



Swellings due to alkali-silica reaction and delayed ettringite formation: Characterisation of expansion isotropy and effect of moisture conditions

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ABSTRACT

This paper investigates the effect of different conditions on the development of concrete expansions due to alkali-silica reaction (ASR), delayed ettringite formation (DEF) and their combination. The presence of products of the two reactions has been observed during structure diagnosis. The aim of this research is to study the two reactions in concretes with close mix designs but with various types of aggregate and moisture conditions. Measurements performed in the three directions of stress-free specimens showed that DEF expansions could be considered as isotropic for stress-free material. DEF expansions were largely influenced by the storage conditions (immersed in water or in sealed conditions). The volume of storage water modified the kinetics. Under sealed conditions, no expansions were measured for mortar containing non-reactive aggregate, while small positive strains were obtained for mortar containing reactive aggregate. In all cases, new water supply caused fast, large expansions. The different effects of alkali leaching and moisture conditions on DEF and ASR expansions are discussed.

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1. Introduction

Alkali-silica reaction (ASR) and delayed ettringite formation (DEF) are endogenous chemical reactions that take place in concrete structures and can cause severe cracking. ASR and DEF occur under specific conditions. ASR results from the attack of reactive silica by hydroxyl ions, which lead to the formation of gels in presence of alkali and calcium. The chemical reactions leading to DEF occur between several ionic species available in the concrete pore solutions when the preliminary ettringite has been inhibited by high temperature (higher than 60–70 °C). Environmental (moisture and temperature) conditions also have important consequences on the development of these two reactions. The products of the two reactions lead to expansion, causing degradation of the concrete, particularly in civil engineering structures subjected to wet environments such as dams, massive bridge parts railroad sleepers and prestressed units. Each reaction and, sometimes, the combination of the two reactions have been observed during structure diagnosis [1–6] and investigations have been performed, leading to several proposed theories concerning the effects of each reaction on the other [5–13]. The reassessment of structures damaged by ASR, DEF or by a combination of the two reactions needs models able to take account of the different parameters acting on the expansions. Particularly, anisotropy of

ASR stress-free expansion has already been shown [14–16]. For ASR, the largest expansion is measured in the direction parallel to casting. It can be explained by the migration of ASR products in the porosity close to aggregate which can be mainly horizontal due to concrete consolidation during the casting. It allows the transfer of gel from the aggregate to the porosity perpendicular to the casting direction and thus an increase of expansion in the casting direction. This phenomenon is important to analyse expansion measured on cores drilled from structures. Indeed, swellings during residual expansion tests are measured in the longitudinal direction of cores. If the swelling is anisotropic, it could lead to under or over estimation of the concrete residual expansion. DEF products are crystallized and according to the place of their crystallization (in the porosity close to the aggregate or randomly in the porosity of the cement paste); it can lead to anisotropic or isotropic expansion. Therefore, it is necessary to be aware of the different parameters describing expansion, such as isotropy or anisotropy, or acting on expansion, such as the effects of aggregate nature and moisture conditions in order to develop a relevant structural reassessment methodology.

The aim of this research is to study the two reactions in concrete with close mix designs but with different aggregate natures and moisture conditions (Table 1). Four aggregates were used: two non-alkaline reactive sands and two reactive ones (Tables 1 and 2). Some of the specimens were exposed to elevated-temperature curing (80 °C) preventing the formation of ettringite during the 24 h after casting (some of these specimens contained alkali

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Table 1

Test conditions (NRA: non reactive aggregate, RA: reactive aggregate, W/S: ratio between the volume of storage water and the volume of specimens, Var. cond: variable moisture conditions).

Mortar	Agg.	Cure (°C)	Conservation		Meas.
			Before 28 days	After 28 days	
NRA1_80°/W/S = 5/ batch 1	NRA	80	20 °C/ Endo.	38 °C/W/ S = 5	Long./ Trans.
NRA1_80°/W/S = 5/ batch 2	NRA	80	20 °C/ Endo.	38 °C/W/ S = 5	Long.
NRA1_20°/W/S = 5	NRA	20	20 °C/ Endo.	38 °C/W/ S = 5	Long./ Trans.
NRA2_80°/W/S = 5	NRA	80	20 °C/ Endo.	38 °C/W/ S = 5	Long./ Trans.
NRA2_20°/W/S = 5	NRA	20	20 °C/ Endo.	38 °C/W/ S = 5	Long./ Trans.
NRA1_80°/W/S = 2	NRA	80	20 °C/ Water	38 °C/W/ S = 2	Long.
NRA1_20°/W/S = 2	NRA	20	20 °C/ Water	38 °C/W/ S = 2	Long.
RA1_80°/W/S = 5	RA	80	20 °C/ Endo.	38 °C/W/ S = 5	Long./ Trans.
RA2_80°/W/S = 5	RA	80	20 °C/ Endo.	38 °C/W/ S = 5	Long./ Trans.
RA1_20°/W/S = 5	RA	20	20 °C/ Endo.	38 °C/W/ S = 5	Long.
RA2_20°/WC/S = 5	RA	20	20 °C/ Endo.	38 °C/W/ S = 5	Long.
RA1_20°/W/S = 2	RA	20	20 °C/ Water	38 °C/W/ S = 2	Long.
NRA1_80°/Var. cond.	NRA	80	20 °C/ Water	38 °C/Var. cond	Long.
RA1_20°/Var. cond.	RA	20	20 °C/ Water	38 °C/Var. cond	Long.
RA1_80°/Var. cond.	RA	80	20 °C/ Water	38 °C/Var. cond	Long.
NRA1_20°/Var. cond.	NRA	20	20 °C/ Water	38 °C/Var. cond	Long.

reactive aggregate to study the coupling of the two reactions). At the same time, the other specimens were stored at 20 °C (Table 1). The specimens were then subjected to several types of storage at 38 °C (Table 1): in a large volume of natural water, in a small volume of water and under sealed conditions after water saturation.

The experimental conditions are described first. The next two parts present the experimental results: measurements performed on specimens immersed in water (quantification of discrepancy and possible anisotropy of DEF expansions, ASR sensitivity of aggregate) and the measurements performed on specimens under various conditions of moisture and leaching. All the experimental results are then recapitulated and discussed with regard to the literature.

