2.1	3.3
Minerals	C_3S: 61%	Glass
	C_2S: 8%	
	C_3A: 9%	
	C_4AF: 8%	

Table 2
Concrete mix design (1 m^3)

Concretes	Ref-R	SF-R
Cement (kg)	475	430
Silica fume (kg)	0	45
Sand (kg)	776	773
Coarse aggregate (kg)	1071	1067
Water (l)	162	171
Superplasticizer (kg)	15.7	15.7
Alkali content (kg/m^3)	3.7	3.4
Water/binder	0.36	0.38
Water/cement	0.36	0.42

3. Experimental results and discussion

3.1. Short-term and long-term results

The expansion results for REF-R and SF-R concretes during the first 6 months of conservation at 60 °C are given elsewhere [2]. According to French standard, only the REF-R concrete is qualified as reactive since the limit of 0.02% (2×10^{-4}) is reached at 3 months and then largely exceeded. In accordance with regulations, the expansion curve of SF-R concrete leads this concrete to be characterized as nonreactive.

Figs. 1 and 2 give the expansion curves of the two concretes up to 7 years, while Figs. 3–5 show the external (Fig. 3) and internal (Fig. 4) aspects of 7-year-old prisms, and the microscopic (SEM) morphology of AAR gels (Fig. 5).

Fig. 1, which gives raw expansion measurements, shows that swelling continues, as far as the last measurement, up to 7 years. Expansion curves can roughly be divided in two phases (Fig. 2), each one being characterized by a nearly constant rate of swelling (the mass gain continues even in the second phase). The relative importance of these two phases is variable. Thus, in our case, the swelling part of the second phase is as significant as the swelling of the first phase. These results can be related to the weak expansions

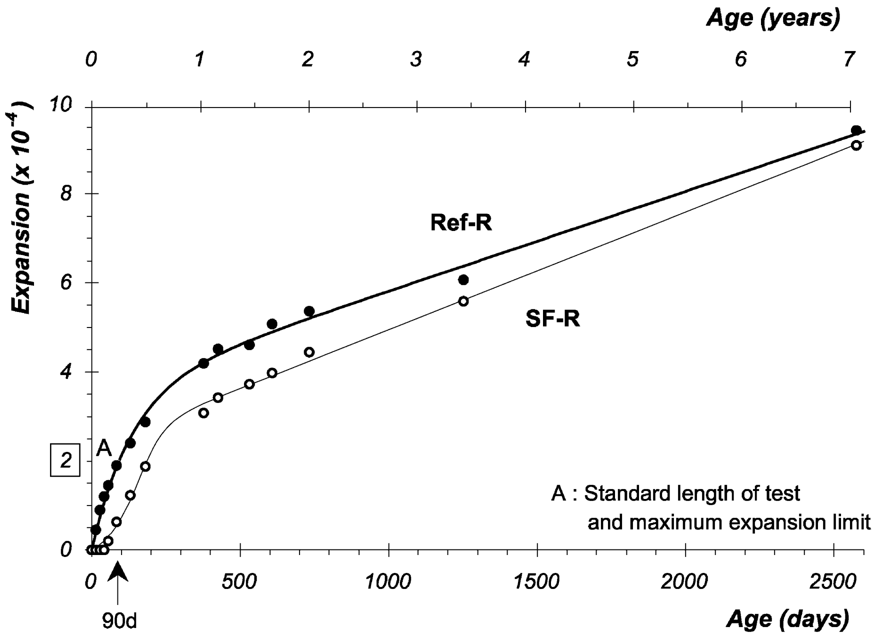

Fig. 1. Expansion of concrete prisms up to 7 years.

obtained in Phase I, compared to higher expansions found by other researchers (see, for example, Fig. 7, which presents results from Duchesne and Bérubé [3]).

This paper will try to answer the questions raised by the existence of two expansion phases:

- is AAR responsible for these expansions?
- can all the swelling be attributed to AAR?

3.2. Can AAR be responsible for concrete swelling?

Primary visual observation of concrete prisms (Fig. 3), after 7 years of conservation at 60 °C and RH > 95%, indicates a probable occurrence of AAR since the external faces show the characteristic patterns of this kind of disorder: a crack network in paste and aggregates, from which white reaction products emerge.

