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EFFECTS OF LATE WATER SUPPLY ON ASR PROGRESS IN DAMAGED STRUCTURES

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ABSTRACT

An important experimental research has been carried out since 2000 at the Laboratoire Central des Ponts et Chaussées (LCPC – Public Works Research Agency), with Electricité de France (EDF – French Power Company) as a partner, concerning ASR structural effects. The experimental data obtained in this program will be used for model calibration and validation of re-assessment methodologies concerning ASR-affected structures, namely bridges and dams.

One major purpose of this study is to point out the water driving effect on the swellings, and to answer the questions, still debated, of an aging behavior of reactive materials and ASR-gel with respect to water. In the experiment, after 14 months-exposure to a unidirectional moisture gradient (bottom of the beams immersed in water and upper face exposed to a 30 % Relative Humidity environment), the six 3 m-long beams were significantly damaged. In fact, the ASR swellings had reached an asymptotic value in an increasing bottom part of the beams, while drying had progressively stopped the development of ASR between the upper face and the depth of 100 mm. Then the upper faces of the beams have been covered by water for 9 months. This late water supply on the upper face rapidly produced intense swellings, which principally occurred along the transverse and the vertical directions, resulting in large longitudinal cracks.

A large number of companion standard specimens have been kept in the same varied environmental conditions, in order to quantify the basic characteristics of moisture-dependent expansive behavior of the material. In order to analyze ASR development in such conditions, specimens kept sealed under watertight aluminum during two years have also been put in water, and their deformations have been measured.

The paper focuses on the effects of late water supply on already damaged structures, which is of significant possible concern for real-life structures. It details and analyzes the numerous measurements obtained during the "re-wetting" period (variation of water content, deformations in beams and standard specimens). Both structural effects of late water supply on ASR progress in already damaged structures, and interpretation of such phenomena with respect to the possibly aging behavior of ASR-gel, are addressed.

Keywords: Beams, Experimentation, Water supply, Structural assessment

1 INTRODUCTION

During the large experimental program carried out at the Laboratoire Central des Ponts et Chaussées (LCPC – Public Works Research Agency), with Electricité de France (EDF – French Power Company) as a partner [1-4], one major aim was to evaluate precisely the water driving effect on ASR-swellings [5-7]. Indeed, this evaluation is necessary to assess the behavior of damaged structures from residual expansion tests [8-11]. However, another still debated question is the behavior of reactive materials and ASR-gel with respect to late water supply [7]. Does ASR-gel swell brutally if large water supply comes into contact with concrete already damaged by ASR?

In order to analyze ASR development in such conditions, 6 specimens kept in air at 100% RH and 6 specimens kept sealed under watertight aluminum during two years have been put in water. Their mass variations and deformations have been measured. The material response to this late supply has been monitored and is presented in section 2 of this paper.

Moreover, the consequences of such change in moisture conditions have been studied on structures.

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As described in previous papers, the studied structures are 3 m long, 0.25 m thick and 0.5 m high simply supported beams [2-4]. After 14 months-exposure to a unidirectional moisture gradient (430 days with bottom immersed in water and upper face exposed to a 30 % Relative Humidity environment), the beams were significantly damaged. In fact, the ASR swellings had reached an asymptotic value in an increasing bottom part of the beams, while drying had progressively stopped the development of ASR between the upper face and the depth of 100 mm [2, 4]. Then, the upper faces of the beams were covered by water and subsequent evolution has been monitored for 9 months under the late water supply conditions.

Numerous measurements have been obtained during the experimental program: variation of water content, relative humidity measurements, local and global deformations and deflection of the beams. Technical considerations are not described in this paper, all necessary details can be found in previous papers [2-4, 12-13].

This paper presents and analyzes measurements on two plain concrete beams (P2: the ASR-damaged beam and P3: the nonreactive expansion one). This allows relevant conclusions about effect of late water supply to be made without be disturbed by reinforcement effect [4, 13].

2 ASR-INDUCED SWELLINGS UNDER LATE WATER SUPPLY

In order to determine the behavior of ASR-gel submitted to late water supply (LWS), specimens kept in air at 100% RH and under watertight aluminum at 38°C during 676 days have been immersed in water at 38°C. Moreover, since anisotropy of free swellings is known [14-18], strains measurements have been performed in two directions with respect to casting direction [11]. Thus deformations of the reactive concrete have been measured along the axial direction of 160 x 320 mm cylinders (measurements parallel to casting direction, called in this paper "vertical direction") and 140 x140x 280 mm prisms (measurements perpendicular to casting direction, called in this paper "horizontal direction"). The mass variations and deformations of specimens submitted to late water supply are plotted in Fig. 1 and Fig. 2 (nonreactive specimens are not presented in this part).

The time-evolution of swellings of the specimens can be compared to ASR-swellings of specimens kept in water at 38°C after the 28 curing days (Fig. 1 and Fig. 2). Measurements on specimens kept in water have been performed during 680 days, but deformations were stabilized when measurements stopped. Thus it was considered that deformations of these specimens were constant and equal to deformations measured at the last time-step between 680 and 900 day.

