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Interaction of DEF and AAR, a review

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Abstract

AAR and DEF can lead to the development of severe cracking in structures. Both are often associated with high cement content mixes: AAR because of the increased availability of alkalis, DEF because the heat of cement hydration can lead to formation of temperatures of over 65ºC, above which sulphates form as monosulfates which in cooler moist conditions slowly reform as expansive ettringite to disrupt the paste.

High cement content mixes, favoured by contractors for early strength gain and workability, also lead to increased early age thermal and shrinkage cracking. This cracking becomes increasingly complex as it is enlarged by the swelling from AAR and/or DEF, which later impose their own characteristics, modified by constraints from stress and reinforcement.

The paper will consider AAR and DEF at the scale of the interaction of paste with aggregate, as observable petrographically and from changed physical properties. Examples of large scale laboratory tests on beams further clarify the interactions which are also illustrated by reference to major structures which have suffered AAR, DEF and combined AAR/DEF damage.

Limiting cement contents is a cost effective environmentally beneficial approach to preventing AAR, DEF and other cracking and creep problems in concrete construction. Warm climates may necessitate cooling concrete mixes.

***Keywords**: concrete; structure; AAR; DEF; cracking*

1. INTRODUCTION

Both Alkali Aggregate Reaction (AAR) and Delayed Ettringite Formation (DEF) can lead to the development of severe cracking in concrete structures over decades as a consequence of internal expansions. This can create structural uncertainty and risks of functional failures in bridges, dams and buildings. In extreme cases, it has led to their demolition and replacement. The processes are distinct, but may interact in real structures.

External sulfate attack from soils or water is distinct from the internal effects of DEF. There are some analogies with DEF and the behaviour of expansive cements which use ettringite formation to give early age expansion to reduce shrinkage or create slight expansion to tension embedded reinforcement while putting concrete into compression to prevent cracking. External sulfate attack is out of the scope of the present article.

1.1 AAR: some historical aspects

AAR was first identified in the late 1930s by Stanton in California with fast reacting opaline aggregates. The alkalis in cement were found to react with disordered forms of silica in aggregate to produce silica gel which is hygroscopic and swells in damp conditions. This swelling of the gel can develop within aggregates splitting them, on the aggregate surfaces or, with fluid gels, as the gel spreads into the adjacent cracks, see Figure 1.1. Over the past 40 years AAR became the subject of detailed studies of the alkalinity of cement paste and pore solution in parallel with petrographic studies of the siliceous minerals and the microcracking and gel formation.

As the years went by, an increasing number of structures were found to be suffering damage from slowly developing severe cracking. Typically, this only became noticeable five or more years after construction. By 1980, petrographic analysis provided a basis for diagnosis of AAR, but not for assessing its structural implications. Since then, specifications and appropriate testing to minimise the risk of AAR damage in new construction have evolved, often tailored to national materials and experience.

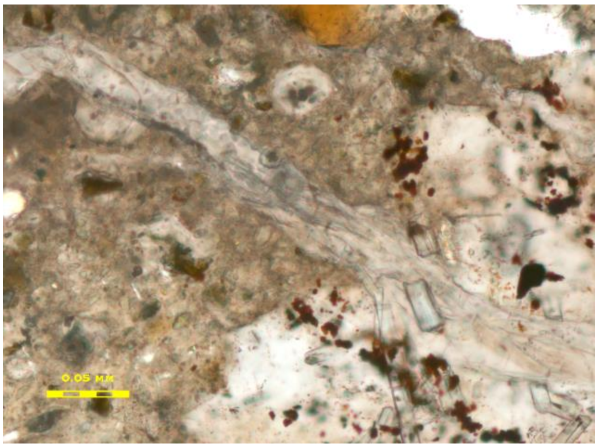


Figure 1.1: AAR with gel in cracked aggregate and into cracked paste.