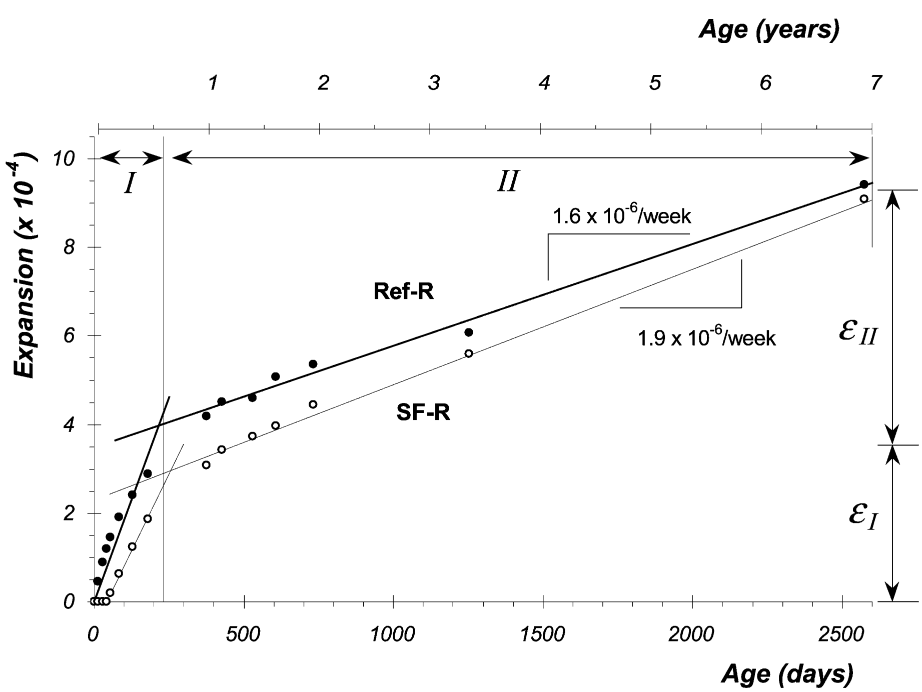

Fig. 2. Separation of expansion curve in two distinct phases.

