BEHAVIOUR OF AAR-AFFECTED CONCRETE, Experimental data

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ABSTRACT

An experimental study has been undertaken to provide data to model the behaviour of a concrete affected by alkali-aggregate reaction. The main results are presented: longitudinal and transverse strain measurements of specimens freely swelling in different environments and on specimens under uniaxial stresses of 5, 10, and 20 MPa; discussion of the role of water in the kinetics of degradation of an AAR-affected concrete; anisotropy of the swelling; evolution of its mechanical characteristics.
Keywords: Alkali-Aggregate Reaction, water, longitudinal and transverse strains, stress.

INTRODUCTION

To answer the various questions raised by the modelling of the alkali-aggregate reaction (Larive & Coussy. 1996), we developed new test methods and means of measurement:

- tests under constant uniaxial stress, with devices making it possible to impose the desired force precisely and repetitively,
- means of measurement of the transverse expansion of cylindrical specimens.

Free swelling tests and other mechanical tests were also carried out to follow the time-dependent change in concrete properties. The main results are presented below.

EXPERIMENTAL

Tests

The creep devices consist of two metallic plates 32 cm square and 10 cm thick, joined by cylindrical columns 5 cm in diameter and 1.5 m high (Le Roy. 1995). Between the two plates, resting on a flexible rubber hydraulic flat jack, four cylindrical specimens 13 cm in diameter and 24 cm high are superposed. The device is calibrated to determine the hydraulic pressure that must be imposed in the jack to obtain the desired force. During loading, the determined pressure value is directly imposed and then checked, using a pressure cell built in the upper plate. A nitrogen accumulator is connected to the hydraulic jack to keep the force constant, even during the concrete creep.

Since the creep devices are very bulky, it is impossible to perform tests under stress in the French Standard NF P 18-587 standardized set-ups. However it is useful to accelerate the reaction by keeping the devices in saturated air at 38°C . It is not possible either to take the specimens out for measurement. We therefore worked in a completely air-conditioned room at 38° C, with enclosures around the devices to impose a saturated atmosphere.

For a straightforward comparison between the tests under stress and those of free swelling, the bulk of the latter set was performed on specimens of the same size, kept in the same enclosures (38°C, 100% R.H.) and also measured at 38°C. Keeping the temperature constant eliminates possible strains of thermal origin, and prevents condensation trickling that occurs when cold specimens are brought into a hot and humid enclosure. The specimens are systematically weighed before and after each measurement.

NF P 18-587 standardized tests were also carried out to check if the adopted conservation mode and specimen size affect the results.

Methods

The cylindrical specimens used are 13 cm in diameter and 24 cm high. During casting, holes 10 cm apart were left on three generating lines 120° apart. Stainless-steel studs 1 cm in diameter and 5 mm thick were set in these holes. A stainless-steel ball was crimped in the centre of these studs. The length measurements are then made with a Pfender ball-type mechanical extensometer of which the mechanical displacement sensor is replaced by a TESA GT21 inductive sensor (resolution 1 micron). Given the amplification of the mechanical system, the total resolution of the apparatus is 0.2 micrometer.

For the transverse measurements, a removable robot was designed . Each specimen is bonded to the centre of a metallic plate having conical holes for the attachment and repositioning of the robot parts. To this base, a circular ring is attached, holding a gear mounted on ball bearings and driven by a motor-reducer with an angle encoder. On the gear, a semi-circular clevis is placed, bearing two diametrically opposed sets of three GT22 pneumatic-lift inductive sensors (TESA). The transverse swelling is measured at 3 levels, distributed over 7 cm in the central part of the specimen, at 10 different angular positions, allowing the measurement of 30 diameters. Each specimen is compared to a reference specimen. The mean of four successive measurements is used.

Materials

We chose reactive aggregates used in several structures affected by the alkali-aggregate reaction in Northern France. These limestone aggregates contain a diffuse network of reactive silica. Our materials were supplied by the reference stock of the Laboratoire Central des Ponts et Chaussées. They are available to interested researchers. Non-reactive limestone aggregates of the same mechanical properties were also used to cast "sound" specimens producing the same creep as the tested reactive concrete.

The cement used is an Ordinary Portland Cement (OPC) which contains 1.13% Na_2Oeq. The cement proportion in the specimens is 410 kg/m^3, the Water/Cement ratio is 0.48, the Gravel/Sand ratio 1.5. To obtain 1.25 % Na_2Oeq, potash was added to the water of both reactive and non-reactive concrete mixes, allowing a better comparison of their mechanical properties.

After casting, the specimens were kept for 3 days at 23°C and 98 % relative humidity, then removed from the moulds and stored for 11 days under a layer of plastic shrink film and self-adhesive aluminium. After this 14-day curing, the specimens for the tests at 38°C are pre-warmed, while still wrapped in the aluminium. The first measurement is taken only on the 15th day to limit the early age creep of the specimens under stress. A large number of measurements then follows under the same conditions.

RESULTS

Controlling step

In a batch of 50 specimens, the longitudinal swellings are well correlated with the water absorption, that can be measured by the weight variation of the specimens. In order to explain the dispersion of the swellings, other parameters are relevant, among them the porosity of the material; but the role of water seems highly preponderant.

In the non-reactive specimens kept under the same conditions, the same values and the same dispersion of weight variations are found. Therefore, no extra-water is consumed in the formation of the reaction products. The movements of water are governed by the same physical phenomena as in a non-reactive concrete.