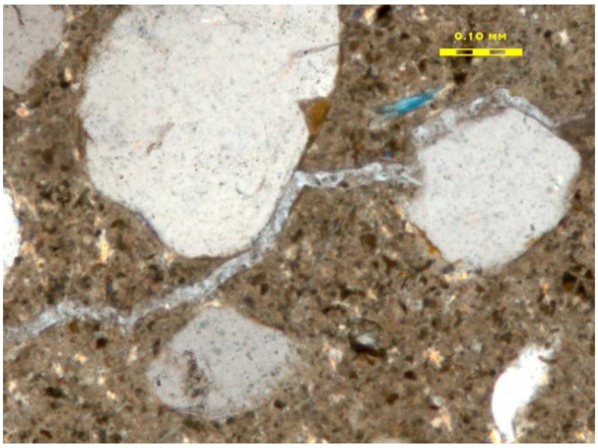


Figure 1.2: DEF forming in cracks in paste and around Aggregate

More recently RILEM has coordinated research to develop these into international guidance on specification [1]. Distinct, but allied, research has developed testing for diagnosis, prognosis and assessment for evaluation of AAR damage in structures [2].

1.2 DEF: some historical aspects

DEF was initially identified in the 1980s by Heinz [3] as a cause of deterioration in precast elements which had been cured at high temperatures to accelerate production. It was established that, at temperatures over about 70ºC, the sulfates in cement would form as monosulfates. With time in moist conditions the monosulfates can revert to ettringite $Ca_6[Al(OH)_6]_2 \cdot (SO_4)_2 \cdot 26H_2O$. This ettringite is formed within the paste or into cracks and voids (see. Figure 2). The swelling results from the large volume of H_20 incorporated into ettringite crystals.

In 1997, Divet [4] observed for the first time in France DEF in the capbeam of the Ondes bridge near Toulouse, whose concrete had been cast on site. Then, other bridges damaged by DEF were discovered and investigated. In these bridges, the damaged parts were primarily massive structural elements (piers, crossbeams on piers or abutments, etc.) in contact with water or subjected to high moisture. In 2001, Divet [5] was able to highlight some important features, based on a comparative study of factors encountered in damaged and non damaged bridges. These general features are the following:

- the minimum delay for observing cracking on structures is around 6 to 8 years;
- the maximum temperature reached in those massive parts affected by DEF are above 75 °C to 80 °C;
- the casting of the concrete took place during the summer months;
- the nature of the cement is a CEM I and the cement content is above 400 kg/m^3;
- the SO_3 content of the cement is above 2.5 % and the C_3A cement content above 8 %.

Lessons learned from these cases were used to develop a prevention strategy [6]. Thereafter, some bridges decks composed of prestressed precast concrete beams were discovered as affected by DEF; longitudinal and shear cracks developed in these pre-tensioned beams. The main cause could be attributed to the use of a high temperature cycle during the heating phase in the factory. In France, now, about one hundred and fifty bridges and very few dams are damaged by DEF to a more or less extent.

1.3 Concomitance of AAR and DEF

Petrographic examination of samples enables the relative importance of AAR and DEF and other deterioration mechanisms to be identified and related to the temperature and moisture history of the concrete. Surface coring can show AAR features in moist concrete. For DEF, the as cast heat profile must first be estimated, followed by coring through the cooler surface zone into hottest zones which may have exceed 65ºC, with moisture in the long term.

In 2001, Taylor [7] reviewed subsequent research on DEF and its interaction with AAR. He refers to some examples of DEF in mass concrete were hydration had raised temperature to above 70ºC. When siliceous aggregates were used, this was associated with extensive damage from AAR. Taylor stresses the need to differentiate between:

- the damaging expansions from the formation of ettringite trapped within the cement paste leading to cracks developing around aggregates
- the migration of ettringite from within the paste to form larger crystals to fill space in cracks and voids without generating expansions. Ettringite in cracks from AAR is often observed when using petrography to study AAR damage.

Taylor and a more recent review by Thomas [8] have confirmed that although aggregate type and sulfate content can influence DEF damage, the dominant factor is the peak temperature after casting. Since Taylor's review, a range of significant cases of DEF damage in major in-situ concrete structures, with and without AAR have been investigated. This justifies rigorous control of peak temperatures during construction particularly when there are high temperatures, massive pours and/or high cement contents.

2. WHY HAVE AAR BECOME WIDESPREAD AND NOT DEF?

The causes, physicochemical mechanisms and kinetics of the reaction that gives rise to the DEF swelling phenomenon, as well as the impact of the various parameters affecting DEF, are not yet thoroughly understood and continue to be the topic of widespread research. It appears however that an adverse combination of several parameters is essential to initiating and extending the DEF. This probably explains the rather low number of structures currently identified as experiencing DEF in the world, compared to the high number of structures affected by AAR where only 2 main parameters (reactive silica in aggregates and level of alkalis in concrete) are essential to trigger the reaction.