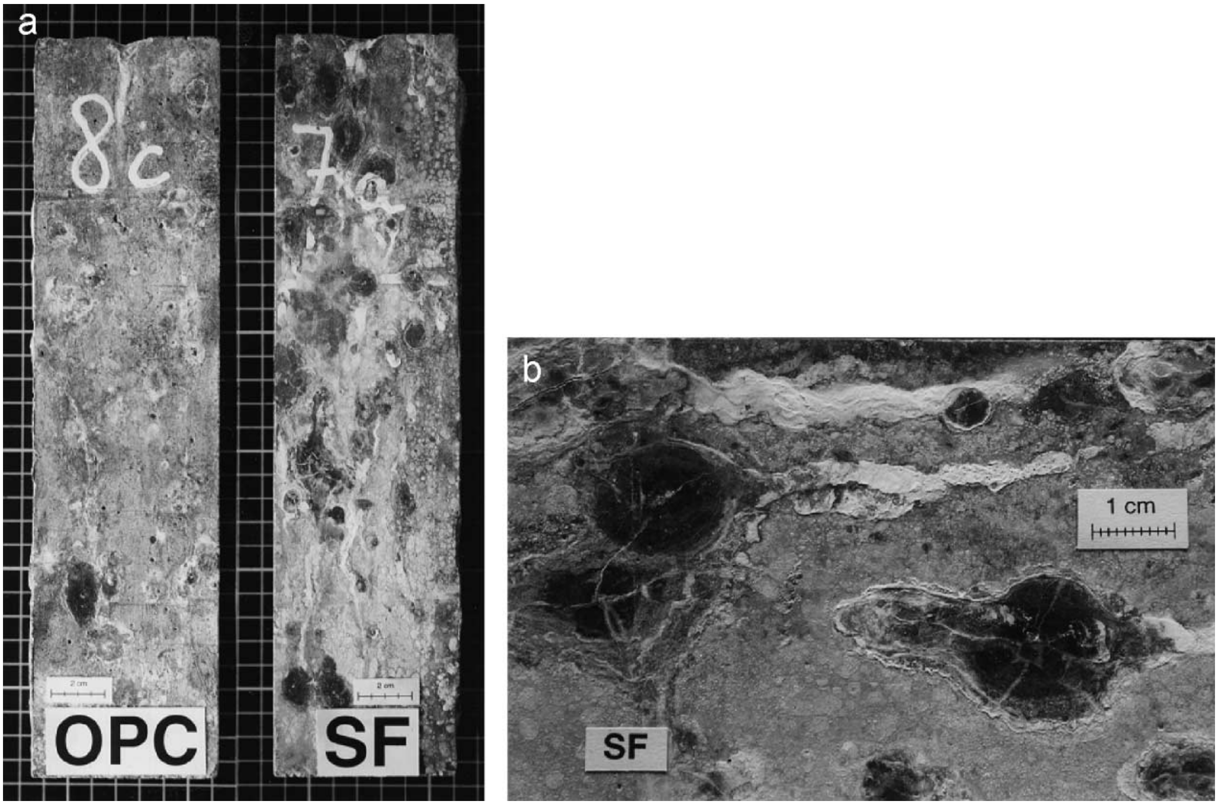

Fig. 3. (a) External aspect of concrete prisms after 7 years of conservation at 60 °C and RH > 95%. (b) External face of a prism affected by cracks and exudations.

Fig. 4 shows the fracture surface of a concrete prism: this rupture occurs on an existing crack (in paste and aggregates) covered by white gel. Many aggregates are fractured and exhibit the classic dark reaction rim at their periphery.

Fig. 4. Break surface of a concrete prism, showing white gel and classic dark reaction rim around some aggregates.

SEM observations, coupled with EDX analysis, confirm that all concretes are affected by AAR. These observations show the abundant occurrence of alkali–silica gels and various crystallized species, as can often be found in literature (Fig. 5).

All these observations lead us to conclude that AAR is present in all concrete prisms and is responsible for a part of the total expansion.

3.3. Is all the swelling related to AAR?

It is commonly assumed that the expansion curve of a concrete prism affected by AAR, the general form of which is represented in Fig. 6 (curve 1), can be characterized by three successive phases: an initial phase where swelling begins (OA), followed by a phase of significant expansion at a nearly constant rate (AB), and ended by a decrease in