2. Experimental conditions

2.1. Materials

The mortar used in this study had already been investigated in previous experiments performed on DEF [17–19]. The chemical

Table 2

Chemical compositions of cement and aggregates (%).

	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	LOi
Cement	19.3	4.6	2.2	63.9	2.4	3.3	1.1	0.3	
NR siliceous aggregate (NRA1)	96.1	–	0.4	1.38	0.24	–	0.72	0.32	0.4
NR siliceous aggregate (NRA2)	92.2	3.7	1.1	0.1	0.08	0.21	0.01	–	0.56
Siliceous limestone agg. (RA1)	20.0	1.3	0.6	40.6	1.2	0.3	0.4	0.4	
Quartzite aggregate (RA2)	87.7	4.01	1.03	0.36	0.18	0.14	0.91	0.14	1.12

Table 3

Bogue analysis of the cement, total alkali content and ratio of SO₃ to the C₃A.

	Content and ratio
C ₃ S Bogue	60%
C ₂ S Bogue	9.1%
C ₃ A Bogue	9.7%
C ₄ AF Bogue	7.3%
Total alkali content (cement and added alkali)	2.4%
(SO ₃ cement)/C ₃ A Bogue	0.34
(Total SO ₃)/C ₃ A Bogue	0.49

Table 4

Particle size distribution.

Particle size (mm)	0.080	0.160	0.315	0.630	1.25	2.0
Passing (%)	0	12.8	32.3	66.7	79.8	100

composition and Bogue analysis of the Portland cement used is given in Tables 2 and 3. The water/cement ratio of the mortar was 0.55 and the sand/cement ratio was 3. As in the previous experiments, 3.1% of Na₂SO₄ was added to the mixing water. Four types of aggregates were used (Table 2): two aggregates were siliceous sands, which do not cause ASR expansion in concrete (NRA1 – composed of well-crystallized quartz grains) and (NRA2 – composed of homogeneous quartz grains having a well-defined extinction without rolling), one was a siliceous limestone potentially reactive in concrete (RA1 – petrographic observations showed the presence of chalcedony and microquartz enclosed in calcite grains and of large veins of quartz presenting high undulatory extinction), and the fourth was a quartzite aggregate potentially reactive in concrete (RA2 – this rock was mainly composed of heterometric quartz grains of sizes varying from less than 1 µm up to a few hundreds of µm, the presence of primary and recrystallised quartz grains, the former were irregular, showed undulatory extinction and were separated by an intergranular cement composed of microquartz and micas). The two non-reactive aggregates have already been studied in [18,19] and the two reactive ones in [20]. The two non-reactive aggregates were studied in order to analyse the sensitivity of DEF to aggregate nature independently of ASR. The chemical compositions of the four aggregates are given in Table 2. The aggregates were crushed and sieved to obtain the same particle size distributions (Table 4). The dimensions of the specimens were 40 × 40 × 160 mm. The potential anisotropy was studied for stress-free specimens. As for ASR, it could be caused by the effect of concrete consolidation due to casting conditions. In this study, the casting direction was perpendicular to the largest dimension.

2.2. Curing temperatures

After casting, some of the specimens were cured at high temperatures with the heat treatment used in previous studies [17–19]: 1 h at 20 °C, an increase from 20 to 80 °C in 4 h, a temperature of 80 °C maintained for 10 h, then cooling to 20 °C in 10 h (Fig. 1). The specimens were steamed in metal moulds, wrapped

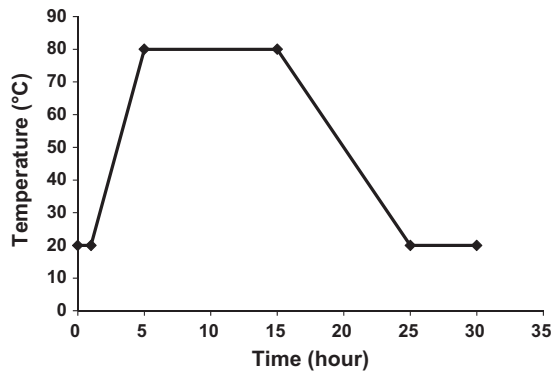


Fig. 1. Heat treatment.

in watertight plastic film and covered by a metal plate to prevent evaporation of water during the heat treatment. At the same time, other specimens made in the same batch were stored at 20 °C (Table 1). For the study of expansion isotropy, some of the specimens were kept at 20 °C in endogenous conditions (sealed in plastic bags) for 28 days after demoulding (Table 1). It was necessary to obtain enough unsaturated material on which to stick the metallic studs used for the deformation measurement in the transversal direction. For the study on specimens kept in sealed conditions, other specimens were kept immersed in natural water at 20 °C for the 27 days following the heat treatment. The aim was to completely saturate the specimens and thus supply the maximum quantity of water for the formation of ettringite in specimens which were kept in sealed conditions at 38 °C after the curing period (Table 1).

2.3. Specimen storage

After 28 days, all the specimens were stored at 38 °C in order to accelerate the ASR and DEF expansions. Three storage conditions were used during this experimental program:

- in a large volume of natural water without renewal (the ratio between the volume of storage water and the volume of specimen was about 5 – Table 1),
- in a small volume of natural water without renewal ($W/S = 2$),
- in variable moisture conditions: first in sealed conditions (watertight aluminium) then, after 385 days, immersed in water for about 60 days, kept under aluminium again for about 150 days and finally immersed in water.

The specimens were kept vertically which avoided potential frictional restraint due to their self-weight.

2.4. Deformation measurements

One of the main objectives of this study was to verify whether stress-free DEF expansions were isotropic or anisotropic. The longitudinal deformations were measured between two stainless steel studs embedded at the ends of the specimens using a ball-extensometer (measurement length: 160 mm). The transversal strains were measured using an external ball-micrometer pointing on two stainless steel studs stuck on the lateral sides of the specimens (measurement length: 40 mm). For each specimen, two perpendicular transversal measurements were performed. Before the measurement, the specimens were cooled from 38 °C to 20 °C and the deformations were measured at 20 °C. At the same time, mass measurements were performed on the specimens. In the following figures, deformations and mass variations are the averages obtained on three specimens from the same batch.