The principal parameters involved in DEF are the following:

- Temperature and its duration of application: The maximum temperature reached as well as the amount of time high temperature is maintained both influence the risk of delayed ettringite formation. Laboratory work has shown that if the temperature exceeds 65°C and if other key parameters are present, DEF can develop to damage concrete. Exothermal heating of the concrete during hydration is a necessary precondition, yet on its own remains insufficient. A mix temperature of 20ºC with 44ºC rise from a 400kg/m3 cement will only just reach 64ºC in the core of a very large pour, so DEF is unlikely in temperate climates with moderate cement contents.
- Sulphate and aluminate contents of the cement: Sulphates and aluminates are directly involved in the reactive mechanism that serves to form ettringite and DEF can only arise if the cement contains a high enough quantity of both tricalcic aluminates (3CaO Al2O3 or C3A) and sulphates (SO3).
- Alkali content of the concrete: the role of this on ettringite solubility is well documented. Ettringite is more highly soluble at higher alkali rates. As a result of ettringite solubility variation with temperature, a strong interaction exists between these two parameters during the DEF process. All other parameters being the same, a drop in the initial alkali content serves to increase the critical temperature value. This parameter plays also a paramount role in the case of AAR.
- Water and high humidity: water is a reactive medium essential to producing the reaction; it is as much involved in the transfer process as in the actual formation of reaction products. DEF primarily affects the parts of structures either in contact with water (submerged zone, tidal zone) or subjected to water ingress (exposure to bad weather, waterproofing defects, absence of drainage, etc.), or sometimes exposed to a high moisture level (at least 92 % RH).

The expansive or non-expansive nature of ettringite depends on the initial chemical composition, particularly on the type of cement (contents of aluminates and alkali, quantity of potentially-formed Portlandite) and the quantity of sulphates capable of being mobilised. There is not a consensus on the detailed mechanism by which ettringite formation is able to generate pressures inside concrete. Two principal mechanisms, which are to some extent linked to each other, have been proposed to explain the swelling caused by ettringite formation:

- swelling due to the crystallisation pressures inherent in ettringite crystal growth,
- swelling due to the osmotic pressures caused by an increase in the amount of colloidal ettringite.

It is likely that both of these mechanisms play a role simultaneously and cannot be dissociated from one another.

3. WHY DO AAR AND DEF MAY COEXIST?

Several conditions are necessary at the time of casting for developing DEF. Even if calcareous aggregates may be more prone to DEF than siliceous ones, the type of aggregates is not among the most important parameters of DEF. In contrast, the type of aggregate has a paramount role in the case of AAR. It is enough to combine the conditions for DEF listed above with a reactive aggregate and an alkali content in concrete greater than 3 kg/m^3 to develop both AAR and DEF.

Designers wanting ever higher strength and contractors wanting earlier strengths has led to cement contents rising from the reasonable 350 kg/m^3 to many examples of 500 kg/m^3 or more. This raised alkali levels in concrete, with 0.8% Na_2Oeq in cement, from 2.8 kg/m^3 to 4.0 kg/m^3, i.e. above the safe 3.0 kg/m^3 threshold for most UK aggregates. When concrete mixes have been pumped, cement contents could exceed 600 kg/m^3.

These high cement contents lead to high temperatures in pours. 350kg/m^3 gives a typical 38ºC temperature rise above mix temperature so there is little risk of exceeding 65ºC to inducing DEF. However, with 500 kg/m^3 of cement in a large pour of concrete mixed at 15 °C, the temperature will reach 70 °C in the core. Higher mix temperatures and/or higher cement contents will produce DEF if moisture can reach the areas which were overheated.

The following question then arises: which is the first reaction initiating damage? It probably depends on the speed of development of each of the two reactions inside concrete. What is clear is that when one of the two reactions is triggered, it creates micro-cracks into concrete which accelerates the development of both reactions because of the easier transport of water and ions within the cracks.