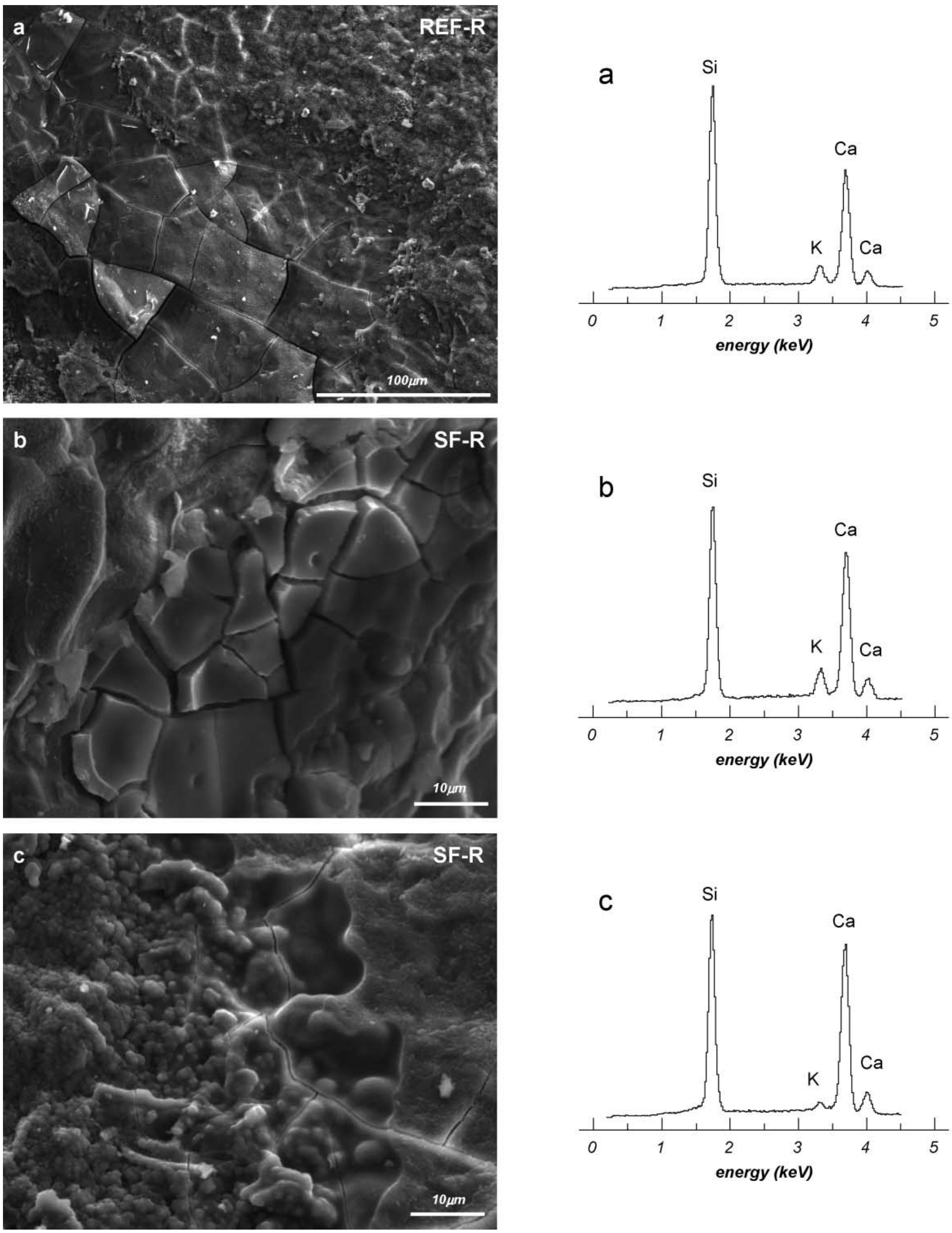

Fig. 5. SEM and EDX of concretes, showing classic AAR gels. (a) Ref-R concrete; (b) and (c) SF-R concrete.

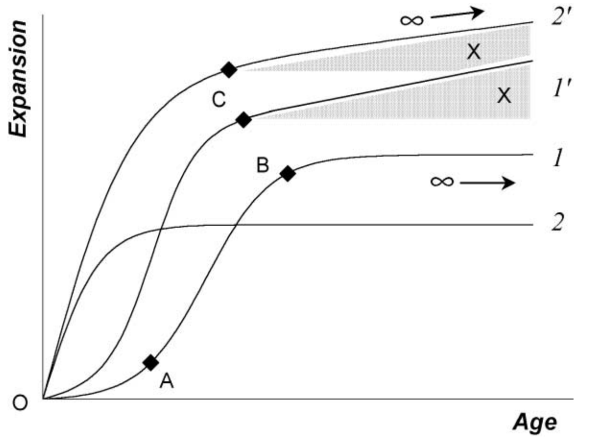

Fig. 6. Typical expansion curves of concretes affected by AAR. X: visible part of expansion characterized by phenomenon independent of AAR.

the expansion rate to reach a final plateau (B∞). Another form of expansion curve is also found (curve 2 of Fig. 6), where the initial phase is not clearly separated from the expansion phase.

This interpretation of the AAR expansion phenomenon seems to be confirmed by in situ observations, as argued by Nielsen [4]: "however the curves always finish horizontal." Generally speaking, this interpretation is used for numerous models proposed by authors such as Larive [5] or Capra et al. [6], who give expansion curves ended by a plateau.

Nevertheless, our curves clearly present other forms (curves 1′ and 2′ shown on Fig. 6). They start like curves 1 and 2 (Fig. 6) but end with a final slope different from zero. At first, these results do not seem to be in accordance with the results usually found, so they lead to a difficult problem of interpretation. An analysis of the literature would clarify this situation.

In actual fact, an extensive analysis of the long-term expansion curves reported by many authors shows that many of them are similar to curves 1′ and 2′ of Fig. 6. Table 3 gives the calculated approximate slopes for the terminal phase C∞, obtained from figures presented in other papers [3,5–24]. These calculations are based on a graphic evaluation on small figures, so they have an uncertainty of ± 10%.

Most of the papers mentioned do not take this final expansion slope into consideration (which is understandable only if the test is short). Nevertheless, a few authors point out this expansion and try to explain it.

Thus, according to Fournier and Malhotra [25], this final expansion is caused by marginally reactive aggregates that have been classified as nonreactive with respect to the expansion limit at 1 year (concrete prism test CSA A23.2-14A). For Ramlochan et al. [8], "the implication of this long-term persistent expansion in the CAN/CSA A23.2-14A concrete prism test on field concrete under normal service conditions is unclear."