3. ASR and DEF expansions in water

3.1. Mortars with non-alkali reactive aggregates

Fig. 2 shows the variations in mass and strain of specimens containing the two non-reactive aggregates (NRA1, NRA2). The specimens containing the NRA1 aggregate were obtained from two batches and stored in a large volume of water ($W/S = 5$ – Table 1). The expansion kinetics was slightly delayed for the specimens made with the other non-reactive aggregates NRA2 (the expansion reached 0.1% at about 85 days – Fig. 2b), but the final expansion of 2% was very close to the expansion obtained with the other non-reactive aggregate NRA1. The specimens were kept in endogenous conditions for the first 28 days. A mass increase corresponding to fast water absorption by the mortar was observed (between 1% and 1.5% during the first days of immersion – Fig. 2a). After the first measurement, the mass variations of the reference specimens were very small, while the specimens subjected to DEF presented very large mass increases (Fig. 2a). Fig. 3 shows the mean longitudinal and transversal strains measured on the specimens containing the same aggregates (NRA1 and NRA2). For all the specimens, DEF expansions were the same in the three directions throughout the experiment (Fig. 3).

All the specimens subjected to the heat treatment during the first day showed significant swelling (between 1.5% and 2% – Fig. 2b) and cracking due to DEF. The specimens from a given batch showed little scatter (coefficient of variation of about 10%). The kinetics appeared not to be modified by the batch (at about 60 days, the expansion already exceeded 0.1% for all the specimens with the siliceous aggregates NRA1 whatever the batch – Fig. 2b). However, the final expansions were different (1.5% for the second batch and 2% for the first one – Fig. 2b). Thus, the heterogeneity of DEF expansions obtained with measurements performed on specimens coming from

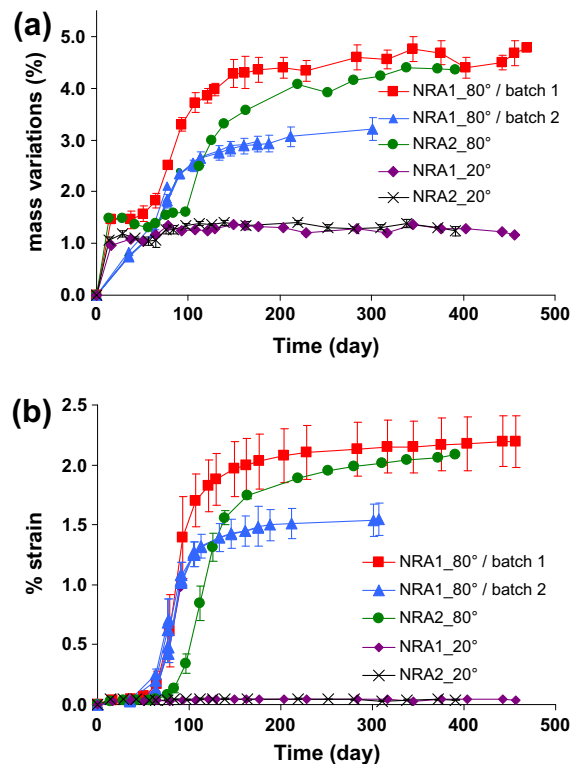


Fig. 2. Mass variations (a) and strain (b) of the specimens containing non-reactive siliceous aggregates in water (stored at 20 °C and 80 °C during the first day of endogenous curing).

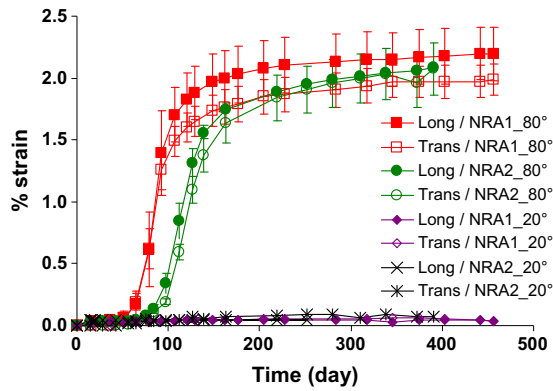


Fig. 3. Longitudinal and transversal deformations measured on specimens containing non reactive aggregates.

several batches for the same mix design and the same storage ($W/S = 5$) can be quantified by a coefficient of variation of about 30%, close to the heterogeneity observed for ASR expansions [14,15]. DEF expansion heterogeneity could be partly explained by the heterogeneity of porosity in the specimens, as part of the delayed ettringite could have been created in the porosity without contributing to expansion [21,22]. An absolute difference of 1% in porosity can thus lead to an absolute difference of more than 0.3% in expansion measured in one direction. This difference represents 20% for a final expansion of 1.5%. This shows how important it is to characterise DEF expansion on several specimens and always plot the scatter.

3.2. Mortars with alkali reactive aggregates

The mass variations and the deformations of the specimens containing the two types of potentially reactive aggregates (the siliceous limestone RA1 and the quartzite aggregate RA2) have been plotted in Fig. 4. Specimens stored at 20 °C for the first 24 h show small expansions (about 0.12% for RA1 and 0.05% for RA2 at 100 days) which can be induced by water absorption and ASR. The expansions of the specimens that had been subjected to the heat treatment during the first 24 h were fast and large in the three directions (Fig. 4b). They became greater than 0.1% between 50 and 65 days and reached a final expansion of 1.2% and 1.5% for both the longitudinal and the transversal strains of RA1 and RA2 respectively. After the first measurement, the mass variations of the specimens stored at 20 °C for the first 24 h were very small while the other specimens showed very large mass increases (Fig. 4a).

3.3. Characterisation of ASR and DEF expansions

The expansion of specimens subject to DEF varied linearly with the mass variations (Fig. 5) as already observed in [9,10]. In the present experiment, the slope was about 0.7 for mortars containing non-reactive aggregate (Fig. 5a) and around 0.6 for mortars containing reactive ones (Fig. 5b).