4. THE IMPACT OF AAR AND DEF ON MECHANICAL PROPERTIES OF CONCRETE

DEF leads to expansion that reduces the mechanical characteristics of concrete according to the extent of the reaction. As the paste expands with Ettringite it separates from the aggregates weakening the concrete. In the case of concretes with a 28-day strength of the order of 35 to 40 MPa, and that are exposed to thermal cycles which are typical of massive structures (a temperature plateau of 81 °C maintained for three days), Martin [12] obtained reductions in compressive strength of over 75% in the case of a concrete in which DEF has generated a maximum unrestrained expansion of approximately 14 mm/m (concrete tested after approximately 1,450 days of ageing). The Young’s modulus was reduced by almost 90 % (as determined by linear regression of the stress-strain plot over three loading cycles at between 5 and approximately 30 % of the concrete’s compressive strength). These drastic reductions in the mechanical performance should nevertheless be seen in the context of the very high level of expansion exhibited by this particular material. In the case of more moderate unrestrained expansion (1.2 mm/m), Martin [12] observed a much smaller reduction in Young’s modulus of approximately 14% at 1,350 days. This expansion and deterioration will only occur in the centre of the pour not the cooler near surface zones which did not exceed 65 °C.

Considering the possible concomitance of AAR and DEF, an important question is to know the mechanical consequences of this coupled phenomenon on the behaviour of structures, and a good way to approach this question is by comparing the mechanical effects of AAR or DEF alone and AAR & DEF together on the behaviour of simple concrete elements, through testing in laboratory.

5. IMPACT OF AAR, DEF AND AAR & DEF ON CONCRETE ELEMENTS

An experimental program was carried out at IFSTTAR in partnership with EDF (Electricité de France) in order to study the behaviour of cylinder and large scale laboratory beams. Its objective was to quantify at a macroscopic scale the mechanical effects of DEF and AAR acting separately or simultaneously. The results are summarized hereafter, which are described more extensively in [9] and [10].

5.1 Impact on concrete cylinders

Three concrete mixes were designed: the first one was AAR-reactive (A) the second one was DEF-reactive (D), and the third one AAR and DEF-reactive (AD). To ensure the development of DEF and AAR, the alkali content of both mixes was increased by adding K_2O in the mixing water, and to trigger DEF under controlled conditions, all cylinders were heat cured in water, after casting, at a temperature of 80 °C during 72 hours. A non reactive siliceous sand was used for D and AD cylinders, and two types of coarse aggregates were used: either a Non Reactive Siliceous aggregate for D cylinders or an Alkali Reactive Limestone aggregate for A and AD cylinders (Table 5.1). A cement C1 (CEM I 52.5) with a high content of alkalis (Na_2Oeq = 0.92 %) was used for the mix A, while a cement C2 (CEM I 52.5 R) with a high content of aluminates, sulfates and alkalis (respectively 3.5, 4.3 and 0.83 wt. %) was chosen to promote DEF.

The investigations were performed on cylinders (110 mm in diameter and 220 mm in height). The cylinders were subjected to free expansion tests under various moist exposures: each cylinder was stored at a temperature of 38 °C and either immersed in water (I) or in a 100 % Relative Humidity atmosphere (H100).

Table 5.1: concrete mixes used for A, D and AD cylinders and beams

Mix	reactivity	Cement type	Cement content (kg)	Water (l)	Non reactive limestone sand (kg)	Non reactive Siliceous aggregate (kg)	Reactive limestone aggregate (kg)	Na_2Oeq (%)
A	AAR	C1	410	205	621	0	1122	1.25
D	DEF	C2	410	188	0	1783	0	1.0
AD	AAR&DEF	C2	410	188	0	797	986	1.0

The first evident result is that the expansion of A cylinders (0.2 %) is much smaller than that of AD cylinders (1.5 %) (see figure 4.1), as well as much smaller than the expansion of D cylinders. This comparison is only available for cylinders immersed in water since the authors did not test cylinders with AAR in 100 % HR condition. But it confirms a common feature observed in other experiments where the expansion of A cylinders cured at 38 °C and 100 % HR is generally lower than the expansion of D cylinders kept in water at 20 °C.