Moreover, mass variations of specimens, used to obtain vertical strains, depend on storage conditions during the night before first measurements [4]. The night before first measurement, some specimens were kept under watertight aluminum (Vert_Water_2), while other were kept under wet conditions (Vert_Water_1). The difference between these two storage conditions, during the night before the first measurements, is just due to technical problems. It implies larger mass variations for the first specimens, but the same ASR-expansions have been measured for both types of specimens whatever storage conditions during the night before first measurements (Fig. 1).

Mass variation of specimens immersed at 676 days reached in about 80 days the mass variation measured on specimens always kept in water (Fig. 1 and Fig. 2). Swellings have quite the same behaviour, however the time-evolution appears to be slower. For the specimens kept under watertight aluminum before the late water supply, the increase in swellings is about 700 μm/m in both directions in less than 150 days.

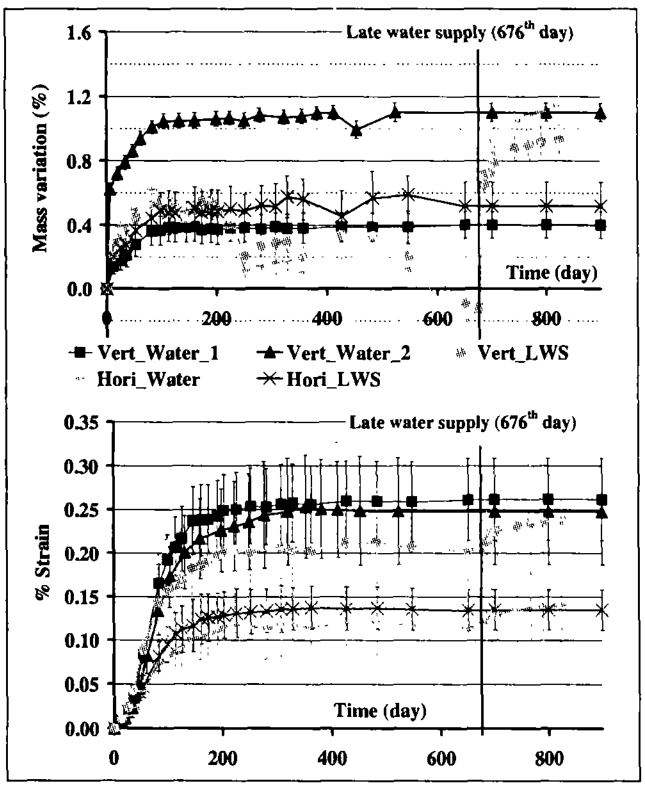

Fig. 1 Mass variations and strains measured on specimens kept in air at 100% RH during 676 days before being submitted to late water supply (LWS)

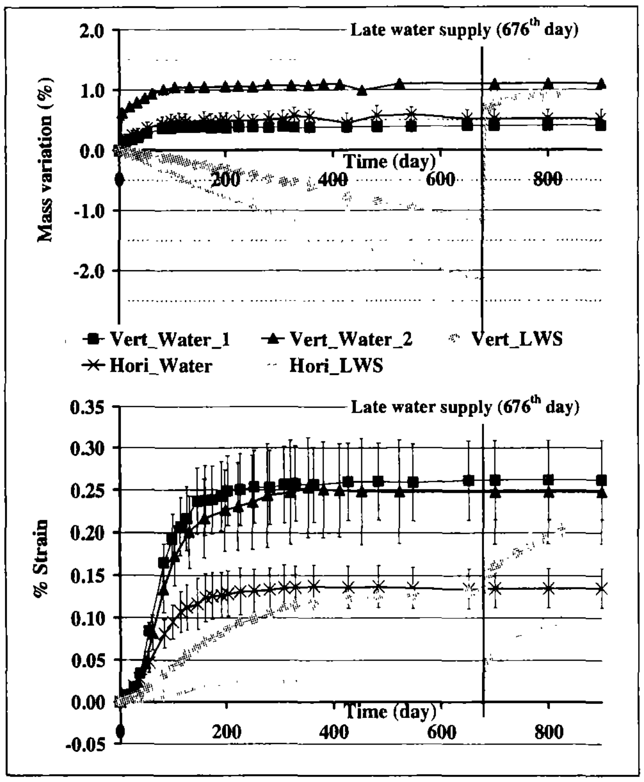

Fig. 2 Mass variations and strains measured on specimens kept under watertight aluminum during 676 days before being submitted to late water supply

For all these specimens, ASR-swellings have reached the maximal value according to storage conditions, and showed stabilization before the late water supply. The large and late water supply caused swellings even for specimens kept, before, in air at 100% RH. Thus, in the first days, large deformations have been measured. Then, they keep on and are not stabilized 150 days after the beginning of water supply.

ASR-gel already produced in the first conditions could have swelled in the first days due to late water supply, which explained large deformations in the first days. However, Fig. 1 and Fig. 2 show that specimens lost water (with negative mass variation just before the late water supply), and thus the chemical reaction could have been stopped by lack of water. The late water supply allowed the reaction to start again, which explains that swellings keep on and are not stabilized.