The kinetics of the expansions appeared to be quite similar for the four siliceous aggregates whatever the sensitivity to ASR (Fig. 6). The non-reactive aggregate NRA2 showed a slight delay compared to the other three aggregates. Final expansions lay between 1.2% and 2%. Mortars containing the non-reactive siliceous aggregates showed greater expansion (between 1.5% and 2%) than mortars containing the reactive aggregates (about 1.2% for the siliceous limestone and 1.5% for the quartzite aggregate). Previous studies have shown the effect of aggregate nature on DEF expansions [23–25] and particularly the effect of limestone aggregate, which decreases or slows down the expansion. The aim of the

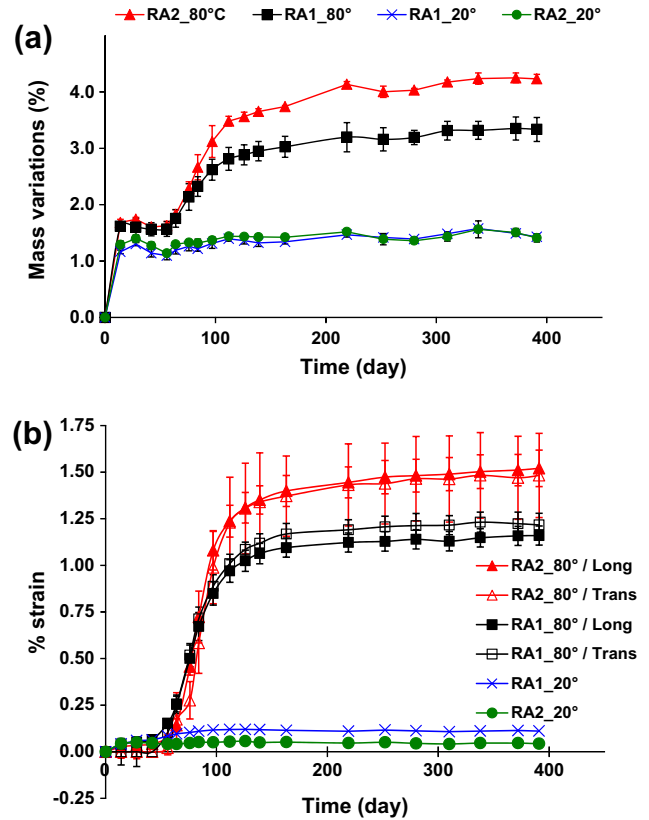


Fig. 4. Mass variations (a) and strain (b) of the specimens containing reactive aggregates (stored at 20 °C and 80 °C during the 24 first hours of curing).

study presented in this paper was to analyse the effect of the sensitivity of siliceous aggregate to ASR on DEF expansions. All the aggregates were totally or partly siliceous. In these conditions, no significant differences appeared during the measurements. It can be noted that the aggregate containing limestone showed the lowest expansions.

The isotropy of the expansions was analysed for mortars containing reactive and non-reactive aggregates. Strain measured in the longitudinal direction of the specimens is plotted versus strain measured in the transversal direction in Fig. 7. The relations between the deformations measured in the transversal and the longitudinal directions were perfectly linear during the whole experiment, with slopes lying between 0.9 and 1.1 for the four mortars (Fig. 7). Therefore, the measured stress-free expansions due to DEF were mainly isotropic and the casting direction did not modify expansion. These results were confirmed by specimens cracking: the cracks were randomly distributed for the DEF-damaged specimens while specimens only damaged by ASR showed oriented cracks perpendicular to their casting direction. In this study, ASR appears not to have influenced the cracking pattern in specimens containing reactive aggregate and showing large DEF-expansion following the heat treatment at 80 °C. However, when ASR and DEF occur together in a same structure, if ASR occurs first in the structure, the cracking pattern due to ASR can influence the following DEF-induced expansion and cracking.

4. Effect of various leaching and moisture conditions

In real structures, large sections of concrete are exposed to various conditions of leaching and moisture. The aim of this part is to complete the experimental knowledge of the effect of water on the ASR and DEF expansions according to the main roles of water: the

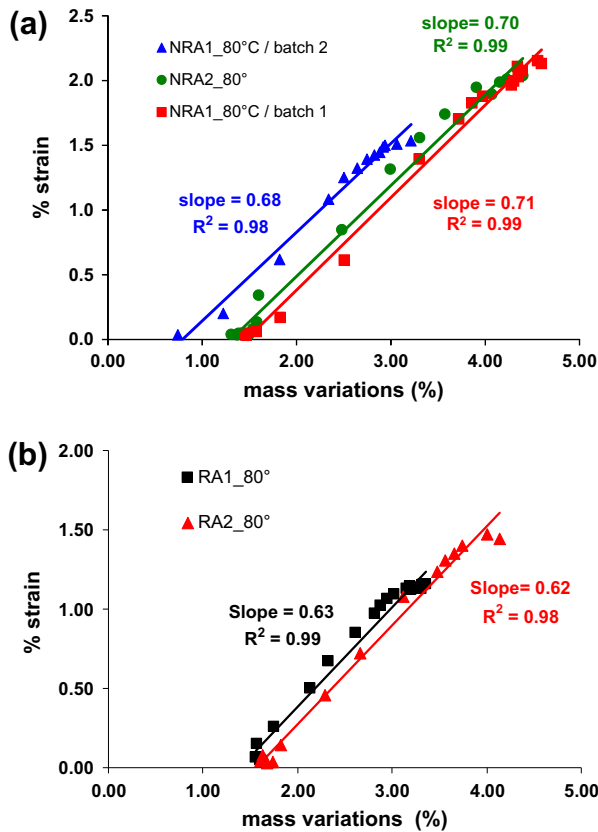


Fig. 5. Expansion according to the mass variations for the specimens containing non reactive aggregate (a) and reactive siliceous aggregates (b).