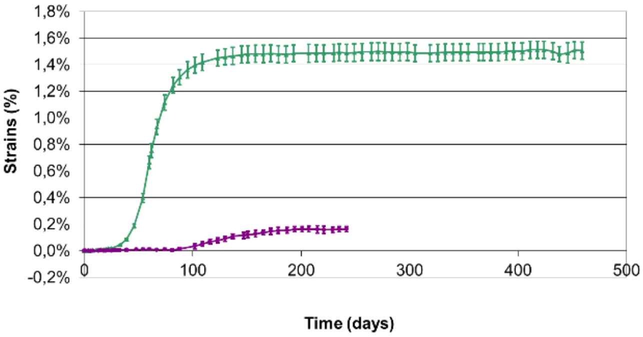
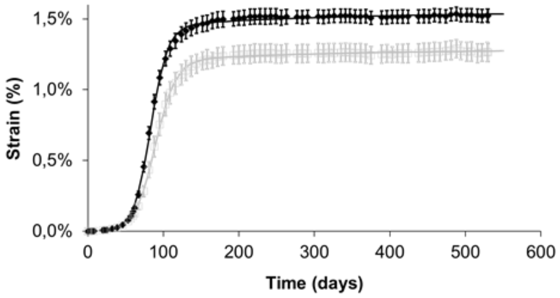


Figure 4.1: Expansion of AAR & DEF-reactive cylinders (Green curve) and AAR-reactive cylinders (purple curve), all immersed in water (from [9]).

Figure 4.2 shows the expansion of DEF-reactive cylinders over a period of 550 days. It may be observed that the final expansion and the kinetics of the D cylinders are greater in water than in 100 % RH (final expansion of 1.5 % versus 1.25 %), which confirms the condition used for the LCPC accelerated expansion test for DEF [11]. One of the reasons is that storage in water promotes the leaching of alkalis and thus the precipitation of ettringite.

Figure 4.3 shows the expansion of AD cylinders over a period of 450 days. As for the D cylinders, the AD immersed cylinders exhibit a slightly faster development of the expansion at the beginning. However, after 120 days of exposure, the strains of the AD cylinders kept at 100 % RH are growing further significantly instead of reaching a plateau at 1.5 % as for the D cylinders stored in water. Finally, after a storage duration of about 350 days, the expansion processes of the D cylinders kept at 100 % RH are reaching also a plateau (for a value of the final expansion equal to 2.1 %).



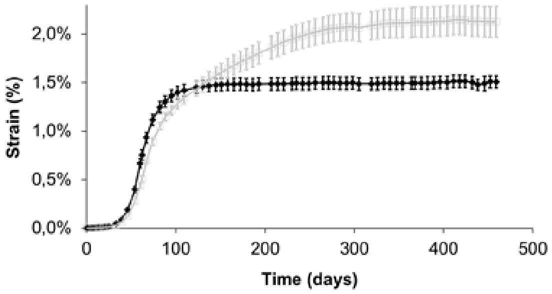
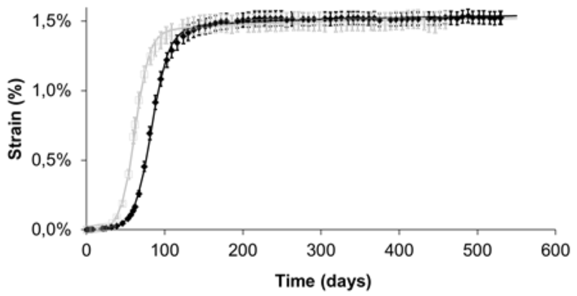


Figure 4.2 : Expansion of DEF-reactive cylinders immersed in water (black curve) and in 100 % HR exposure (grey curve) – From [9]

Figure 4.3 : Expansion of AAR & DEF-reactive cylinders immersed in water (black curve) and in 100 % HR exposure (grey curve) – From [9].

Figure 4.4 shows a comparison between expansion of D and AD cylinders, all immersed in water. If the final expansion that reaches 1.5 % is the same, the onset of the swelling is earlier for AD cylinders than for D cylinders, and the speed of expansion is rather similar. However, for this comparison, we must also take into account the fact that a reactive limestone aggregate was used for casting A cylinders and that a non-reactive siliceous aggregate was used for DEF. The difference in terms of behavior is too small to try to explain it.