It can be concluded that:

- in the literature, there are many examples of expansion curves of concretes with and without mineral admixtures in which swelling continues linearly for many years, especially in accelerated tests;
- this swelling behavior is observed while some indications, like concrete pore solution analysis, show that AAR has been completed [3].
- this swelling is seldom mentioned and never explained.

This analysis leads us to think that the final expansion is related to one or many physical phenomena that are not directly linked to AAR.

3.4. Possible causes of non-AAR dimensional changes

There are several physical or chemical causes leading to dimensional changes in concrete. These dimensional changes can notably be related to storage conditions (RH, temperature) or to cement and admixture reactions (hydration or secondary reactions like delayed ettringite formation). Among these causes, some are more able to affect concrete exposed to conditions such as those of AAR accelerated tests.

Table 3
Final expansion rates of alkali–aggregate-reactive concretes

Reference	Concrete properties	Final slope (10^{-6}/week)	Test conditions	Test time (years)
Duchesne and Bérubé [3]	Spratt aggregate and rhyolitic tuff (42 mixes)	0.9–1.7	38 °C, 100% RH	9
Fournier et al. [7]	Rg aggregate	1.5	38 °C, 100% RH	3.5
	NM aggregate	1.7		
Ramlochan et al. [8]	Spratt aggregate	3.3	38 °C, 100% RH	2
	Spratt with metakaolin	1.2		
	Sudbury aggregate	6.1		
	Sudbury with metakaolin	1.2		
Rogers et al. [9]	Mix 6, hapc	0.4	38 °C, 100% RH	8
	Mixes 2, 3, 4	0.5		
Durand [10]	18 mixes	2–6	23 °C, 100% RH	3.5
Thomas et al. [11]	Flint aggregate	1.9	38 °C, 100% RH	4.5
	Gneiss aggregate	3.5		
Our values	Ref-R	1.6	60 °C, 100% RH	7
	SF-R (silica fume)	1.9		

Other similar results can be found in the literature: see, for example, Refs. [5,6,12–24].

Thus, the analysis of some papers (not always from AAR studies) allows us to propose an explanation for the final swelling phase observed for some expansion curves. This is the case for Duchesne and Bérubé [3], who measured the expansion of concrete prisms (according to CAN/CSA A23.2-14A) for up to 9 years and analyzed the corresponding pore solution. They studied several mixtures, including: two cements (high and low alkali), two reactive aggregates, and six mineral admixtures. Fig. 7 summarizes most expansion curves supplied in their paper. It appears that, in nearly all cases, the expansion rate slows down between 1 and 1.5 years and then reaches a pseudo plateau. It can be seen that, independently of the total expansion reached in Phase I, the expansion rate of Phase II is almost constant and significant: it ranges from 0.9 to 1.7×10^{-6}/week.

An attentive analysis of the literature shows that it is not so unusual to find expansion curves for nonreactive concretes, as reported in Fig. 8. For these concretes, made with inert aggregates (no AAR detected, as written by authors), it can be seen that the expansion curves exhibit final slopes (Fig. 8 and Table 4) that are similar to those calculated for reactive concretes (Table 3). These results tend to show that a fraction of the expansion is not imputable to AAR.

Therefore, we suppose that one of the possible causes of the expansion slope observed in Phase II is related to the ambient conditions when the concrete is maintained in a hot and saturated atmosphere (38 or 60 °C, RH > 95%). In other words, it could be a question of the well-known dimensional behavior of concrete: shrinkage in air and swelling in water. Moreover, it is surprising that, in most cases, this phenomenon is not explicitly mentioned in papers devoted to AAR.