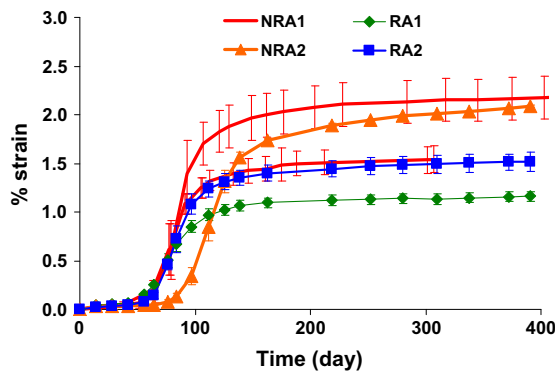


Fig. 6. Effect of aggregate nature on expansions.

transfer of the ionic species and the supply of water necessary to form ASR-gels and ettringite in significant quantities.

4.1. Effect of leaching due to water

The effect of leaching on ASR and DEF expansions was investigated on specimens containing the aggregates NRA1 and RA1 kept in two different volumes of water (ratios between the volume of water and the volume of specimen W/S equal to 2 and 5). The DEF expansions measured on the specimens stored in the small volume of water were strongly delayed compared to the expansions of specimens kept in the large volume of water (expansion reached 0.1% after 120 days of storage in the small volume versus 60 days in the larger one – Fig. 8). The ratio between the volume of

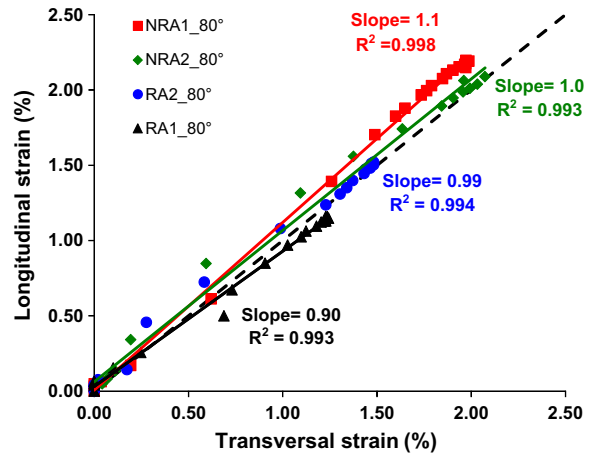


Fig. 7. Longitudinal strains according to the transversal strains for specimens submitted to ASR and/or DEF.

water and the volume of specimen thus had an important effect on the expansion kinetics. However, the difference of storage appeared not to modify the final expansion (about 1.5% – Fig. 8). No differences were observed for the specimens containing RA1 stored at 20 °C after casting. ASR expansions of about 0.12% were measured whatever the volume of storage water, with similar kinetics (Fig. 8). During this experiment, the difference of leaching had little effect on ASR final expansion while other experiments have shown a reduction of ASR expansion due to leaching [26]. This can be explained by the speed of ASR expansion. Leaching did not have time to modify ASR expansions because they were particularly fast for the mortar studied here. DEF expansions are significantly accelerated by leaching. The volume of storage water modified the leaching kinetics and, consequently, the expansion kinetics: when the volume of storage water was small, expansion was delayed but the effect on final expansion was small (Fig. 8). Storage water plays two roles. It allows the transfer of ionic species by diffusion and advection, and supplies water to form ASR gels and ettringite in significant quantities. The quantity of alkalis leached from specimens was higher in the large volume of water than in the small (unlike the small water volume, the large water volume leads to a strong alkali gradient between specimen and surrounding water and thus to greater alkali leaching). Thus, the development of DEF expansion was accelerated as already shown in [18,27–30].

4.2. Effect of variable moisture conditions

The four mortars mentioned in Section 4.1 (containing the potentially reactive RA1 and the non-reactive aggregates NRA1, subjected to heat treatment at 80 °C or stored at 20 °C for the first 24 h) were exposed to variable moisture conditions. After 27 days of curing in water at 20 °C in order to saturate the porosity, the specimens were kept at 38 °C:

- sealed for 385 days after saturation,
- then immersed in water (ratio $W/S = 2$) for 65 days,
- then under sealed conditions for 160 days,
- and finally immersed again in water to reach the final expansion.

The mass variations and the deformations of specimens kept at 20 °C after casting, immersed in water and kept under watertight aluminium at 38 °C after the 28 days of curing are plotted in Fig. 9. These specimens were kept in water during the curing. Thus,

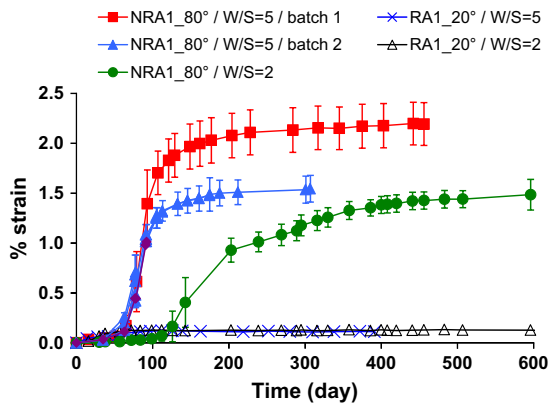


Fig. 8. Deformations measured on specimens kept in various water volume (W/S: ratio between the volume of storage water and the volume of specimens).

the mortar specimens immersed in water showed a small mass increase during the beginning of the measurement (about 0.2%, Fig. 9a, versus 1.5% for specimens kept in endogenous conditions during the curing, Fig. 2). Therefore, specimens were almost saturated, as expected, for the experimentation concerning DEF development in endogenous conditions (without external water supply).

For sealed conditions, the mass variations showed water losses which became significant after more than 100 days at 38 °C (Fig. 9a) in spite of the use of three layers of aluminium and two plastic bags to decrease the drying. The specimens containing reactive aggregates showed expansion (about 0.06% at 125 days) in spite of water losses, while non-reactive mortars showed shrinkage. Expansions were slower and about half those measured on specimens stored in water. After 125 days, only shrinkage was measured. At 385 days, when specimens were immersed in water, fast expansion was observed on mortar containing reactive aggregate. Expansion reached 0.12%, equal to the expansion measured on the specimens kept in water from the age of 28 days. The modification of moisture conditions, made after final expansion was reached, did not significantly modify the deformations. These results were in accordance with the literature [31]:

- ASR expansion could occur in sealed conditions if sufficient water was present in the porosity,
- expansions were smaller than for specimens in water but restarted as soon as specimens were put in water. If expansion is stopped by a lack of water, supplying water causes fast expansion, which tends to catch up with the expansion of specimens immersed in water, as considered in some ASR models [32,33].