These results illustrate that ASR-expansion rate and range depend on moisture conditions even if ASR has already occurred in drier conditions. Large water supply can always cause new ASR-swellings if the maximal potential swellings have not been reached yet.

3 STRUCTURAL EFFECTS OF LATE WATER SUPPLY

3.1 Moisture distribution in concrete beams

Moisture distribution in the six concrete beams has been analyzed in [4, 19]. During the first 14 months, the upper part of the beams is submitted to severe drying. The mass losses can be evaluated by the gammadensitometry device between the upper face and 0.30 m of depth. In the lower part, the depth of water penetration in unsaturated ASR-damaged concrete can be assumed as proportional to the square root of time [19] as for usual concrete [20-22]. This penetration appears not to be affected by ASR, and the mean sorptivity calculated in the lower part of the beams is about 5.8E-3 m.day$^{-1/2}$ [19].

After the late water supply (430th day), water movements can be analyzed as consisting in two steps. First, analysis of gammadensitometry measurements has shown that concrete seems to recover quasi-instantaneously moisture conditions measured after the 28 curing days [4]. This first stage is modeled in Fig. 3. Then, the penetration of water can be modeled as proportional to the square root of time (Fig. 4). After the first 14 months, the reactive beams are significantly damaged, and transversal large cracks appear on the upper faces (Fig. 16). Thus, the sorptivity determined in the upper part of these beams is different of those determined in the lower part. It is about 4.35E-3 m.day$^{-1/2}$ for the plain and reactive beam.

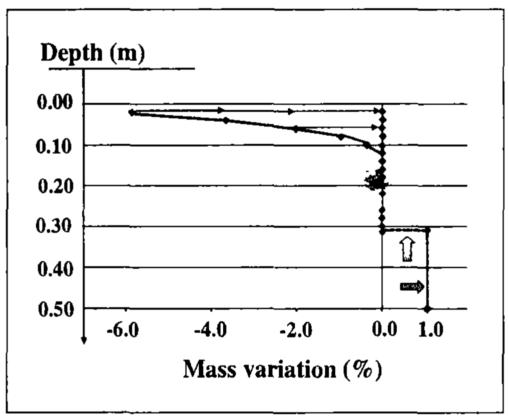

Fig. 3 First stage of moisture distribution in concrete beams due to late water supply

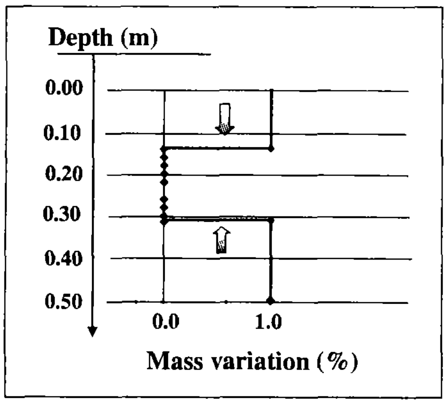

Fig. 4 Second stage of moisture distribution in concrete beams due to late water supply

This analysis allows profiles of mass variations along the depth of the beams to be plotted. These profiles are useful in order to evaluate the structural behavior of the beams [2].

3.2 Structural behavior of the reactive plain concrete beam

3.2.1 Longitudinal deformation of plain concrete beam

In order to analyze the longitudinal deformations of the beam, mechanical calculations have been carried out according to Strength of Materials theory. This relies on the assumption that cross sections remain plane. Fig. 5 represents mean longitudinal strains along the reactive beam at five time-steps (measurements are given by two or three strain sensors).

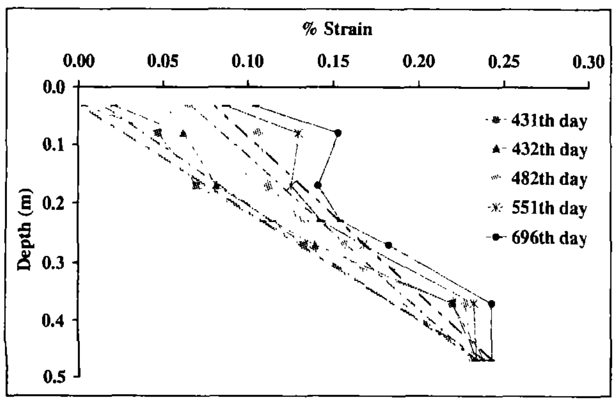

Fig. 5 Longitudinal strains along the depth of the plain and reactive beam

Longitudinal strains appear to be more scattered after the late water supply (after 432 day) than before (431^{th} day). During the first 14 months, the cross-sections have been defined by the line between the strain measurements performed at 0.03 m and 0.47 m [2]. During this second stage, large longitudinal cracks appeared on the upper faces of the plain and reactive beams, which disturbed measurements. Thus, cross-sections appears to be better represented by the line between measurements performed at 0.23 m and 0.47 m as shown Fig. 5. Thus, standard deviations between these lines and measurements are about 0.035% of strains compared to 0.02% before the late water supply.