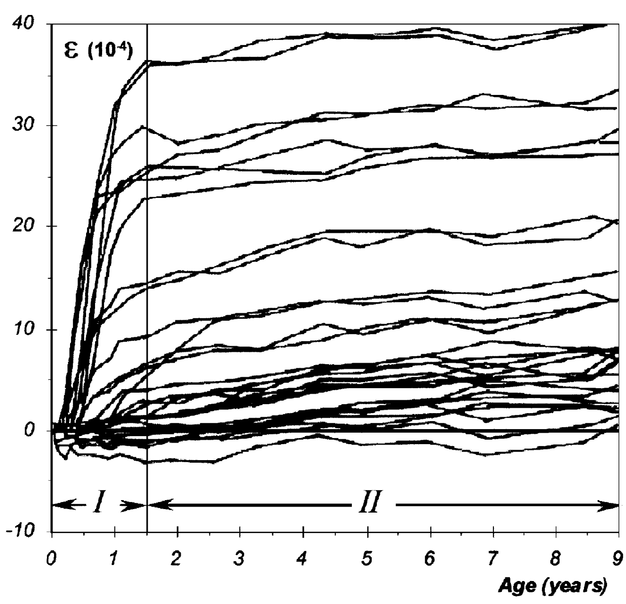

Fig. 7. Expansion curves of all concrete of Duchesne and Bérubé paper [3], showing a terminal phase (II) in which swelling continues.

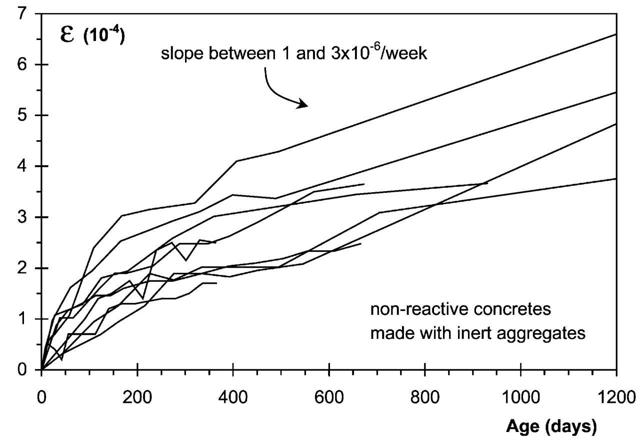

Fig. 8. Examples of expansion curves of nonreactive concrete, made with inert aggregates, after Refs. [10,26–29].

In fact, only a few authors set out to consider the part of this "primary" expansion in their calculations of the net

Table 4
Final expansion rates and final expansion of nonreactive concretes

Reference	Concrete properties	Final slope (10^{-6}/week)	Expansion (end of test)	Test conditions
Durand [10]	five nonreactive concretes (limestone, granite, nepheline syenite)	1.5–2.5	$4–7 \times 10^{-4}$ at 3.5 years	38 °C, 100% RH
Bakharev et al. [24]	two concretes (nonreactive aggregates)	0.6	0.8×10^{-4} at 1.7 years	38 °C, 100% RH
		1.3	3×10^{-4} at 1.7 years	38 °C, 100% RH
Durand [26]	St-Jacques aggregate (limestone)	1.0	3.7×10^{-4} at 2.5 years	38 °C, 100% RH
Play [27]	Nonreactive concrete (inert limestone)	2.2	1.7×10^{-4} at 1 year	60 °C, 100% RH
Pleau et al. [28]	Limeridge (limestone)	1.3	2.5×10^{-4} at 1.8 years	23 °C, 100% RH 38 °C, 100% RH
		2.7	3.7×10^{-4} at 1.8 years	38 °C, 100% RH
Tomosawa et al. [29]	Nonreactive concrete	3.1	2.5×10^{-4} at 1 year	40 °C, 100% RH
Miyazawa and Tazawa [30]	W/C = 0.20 and 0.30	[a]	3×10^{-4} and 1×10^{-4} at 1 year	20 °C, 90% RH
Dahl et al. [31]	two concretes (greenstone and granite aggregates)	[a]	1×10^{-4} at 1 year	38 °C, RH >95%

[a] Slopes are difficult to measure on these curves.

AAR expansion. These authors suggest subtracting the primary expansion part obtained in the first days of the test, but rarely in the long term. This is the case of Jones and Poole [32], who consider that sharp initial expansion during the first 2 or 3 days is due to moisture uptake and thermal adjustment, and of Mukherjee and Bickley [33], who subtract the first 7 days of expansion. Finally, we should mention Olafsson [34], who corrects his expansion values for concrete shrinkage.

3.5. Significance of non-AAR dimensional changes

Considering that several phenomena can explain the expansions observed in concrete prisms, it becomes necessary to evaluate the fraction of the total expansion which is independent of AAR. If this fraction is negligible, then it is not necessary to continue the research along these lines. On the other hand, if the primary expansion is not negligible, it will be necessary to study the effect of mix design parameters and of concrete storage on the part of swelling independent of AAR, called "primary expansion" here.