Fig. 10 shows the mass variations and the deformations of specimens which had been subjected to the heat treatment during the first 24 h of curing and to variable moisture conditions after 28 days. During the first 150 days under sealed conditions, the behaviour of specimens that had been subjected to the heat treatment appeared to be dependent on the nature of the aggregate (Fig. 11). Mortar containing non-reactive aggregate showed mainly shrinkage strains (−0.02%) after 385 days of storage, like the reference mortar. Specimens of the same batch, stored in water in the same conditions (W/S = 2), showed expansions after only 100 days (Fig. 8). The DEF expansion could have been prevented by the lack of water or by the large alkali concentration in the cement paste [18,27–30]. If insufficient water is available, ettringite cannot be formed; and if alkali cannot leach out of the cement paste, sulphate cannot be released by CSH and cause DEF [28,29]. In terms of water quantity, the specimens had been saturated during the 28 days of

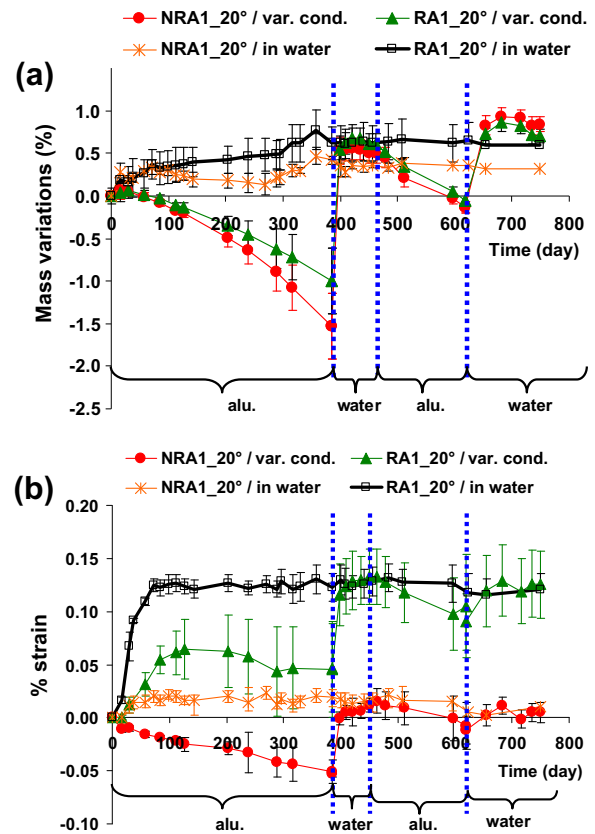


Fig. 9. Mass variations (a) and strain (b) of specimens immersed in water and specimens subjected to variable moisture conditions (stored at 20 °C during the 24 first hours of curing).

curing and the mass losses were lower than 0.2% at 100 days in sealed conditions. For the alkali leaching, in water, alkali can leach out of the specimens while, in sealed conditions, only internal movement into aggregates is possible. This internal movement causes a slight decrease in the alkali concentration in the cement paste but the phenomenon is small compared to external leaching. A greater decrease of alkali concentration in the cement paste could have been expected in the case of mortar containing reactive aggregate as explained by Diamond [27] since part of the alkali is consumed by ASR, which could then occur even in sealed conditions.

Mortar containing such potentially reactive aggregate showed only slight expansion (0.01%, which is smaller than expansions measured on specimens kept at 20 °C during the first 24 h, 0.05%). In spite of a slight positive strain, ASR did not exhibit the same expansion in the specimens which had been subjected to the heat treatment as in specimens cured at 20 °C. During the heat treatment, ASR mechanisms are accelerated and ASR can be largely advanced at the end of the curing period [8,10–12] and before the beginning of the measurement. The proportion of ASR already developed can be particularly significant for mortar using small aggregates like the mortars studied in these experiments. This could explain why only small expansions were measured on the mortar which had been subjected to the heat treatment. Moreover, either the residual alkali content after ASR consumption appears to remain too high in these experiments and to limit the DEF formation if there was no external leaching (sealed specimens) or mass losses observed led to a little unsaturation, perhaps sufficient to limit ion transfer and prevent the occurrence of DEF. Future works should be carried out with lower alkali content to increase the impact of alkali consumption by ASR on DEF.

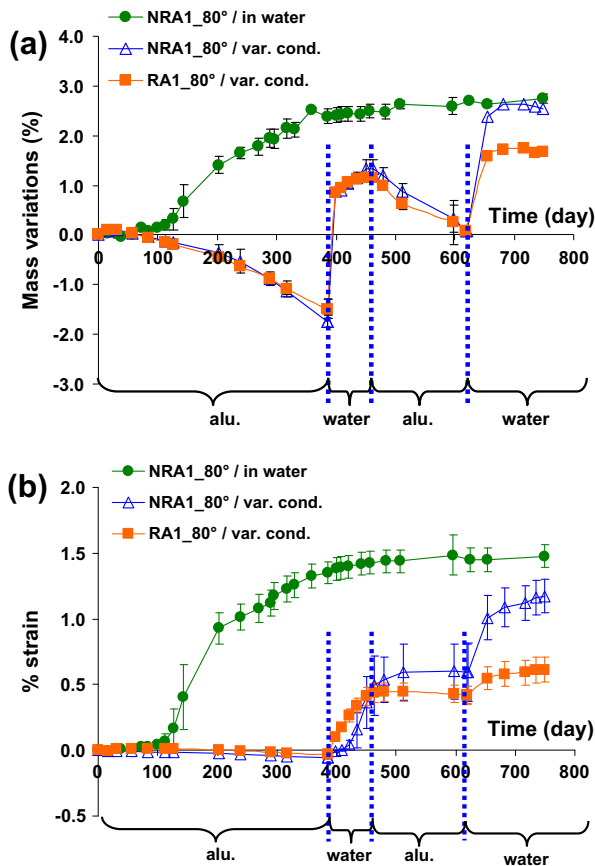


Fig. 10. Mass variations (a) and strain (b) of specimens immersed in water and specimens subjected to variable moisture conditions (specimens stored at 80 °C during the 24 first hours of curing).