However, by assuming that chemical swellings impose the curvature of the beams, the deflection at mid-span can be determined by: $\mathbf{f = \chi . l^2 / 8}$,

with f : deflection (m),

χ : curvature of the cross-section (m^{-1}),

l : span of the girder (m).

Considering that curvature of the cross section can be represented by the line connecting the strains given by the measurements performed at 0.23 m and 0.47 m, deflection can be computed from the slope of this line (which represents χ). Time-evolutions of calculated deflection and measured one, obtained with displacement sensors at mid-span, are quite close (Fig. 6).

This allows to validate the consistency of strain measurements at 0.23 m and 0.47 m with displacement measurements and with the Strength of Materials theory. In spite of the scattering of measurements around the cross-section, this proves the applicability of Strength of Materials theory in order to represent the behavior of this beam.

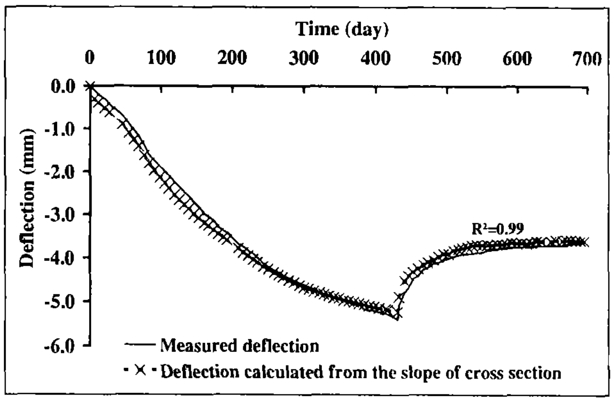

Fig. 6 Deflection measured at mid-span by displacement sensors and deflection calculated from the slope of cross-section

3.2.2 Moisture dependent ASR-induced strains

The structural analysis can be based on a chemo-mechanical approach [2], inspired by a more global approach [8]. Thus, mechanical calculations can be carried out with the following assumption: ASR-swellings can be considered as imposed strains which depend on water supply.

Profiles of imposed strains can be deduced from profiles of mass variations. During the first 14 months, structural behavior of the plain concrete and reactive beam has been explained with the assumptions described in Fig. 7, imposed strains being equal to:

- isotropic shrinkage measured on specimens kept in air at 30% RH between 0.0 and 0.08 m (decrease in mass higher than 1% with a linear relationship between the relative mass loss and shrinkage with a maximum value ε_{shr}),
- isotropic ASR-swellings measured on specimens kept under watertight aluminum between 0.08 and 0.12 m [11], ε_{alu}
- isotropic ASR-swelling deduced from deformations measured on specimens kept under watertight aluminum and kept in water (assuming linear relationship between mass variations and ASR-swellings as shown in [11]), for part of the beam without mass losses, $\varepsilon_{\delta m=0}$,
- isotropic ASR-swelling measured on specimens kept in water, for concrete reached by water penetration [11], ε_{wat_iso},
- anisotropic ASR-swelling measured on cylinders kept in water in the cracked part (about 50 mm high – [4, 11]), ε_{wat_cyl}.

Thus, the imposed strains have been determined considering water supply. In addition, imposed strains deduced from ASR-swellings have been assumed as isotropic in part of concrete which shows random map-cracking. At the opposite, they have been assumed as maximal in the direction perpendicular of cracks in the part close to immersed faces which has shown important transversal cracking (Fig. 17 - [2, 4, 13]).

The profiles of imposed strains following the late water supply can be deduced from the previous profiles, which exhibited good agreement in assessing the behavior of the plain and reactive beam [4], accounting for the water distribution described in Fig. 3 and Fig. 4.

In the first stage, concrete in the whole beam is considered to be in the same state than concrete without mass losses. Therefore, isotropic ASR-swelling deduced from deformations measured on specimens kept under watertight aluminum and kept in water (assuming linear relationship between mass variations and ASR-swellings as shown in [11]) have been first assumed in the whole upper part (Fig. 8). These ASR-swellings begin as soon as the upper face is exposed to water supply (t_{LWS}: time-step corresponding to the late water supply).

In the second stage, concrete in the upper part is saturated by the penetration of water. The square root of time evolution allows the depth reached by the water to be evaluated: 700 days after the beginning of experiment (and thus about 270 days after the late water supply), this depth is about 0.07 m.