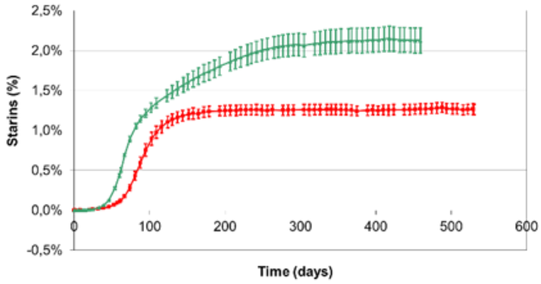


Figure 4.4 : Expansion of DEF-reactive cylinders (black curve) and AAR & DEF-reactive cylinders (grey curve), all immersed in water– From [9] .

Figure 4.5 : Expansion of DEF-reactive cylinders (red curve) and AAR & DEF-reactive cylinders (green curve), all in 100 % RH exposure - From [9] .

Figures 4.5 shows a comparison between expansion of D and AD cylinders, all in a 100 % RH exposure. It appears that the expansion of AD cylinders is much greater than that of D cylinders. The effect of a saturated humidity is boosting AAR in the cylinders affected by AAR and DEF, but rather on the long term. At the beginning, a similar latency period is observed. Then an intense swelling with a higher speed mainly due to DEF is taking place for cylinders immersed by comparison with those at 100 % RH. According to [9], because of the development of a cracks network, leaching of alkalis may arise particularly in the case of immersed cylinders where water can penetrate into the cracks. This difference in terms of alkalis leaching means that more alkalis are present in the case of 100 % RH and can promote AAR, while less alkalis are present in the case of an immersed cylinders and reduce the AAR development. This mechanism assumes that DEF acts prior to AAR, what can be seen on figure 4.1.

In all the experiments, there is a rather good linear relationship between strains and mass variations for D and AD cylinders.

5.2 Impact on concrete beams

To study the structural effects of AAR and DEF acting separately or together, tests were performed by Martin & al. [10] on beams subjected to a controlled moisture gradient with the final objective to induce a gradient of imposed expansion. These tests were conducted on 6 beams (0.25m x 0.50m x 3.00m) named B1 to B6, as described in Table 5.2. Three of them were unreinforced and the other three were reinforced in the longitudinal direction with two rebars of 32 mm in diameter in the lower part and two rebars of 20 mm in diameter in the upper part. These simply supported beams were subjected to a moisture gradient during 430 days: the lower part of the beam was immersed in water on a depth of 7 cm while its upper face was drying in an atmosphere at 30% RH, and all lateral sides were sealed with adhesive aluminium sheets. All tests were performed at a constant temperature of 38 °C to speed up the drying process and the swelling reactions.

Table 5.2: Beams tested (U = unreinforced, R = reinforced)

	B1	B2	B3	B4	B5	B6
Reactivity	AAR	AAR	DEF	DEF	AAR & DEF	AAR & DEF
Concrete mix	A	A	D	D	AD	AD
Reinforcement	U	R	U	R	U	R

The vertical expansion measured was strongly dependent of the amount of water migrating from the immersed lower part up to the drying upper face. Because of the very high potential of free expansion (and associated cracking) of the concrete mixes D and AD, unreinforced beams B3 and B5 collapsed under dead weight effect after only 180 and 330 days of exposure, respectively. If we focus on the mechanical behaviour in the longitudinal direction, many interesting results were obtained.

Figure 4.6 shows that the longitudinal strains remain linear along the height during time for the unreinforced D-beam B3. This allows to calculate by double integration a deflection. Figure 4.7 presents this calculated deflection at mid-span with the deflections measured on the West (W) and East (E) sides of the beam B3, and indicates a good correlation.

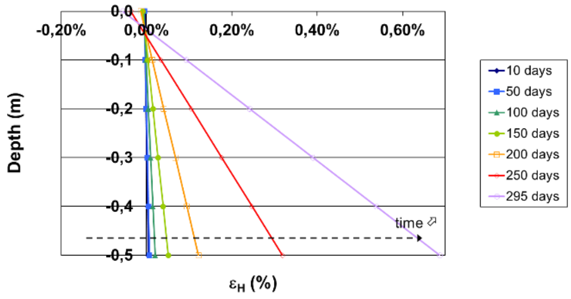


Figure 4.6: Evolution during time of the longitudinal strains with depth for DEF-beam B3- (From [10])