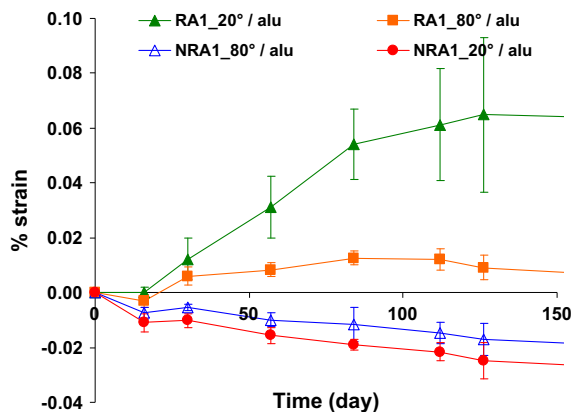


Fig. 11. Strains of specimens under aluminium during the first 150 days.

Once the specimens were immersed in water, expansion started very quickly for specimens containing the potentially reactive aggregates (expansion of more than 0.1% after 15 days of water supply). Specimens containing the non-reactive aggregates showed expansion with a slight delay (expansion of about 0.1% after 35 days in water). 65 days after rewetting, all the specimens presented a mean expansion of about 0.45%. These expansions were compared to the expansion of specimens immersed in the same volume of water just after the demoulding and coming from the same batch (NRA1 – Fig. 12). For mortar immersed in water just after demoulding, expansion appeared after 100 days of

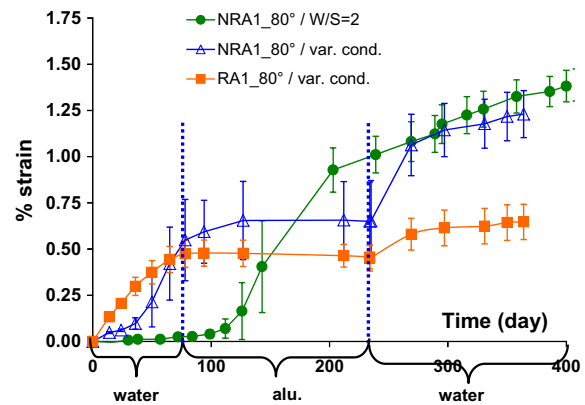


Fig. 12. Specimens immersed in water and specimens subjected to variable moisture conditions (in this figure, the date when the samples were again placed in contact with water, day 385, has been taken as the origin for specimens subjected to variable moisture conditions).

immersion. Therefore, it appears that some of the chemical reactions that create delayed ettringite were already well-advanced in the specimens under sealed conditions, and only required new exposure to water to cause large expansions. Expansion stopped immediately in mortars containing potentially reactive aggregate when the specimens were again put in sealed conditions (after 65 days of immersion). For specimens containing the non-reactive aggregates, expansion slowed but continued for 60 days and finally reached about 0.6%. Therefore, DEF continued even when water supply and external alkali leaching were stopped. After the last immersion, all the specimens showed new expansions and reached 1.2% and 0.6% for the mortars containing the non-reactive and the reactive aggregates, respectively, at 750 days. In the case of the non-reactive mortar, expansions reached the same value as in the mortar that had been immersed during the whole experiment.

5. Conclusion

Alkali silica reaction and delayed ettringite formation are two chemical reactions that cause expansion and damage in concrete structures. Great attention has to be paid to the mechanisms involved (ASR, DEF or combination of the two reactions) when assessing the safety of the damaged structures. The aim of this work was to study ASR and DEF in mortars with similar mix designs in various environmental conditions. DEF expansions can be characterised by:

- Discrepancy: DEF expansion heterogeneity was of the same order as ASR heterogeneity (coefficient of variation of about 30% for two batches of a given mix-design). It shows the necessity to have enough cores drilled from the same structure to have a good estimation of the residual expansion of the damaged concrete.
- Isotropy: anisotropy coefficients lay between 0.9 and 1.1, which are very low values compared to the anisotropy of ASR expansions due to casting direction. DEF expansions in stress-free conditions can be considered as isotropic. The measurement direction should not have consequences on the residual expansion assessment performed on cores drilled from damaged structures. It will simplify the evaluation of volumetric expansion necessary for structural modelling.
- The sensitivity of siliceous aggregate to ASR did not significantly modify the DEF kinetics in the conditions of this work (high alkali content).
- DEF expansions were largely influenced by the storage conditions (immersed in water or under sealed conditions).

- For storage in water, the volume of water modified the kinetics, which confirms the important effect of ionic species leaching on the DEF kinetics.
- Under sealed conditions, no expansions were measured for mortar containing non-reactive aggregate while very small positive strains were measured for mortar containing reactive aggregate.
- New water supply caused fast, large expansions. Even if no expansions were measured in sealed conditions, reactive elements were available to cause fast expansion as soon as water was supplied. This point has to be considered for the assessment of damaged structures with variable moisture conditions.

The effects of leaching and moisture conditions on DEF appear to be significantly different than the effects known to occur on ASR expansions. First, leaching causes a significant acceleration of DEF expansion. In this study, ASR expansion occurred for mortar in sealed conditions while no DEF expansions were measured in the same conditions. Thus, the moisture threshold necessary to obtain DEF expansion appears to be higher than for ASR. Finally, later water supply led to similar behaviour for ASR and DEF with fast new expansions. The future models developed to quantify the effect of DEF on structures will have to take these phenomena into account and thus will be different from the modelling used for ASR-damaged structures. The modelling of concrete with little alkali should consider alkali consumption by ASR. Indeed, in this case, the consumption by ASR can have as much importance as the effect of external leaching. Such considerations will lead to the complete coupled modelling necessary to obtain a relevant methodology of structural reassessment.