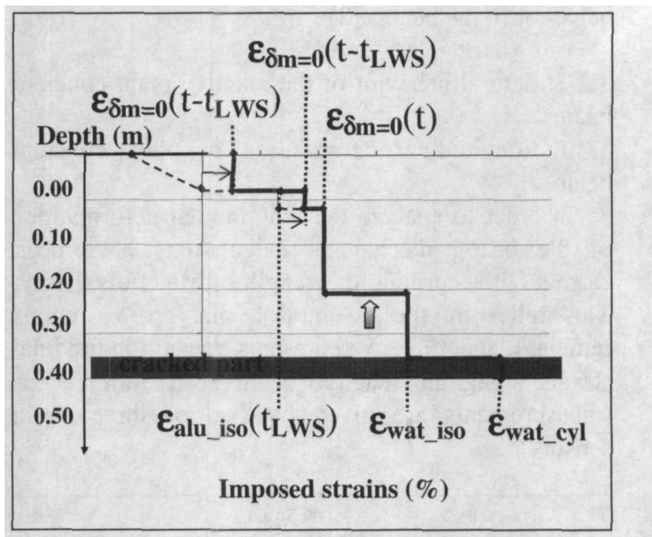

Fig. 8 Imposed strains during the first stage following the late water supply (t_{LWS}: time-step corresponding to the late water supply)

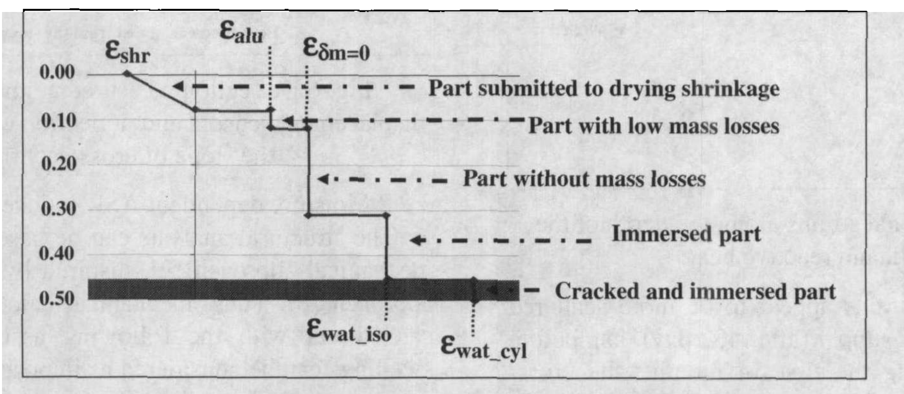

Fig. 7 Profile of imposed strains during the first 14 months

Along the depth of concrete saturated by water, the imposed strains had to be larger than in the part only reached by the first stage following the late water supply. For the sake of simplicity, imposed strains in concrete reached by the water penetration have been assumed to be equal to deformations measured on specimens kept in water since 28 days. These ASR-swellings begin as soon as the concrete is reached by the water penetration, which is evaluated by the square root of time evolution.

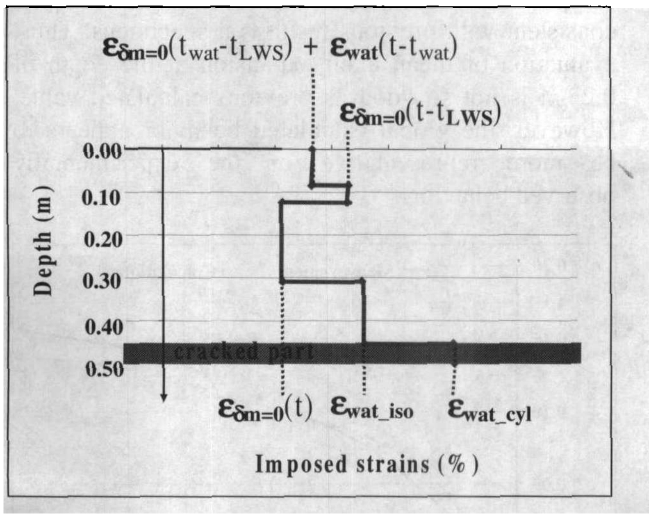

Fig. 9 Imposed strains during the second stage following the late water supply (t_{wat}: time when concrete is reached by the water penetration)

In the lower part, the scheme of moisture distribution did not change, the water penetration in the lower part kept on with the same time-evolution.

These assumptions allow the behavior of the plain and reactive beam to be evaluated from the combination "material data" (obtained on specimens, see section 2) and "moisture data". The aim of the following part is to assess the quality of such predictive calculations by comparison of calculated values with strains measured on the beam.

3.2.2 Structural analysis

The beams are submitted to chemical swellings, considered as imposed strains. By neglecting the self-weight, the two equations of equilibrium read:

$$\begin{cases} N = \int_0^h \sigma(z).w.dz = 0 \\ M_b = \int_0^h \sigma(z).z.w.dz = 0 \end{cases}$$

with N and M_b, axial force and bending moment in the section, h and w, the height and the width of the beam. If chemo-elasticity applies [2, 8], the longitudinal stresses in a section of a beam subject to imposed strain read:

$$\sigma(z) = E.(\varepsilon(z) - \varepsilon_{imp}(z))$$

with E, the Young's Modulus of reactive concrete, $\varepsilon(z)$, the longitudinal strain and $\varepsilon_{imp}(z)$, the imposed longitudinal strain according to water supply.

Moreover, the assumption that cross sections remain plane allows to represent the longitudinal strains profile by a straight-line:

$$\varepsilon(z) = a.z + b$$

Therefore, integration of equilibrium equations of the section leads to two equations with two unknown factors (a and b).