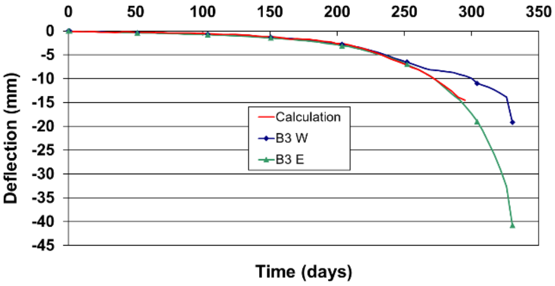


Figure 4.7: Mid-span deflection of the unreinforced DEF-beam B3 (From [10])

Figure 4.8 and 4.9 present the same type of results for the reinforced D-beam B4. Again, the plane strains remain plane during the test, but for this beam, there was a big change around 250 days where the presence of the reinforcement in the bottom modified the structural behavior. In particular, for significant expansions developed in the lower part, the mechanical reaction of rebars to the imposed concrete expansion led to the development of a compression in this area leading to a bend upward of the beam.

Figure 4.10 illustrates the evolution of the mid-span deflection with time for the three unreinforced beams.

A-beam B1 reached a deflection value of about 5 mm that remains linear, while the deflection of B3 and B5 reached up to about 40 mm and 60 mm respectively. As for the cylinder, the AD-beam B5 presents a more rapid and more important deflection than the D-beam B3.

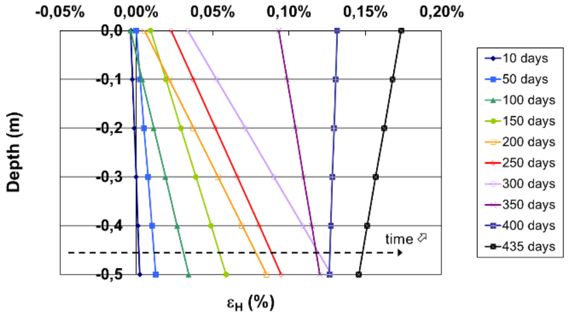


Figure 4.8: Evolution during time of the longitudinal strains with depth for DEF-beam B4 (From [10])

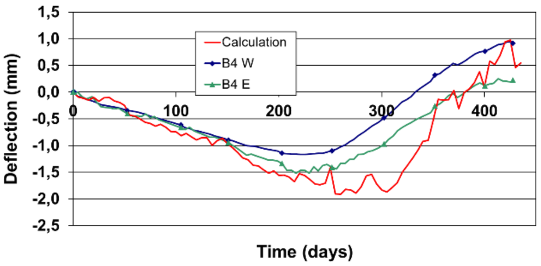


Figure 4.9: Mid-span deflection of the reinforced DEF-beam B4 (From [10])

Figure 4.11 presents the evolution of the mid-span deflection with time for the 3 reinforced beams. For all beams, the curvature begins to decrease and then increases because of the "prestressing effect of the rebars": however, this effect is more important and rapid for the AD-beam B6 than for the D-beam B4 and rather negligible for the A-beam B2.

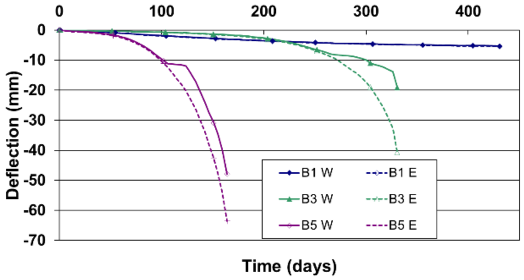


Figure 4.10: Mid-span deflection of the three unreinforced beams A-B1, D-B3 and AD-B5 (From [10])

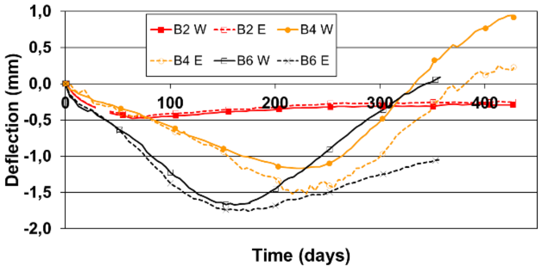


Figure 4.11: Mid-span deflection of the three reinforced beams A-B2, D-B4 and AD-B6 (From [10])

As a conclusion, it appears globally that AAR (with a typical magnitude of expansion 0.2- 0.3 %) is less damaging than DEF (with a typical magnitude of expansion 1.4-1.5 %), and that a combination of AAR and DEF is obviously the worst case. DEF and AAR & DEF may lead to a total collapse of unreinforced beams under their own weight. As for cylinders, there is a rather good linear relationship between strains and mass variations of the beams due to uptake of water for D and AD beams, what is not the case for A beams. Like Martin & al. [10], we may also conclude that the structural behavior of the beams can be described within the frame of the Strength of Materials.