References

- [1] Shayan A, Quick GW. Microscopic features of cracked and uncracked concrete railway sleepers. *ACI Mater J* 1992;89:348–61.
- [2] Larive C, Louarn N. Diagnosis of alkali-aggregate reaction and sulphate reaction in French structures. *Proceedings of 9th international conference AAR*, vol. 106. London: Concrete Society Publication CS; 1992. p. 587–98.
- [3] Johansen V, Thaulow N, Skalny J. Simultaneous presence of alkali-silica gel and ettringite in concrete. *Adv Cem Res* 1993;17:23–9.
- [4] Thomas M, Folliard K, Drimalas T, Ramlochan T. Diagnosing delayed ettringite formation in concrete structures. *Cem Conc Res* 2008;38:841–7.
- [5] Tepponen P, Ericksson B-E. Damages in concrete railway sleepers in Finland. *Nord Conc Res* 1987;6:199–209.
- [6] Shayan A, Quick GW. Alkali-aggregate reaction in concrete railway sleepers from Finland. In: *Proceedings of 16th international conference on cement microscopy*, TX: Duncanville; 1994. p. 69–79.
- [7] Pettifer K, Nixon PJ. Alkali-metal sulphate – a factor common to both alkali-aggregate reaction and sulfate attack on concrete. *Cem Conc Res* 1980;10:173–81.
- [8] Eklou SO, Thomas MDA, Hooton RD. Dual effectiveness of lithium salt in controlling both delayed ettringite formation and ASR in concretes. *Cem Conc Res* 2007;37:942–7.
- [9] Martin RP, Renaud J-C, Toutlemonde F. Experimental investigations concerning combined delayed ettringite formation and alkali aggregate reaction. In: *Proceedings of 6th international conference on concrete under severe conditions CONSEC*, Merida, Mexico; 2010. p. 287–95.
- [10] Martin R-P. Analyse sur structures modèles des effets mécaniques de la réaction sulfatique interne du béton. PhD Thesis. University Paris-Est; 2010.
- [11] Diamond S, Ong S. Combined effects of alkali silica reaction and secondary ettringite deposition in steam cured mortars. In: Gartner EM, Uchikawa H, editors. *Cement technology*, Ceramic transactions, vol. 40, Amer Cer Soc, Westerville, Ohio, 1994. p. 79–90.
- [12] Shayan A, Ivanusec I. An experimental clarification of the association of delayed ettringite formation with alkali-aggregate reaction. *Cem Conc Comp* 1996;18:161–70.
- [13] Hanehara S, Oyama T, Fukuda S, Fujiwara T. Delayed ettringite formation and alkali aggregate reaction. In: *Proceedings of creep shrinkage and durability mechanics of concrete and concrete structures CONCREEP 8*, Ise-Shima, Japan; 2008. p. 1051–6.
- [14] Larive C, Joly M, Coussy O. Heterogeneity and anisotropy in ASR-affected concrete – consequences for structural assessment. In: *Proceedings of 11th international conference on alkali-aggregate reaction*, Quebec, Canada; 2000. p. 969–78.
- [15] Multon S, Seignol J-F, Toutlemonde F. Structural behavior of concrete beams affected by alkali-silica reaction. *ACI Mater J* 2005;102(2):67–76.
- [16] Smaoui N, Bérubé MA, Fournier B, Bissonnette B. Influence of specimen geometry direction of casting and mode of concrete consolidation on expansion due to ASR. *Cem Conc Aggr* 2004;26(2):58–70.
- [17] Escadeillas G, Aubert J-E, Segerer M, Prince W. Some factors affecting delayed ettringite formation in heat-cured mortars. *Cem Conc Res* 2007;37:1445–52.
- [18] Leklou N. Contribution à la connaissance de la réaction sulfatique interne. PhD thesis. Toulouse. Université de Toulouse; 2008.
- [19] Leklou N, Aubert J-E, Escadeillas G. Microscopic observations of samples affected by delayed ettringite formation (DEF). *Mater Struct* 2009;42:1369–78.
- [20] Carles-Gibergues A, Cyr M, Moisson M, Ringot E. A simple way to mitigate alkali-silica reaction. *Mater Struct* 2008;41:73–83.
- [21] Glasser FP, Damidot D, Atkins M. Phase development in cement in relation to the secondary ettringite problem. *Adv Cem Res* 1995;26:57–68.
- [22] Diamond S. Delayed ettringite formation – processes and problems. *Cem Conc Comp* 1996;18:205–15.
- [23] Fu Y, Ding J, Beaudoin JJ. Expansion of Portland cement mortar due to internal sulfate attack. *Cem Conc Res* 1997;27:1299–306.
- [24] Grattan-Bellew PE, Beaudoin JJ. Effect of aggregate particle size and composition on expansion of mortar bars due to delayed ettringite formation. *Cem Conc Res* 1998;28:1147–56.
- [25] Brunetaud X, Linder R, Divet L, Duragrin D, Damidot D. Effect of curing conditions and concrete mix design on the expansion generated by delayed ettringite formation. *Mater Struct* 2007;40:567–78.
- [26] Rogers CA, Hooton RD. Reduction in mortar and concrete expansion with reactive aggregates due to alkali leaching. *Cem Conc Aggr* 1991;13(1):42–9.
- [27] Diamond S. The relevance of laboratory studies on delayed ettringite formation to DEF in field concretes. *Cem Conc Res* 2000;30:1987–91.
- [28] Famy C, Scrivener KL, Atkinson A, Brough AR. Influence of the storage conditions on the dimensional changes of heat-cured mortars. *Cem Conc Res* 2001;31:795–803.
- [29] Taylor HFW, Famy C, Scrivener KL. Delayed ettringite formation. *Cem Conc Res* 2001;31:683–93.
- [30] Collepardi M. A state of the art review on delayed ettringite attack on concrete. *Cem Conc Comp* 2003;25:401–7.
- [31] Multon S, Toutlemonde F. Effect of moisture conditions and transfers on alkali silica reaction damaged structures. *Cem Conc Res* 2010;40(6):924–34.
- [32] Poyet S, Sellier A, Capra B, Thèvenin-Foray G, Torrenti J-M, Tournier-Cognon H, et al. Influence of water on alkali-silica reaction: experimental study and numerical simulations. *ASCE J Mater Civ Eng* 2006;18:588–96.
- [33] Grimal E, Sellier A, Le Pape Y, Bourdarot E. Creep shrinkage and anisotropic damage in AAR swelling mechanism, part I: a constitutive model. *ACI Mater J* 2008;105:227–35.