These equations can be solved for every time-step corresponding to experimental measurement. Since swellings are quite heterogeneous and calculations are based on mean swellings, standard deviation of calculations could be evaluated, which allows accuracy of calculations to be determined [4]. In order to analyze the capacity of calculations to predict the behavior of the plain and reactive beam, calculated strain and measured one at the depth of 0.23 m (Fig. 10) have been plotted in the same figure. The same comparison has been made for deflection at mid-span (Fig. 11)

The mean quadratic deviation between calculated and measured values is about 0.005% for strain and about 1.0 mm for deflection. Therefore, mean strain at the depth of 0.23 m is quite well evaluated by the calculations. At the opposite, the deflection at mid-span is significantly under-estimated. The distinctions between calculated and measured deflections can be explained by large compressive stresses, appeared with the late water supply. Indeed, calculations allow compressive stresses of about 10 MPa, 70 days after the late water supply to be evaluated. Such compressive stresses can cause large reduction of ASR-induced strains along the compressed direction and the "expansion transfer" along perpendicular directions [23-24].

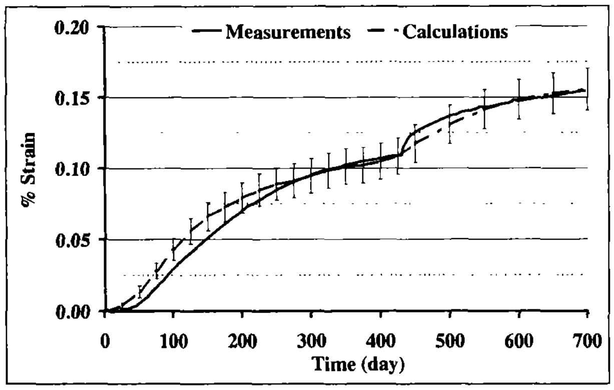

Fig. 10 Comparison of calculated strain with measured one at the depth of 0.23 m

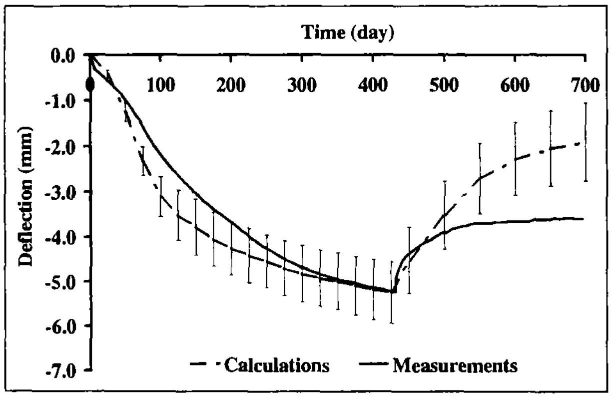

Fig. 11 Comparison of calculated deflection with measured one at mid-span

Therefore, compressive stresses should induce a reduction in imposed strains due to the late water supply along the longitudinal direction. New calculations have been computed with imposed strains reduced in the whole upper part using a simplified first approach reduction factor. Imposed strains due to the late water supply become:

- $\varepsilon_{imp} = \alpha.\varepsilon_{\delta n=0}(t - t_{LWS})$

  in the whole upper part concerned with the late water supply,

- $\varepsilon_{imp} = \alpha.(\varepsilon_{\delta n=0}(t_{wat} - t_{LWS}) + \varepsilon_{wat}(t - t_{LWS}))$

  in the part of concrete reached by water penetration.

α is the reduction factor which takes into account reduction due to compressive stresses.

In this rough approach, calculations use a global coefficient, while the reduction should be calculated at every depth of the beam, according to compressive stresses. Moreover, no definitive relationship has already been established between the range of compressive stresses and the reduction rate. Thus and for the sake of simplicity, the global reduction factor has been evaluated to obtain calculated deflection at mid-span close to measured one (Fig. 13). Therefore, calculations are not predictive, but they allow behavior of the plain and reactive beam due to the late water supply to be explained.

With a reduction factor of about 0.4 (which represents 60% reduction of ASR-induced strains), the mean quadratic deviation between calculated and measured values is about 0.15 mm for deflection and about 0.015% for strain. This 60% reduction of ASR-induced strain is quite close to calculated reduction on specimens submitted to a 10 MPa axial compressive stress [4]. Therefore, the result is quite consistent with previous results on specimens. Thus, evaluation of mean axial expansion at the depth of 0.23 m is not so good as previous calculated value. However, the global calculated behavior appears to be more representative of the experimentally observed behavior.