The evaluation of this primary expansion requires several parameters to be taken into account. The main ones, as mentioned in the literature, concern the mix design parameters (water/binder ratio [30], aggregate properties (stiffness and reactivity) [35], the presence of mineral admixtures and additives [36]) and the test parameters (RH [30,37], test temperature [38,39], sample shape and dimensions [40]). Since there are many parameters to consider, it seems difficult to predict all cases and the relative significance of each one.

To correctly separate the primary expansion from that related to AAR, it appeared necessary to study different concretes containing nonreactive aggregates. Since the expansion measurements of our own nonreactive concretes had been stopped at 6 months, we needed to use results from the literature, mainly those of Play [27], to obtain a correct estimation of primary expansion. These results concern concrete made with certified nonreactive aggregates and stored for up to 1 year in a reactor at 60 °C and 100% RH.

Fig. 9, which displays the expansion range of reactive concretes compared to the expansion curve of the nonreactive concrete, shows that primary expansion of nonreactive concrete first follows a power law for a few weeks (expansion reaches about 0.4×10^{-4}), then progresses at a constant rate of 2.2×10^{-6} per week. At 90 days, the primary expansion (point A on Fig. 9) reaches 0.7×10^{-4}, representing 35% of the limit value (2×10^{-4}, point B on Fig. 9) that separates reactive and nonreactive concretes (Section 3.1).

In short, it does not seem realistic to neglect the primary part of the expansion of a concrete subjected to an AAR accelerated test, since this non-AAR expansion could reach nonnegligible values compared to the expansion limit fixed by standards. This observation is confirmed by the results shown in Table 4, which gives the total expansion obtained

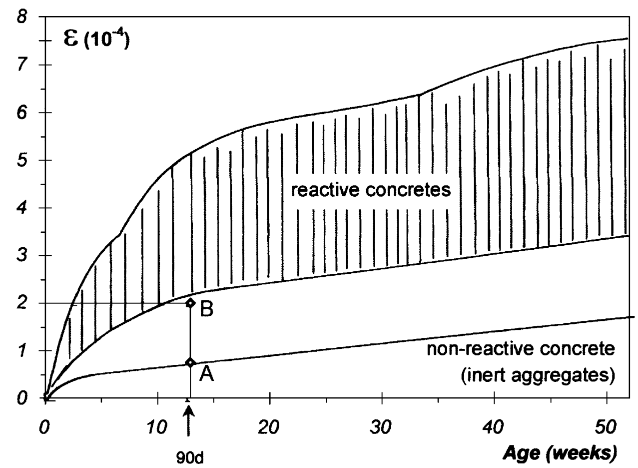

Fig. 9. Comparison between expansion of nonreactive and reactive concretes, after Play [27].

on several non-alkali–aggregate-reactive concretes found in the literature.

This behavior, which has been underlined by a long-term nonstabilized expansion, is also important for short-term measurements, since the primary phenomena of shrinkage and expansion start rapidly. It can greatly affect short-term total expansion, thus distorting the classification of a concrete since, in accelerated tests (like the French test P 18-454), it is the 3-month expansion that is used to state whether a concrete mix is considered as reactive or not.

4. Conclusion

Many long-term expansion results (from our own experiments and from the literature) for concretes subjected to accelerated AAR tests show that, in some cases, the expansion continues for a long time after AAR has stopped.

For these cases, the overall concrete swelling is certainly not only caused by AAR, and the expansion continuation probably reveals the swelling behavior of concrete when it is placed in saturated moisture conditions. Considering that this part of swelling, named the primary expansion, is not negligible compared to the limit expansions fixed by standard AAR tests (2×10^{-4} at 90 days for the French performance test), it becomes important to evaluate it in order to avoid a wrong interpretation of the laboratory test.

Thus, since the primary expansion is not characteristic of AAR and may not occur in field conditions (temperature between 15 and 20 °C and RH < 90% in temperate climates), the calculation of primary expansion could allow for some cases to avoid the inappropriate rejection of an aggregate that does not present any true risk for structures. This problem, which has significant economic consequences for the construction industry, has already been pointed out by concrete producers [41].

In order to separate the non-AAR part of the total expansion, it is necessary to understand the behavior of concrete conserved at high temperature in saturated conditions. This will be the subject of future work, the first part of which will be to propose a formal mathematical expression for an expansion curve.

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