6. ABOUT DISORDERS ON STRUCTURES

The disorders on structures affected by DEF are similar to those observed on structures damaged by alkali-aggregate reaction, except for pop-outs, exsudation of gel and discoloration along cracks that are not encountered on structures having DEF. For both reactions, map cracking is the most frequent disorder observed on the facings of structures. Cracking is generally anarchic and can take the shape of a crazing with small mesh size (20 to 50 mm) and a rather small crack depth (a few centimeters), or take the shape of a larger crack network (30 to 40 cm size) with greater crack depth (greater than 10 cm).

Although the crack opening is variable in each observed zone according to the evolution rate of the reaction, this opening is generally greater with DEF than with AAR. The crack depth also varies with the degree of evolution of the disorders: cracking may be superficial (a few centimeters deep) or propagate in depth, until a through cracking. For both reactions, the map cracking can leave room for an oriented cracking in a structural element where there is a predominant direction of compression stresses. The cracks are opening in the direction perpendicular to the main compression axis. It is particularly the case of horizontal cracks developing in prestressed precast concrete beams, or vertical cracks occurring in columns or piers.

In the case of AAR, damage starts to become significant with expansions in the range 0.6 to 1.0 mm/m which can be detected by a Young's modulus reduction from microcracking of about 25 to 30 % [17]. Severe damage from AAR is associated with expansion in the range 2.0 mm/m to maximum seldom exceeding about 5.0 mm/m (Figure 6.1). It appears that expansions from DEF in extreme cases can exceed those from AAR (Figure 6.2). However the damage from AAR arises from the variability of expansion within pours due to heterogeneity giving variations in local expansions determined by local moisture, alkali and reactive aggregate concentrations. It appers that the expansions are generally less that those observed with DEF, and consequently the reductions of the mechanical characteristics of concrete are lesser.

Figure 6.1: AAR damage from severe 2 mm/m to 4 mm/m variable expansions.

Figure 6.2: DEF damage from severe 1.5 to 5.5 mm/m variable expansions - (the white exsudations are calcite due to the dissolution of the lime of the cement and its carbonation with air).

7. CONCLUSIONS

Common features and differences between AAR and DEF have been presented, in the context of microscopic scale, materials and damages of affected structures. Although the reactions have similar macroscopic effects, the microscopic phenomena are very different.

The presence of alkalis has contrary effect: high alkali content tends to delay DEF while it boosts extensive AAR.

The tests performed confirm the generally observed higher magnitude of DEF expansion leading to collapse of the unreinforced beams under self weight, a phenomenon not found in testing AAR. The combination of both reactions accelerates the development of swelling and emphasizes the expansions; the consumption of alkalis to form the AAR gel leading to the precipitation of ettringite.

Both AAR and DEF lead to a decrease of the Young's modulus that can be explained by cracking of the matrix. With AAR, cracks develop in reactive aggregates and extend into the paste, but with DEF cracks degrades the paste and separate it from aggregates.

The reduction in strength can be more extreme with DEF than with AAR.

It seems that the migration of moisture and leaching of alkalis needs to be considered in modelling both reactions. With the initial heat needed for DEF being confined on site to the core of the concrete, moisture takes time to penetrate and to trigger damage. Limiting moisture is the only means of slowing damage with both AAR and DEF.

Limiting cement contents is a cost effective and environmentally beneficial approach for preventing AAR, DEF and other cracking such as cracks due to thermal gradients.

The costs and disruption from damage to structures from AAR and DEF make reliable specification and quality control essential.

8. ACKNOWLEDGMENTS

Mike Eden, Sandberg LLP, for petrographic thin section (Figures 1.1 and 1.2) and Renaud-Pierre Martin, IFSTTAR, for Figures 4.1 to 4.11.

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