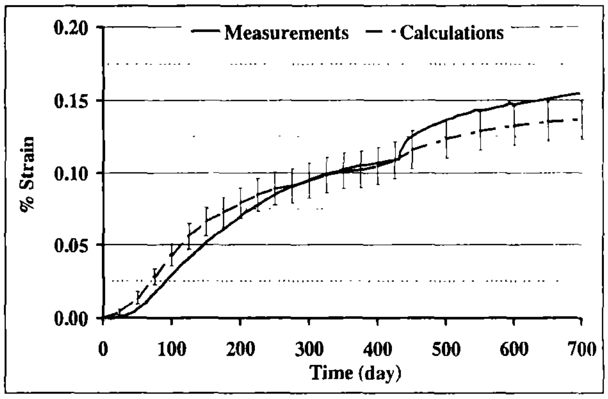

Fig. 12 Comparison of calculated strain with measured one at the depth of 0.23 m, with calculations taking into account reduction due to compressive stresses

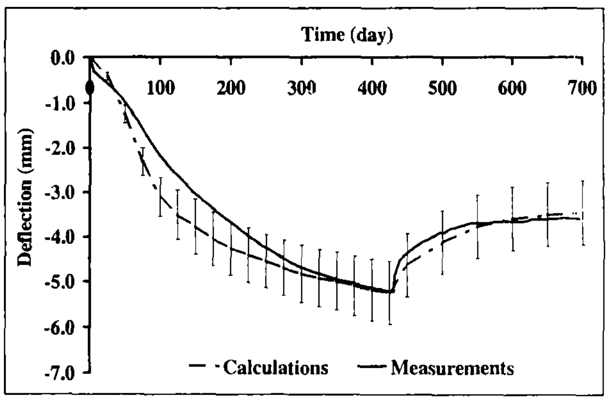

Fig. 13 Comparison of calculated deflection with measured one at mid-span, with calculations taking into account reduction due to compressive stresses

As a conclusion of this structural analysis, longitudinal behavior of this plain and reactive beam was successfully explained by the development of

ASR-induced strains in the upper part of concrete due to the late water supply. These strains cause longitudinal compressive stresses which imply reduction of ASR-swellings in the longitudinal direction. The same analysis can be carried out on the reactive and reinforced beams of this experimental program [4], which have not been presented in this paper by sake of simplicity. However, previous papers have shown that such reduction along one direction implies "expansion transfer" in perpendicular directions, that ASR-induced volumetric expansion is kept roughly constant [23-24]. Therefore, it is important to analyze the behavior of concrete in the two other directions. Moreover, it is important to analyze the behavior of expansion of the reactive concrete in the vertical direction which is free of self equilibrated stresses.

3.2.4 Vertical and transversal directions

During the first 14 months, the range of vertical strain was directly related to water supply, both for reactive and non reactive plain beams (Fig. 14 and Fig. 15). For the nonreactive one, shrinkage was measured at the depth of 0.08 and 0.17 m, and expansions due to water absorption at 0.27 and 0.37 m (Fig. 15). For the reactive beam, the closer of water supply concrete is, the larger ASR-swellings are (Fig. 14). At 0.08 m, ASR-swellings are smaller than in the lower part, but ASR appear not to be stopped. The transversal strains show similar results (Fig. 14 and Fig. 15).

After the late water supply, strains in the nonreactive beam increase quickly, to reach positive values in almost the whole beam (expansions due to water absorption). For the reactive beam, ASR-swellings increase a lot, as soon as the late water supply occurs. These new swellings are particularly important between the upper face and the depth of 0.08 m. At the depth of 0.17 m, ASR-swellings appear to be slightly accelerated. Below this depth the strains keep on increasing with the same expansion rate.

These measurements are consistent with measurements on specimens exposed to late water supply. Moreover, they show that ASR-swellings measured in the upper part of the plain and reactive beam after the late water supply are larger than swellings measured during the first 14 months (drying period), particularly in the vertical direction at the depth of 0.08 m. This result and the important longitudinal cracks on the upper face of the beam (Fig. 16) tend to confirm that longitudinal compressive stresses have caused the "transfer" of ASR-induced swellings in vertical and transversal directions.

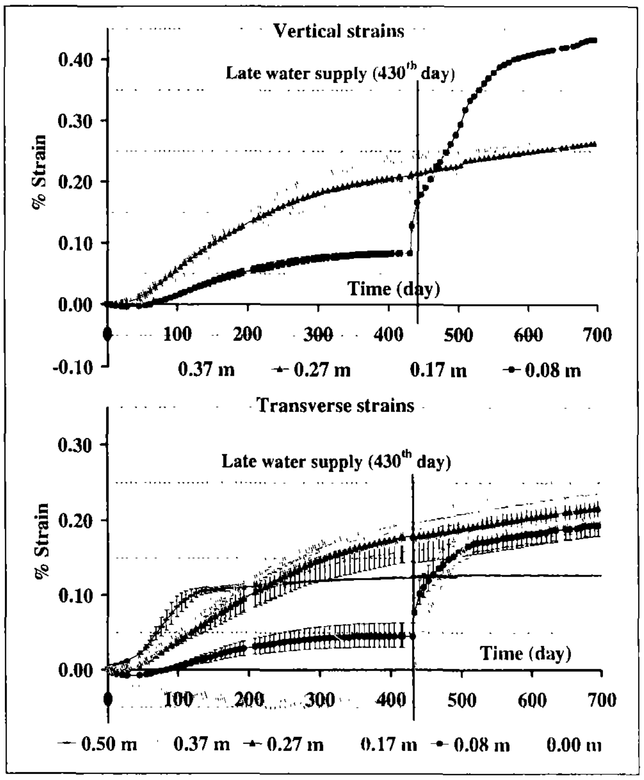

Fig. 14 Vertical and transverse strains of the reactive and plain beam measured at four depths (0.08, 0.17, 0.27 and 0.37 m from the upper faces)

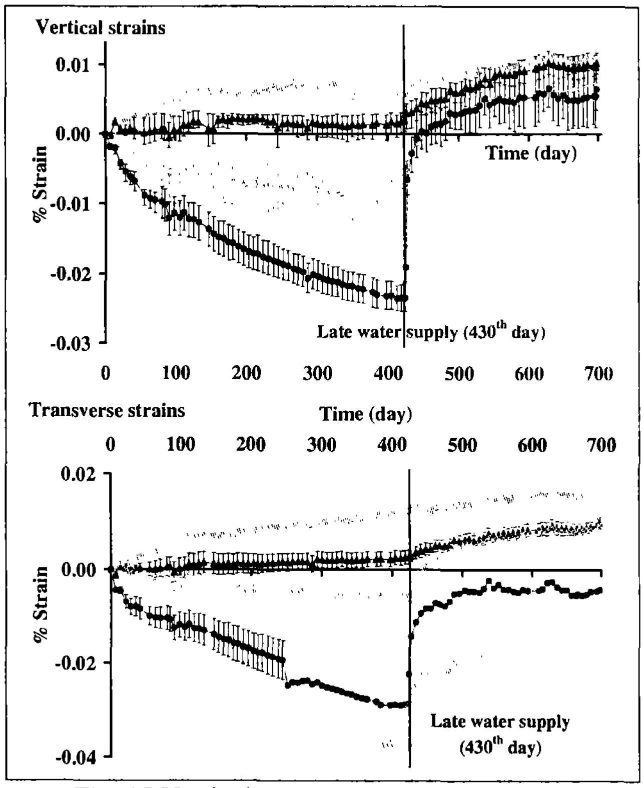

Fig. 15 Vertical and transverse strains of the nonreactive and plain beam measured at six depths (0.00, 0.08, 0.17, 0.27, 0.37 and 0.50 m from the upper faces)

4 CONCLUSION

Characterization of ASR-induced swellings due to late water supply has been carried out on specimens and structures.

Measurements on specimens have proved that water supply can cause new ASR-swellings in concrete if the maximal potential swellings have not been reached before due to lack of water. Characterization of the structural behavior of the plain and reactive beam analyzed according to the moisture distribution in the beam and the behavior of the non reactive beam confirms this conclusion. Thus, the behavior of the plain and reactive beam after the late water supply can be explained by two main processes. First, new ASR-swellings occur due to water supply. Secondly, these new imposed strains imply large longitudinal compressive stresses, which reduce longitudinal imposed strains and cause the transfer of expansion in directions free of restraint.

At last, structural calculations based on chemo-mechanical approach have been carried out using Strength of Materials theory. They validate the assumption of considering ASR-swellings as imposed strains directly related to local water supply. They also confirmed that the imposed strains have to depend on the stress state of studied structures [4, 24].

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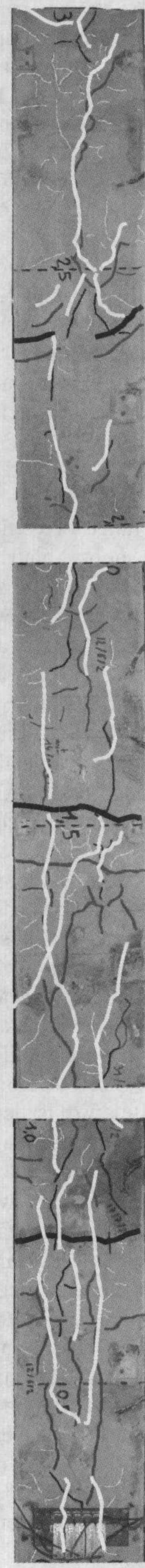

Fig. 16 Upper face of the plain and reactive beam (in black: cracks appeared during severe drying - 14th first months - in white: cracks appeared after the late water supply)

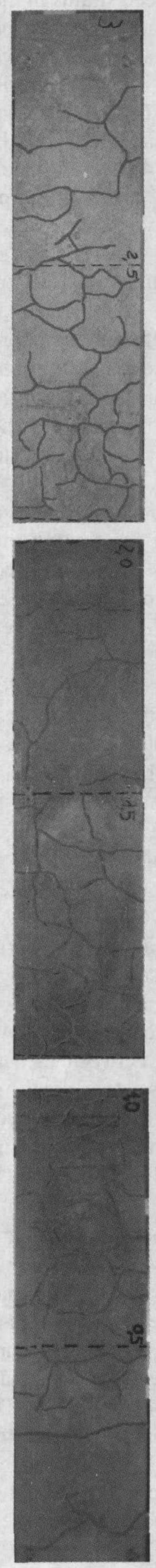

Fig. 17 Immersed face of the plain and reactive beam

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