Figure 1 shows that identical concrete specimens have totally different swelling values, depending upon the water exchange with the environment (Tomosawa *et al.* 1989).

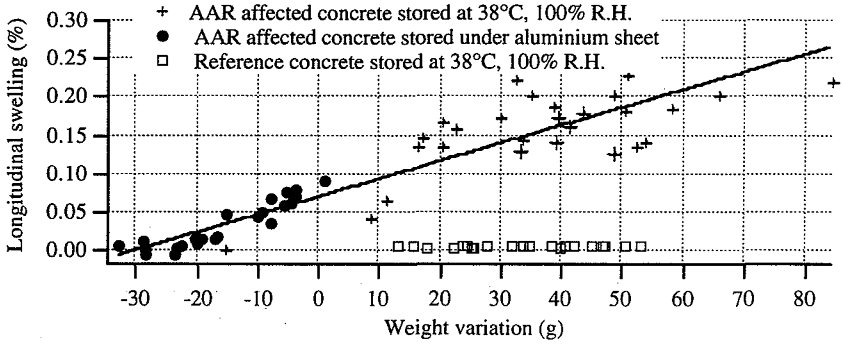

Fig. 1: Correlation between longitudinal swelling and change of weight

Others results illustrate the influence of water penetration in the specimens (Fig. 2). The NF P 18-587 standardized prisms (7 x 7 x 28 cm) have a surface/volume ratio twice as large as that of our cylindrical specimens and they are only slightly more than half as thick. Water can therefore penetrate much more easily and the standardized specimens start swelling before the more bulky ones, used in our test program. On the other hand, the final swelling value is clearly less in the standardized tests, either because there is much more condensation trickling in the NF P 18-587 containers, leaching out the alkalis (Rogers & Hooton. 1991), or due to the size of the specimens (Clark & Leslie. 1993).

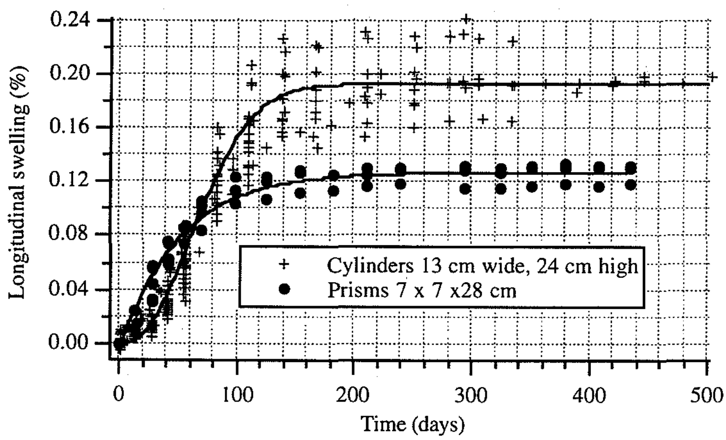

Fig. 2: Swelling of prisms and cylinders of the same composition, kept at 38°C, 100% R.H.

Reaction products are found even in specimens kept with no external input of water but microscopic examinations indicate that there are less products than in specimens of the same age kept in water saturated air (Louarn. 1995). Moreover the swelling is decreased. This confirms that external water supply modifies the swelling of the material (IStructE. 1992). But this swelling does not depend only on external water supply.

Comparing swelling tests at 23 and 38°C, we can see on Fig. 3 that water absorption is faster for the specimens at 23°C than for those at 38°C (humidity even higher in our enclosures at 23 than at 38°C) but the swelling is much faster at 38°C than at 23°C; more water penetrated the specimens at 23°C but the final value of expansion does not seem to be modified. Thus, when water is available *ad libitum*, it seems that the rate of dissolution of the silica limits the velocity of the process as a whole.

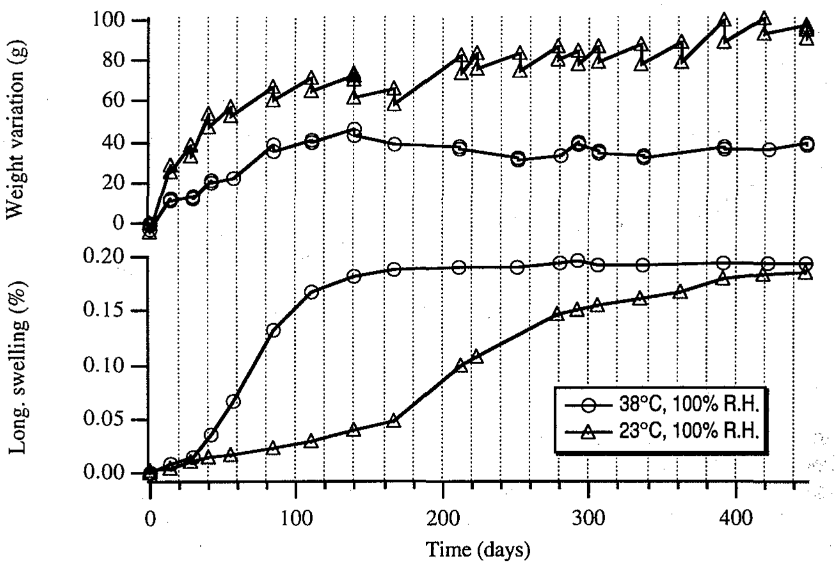

Fig. 3: Weight variation (upper) and longitudinal swelling (bottom) at 23 and 38°C

It is therefore necessary to combine the two phenomena, dissolution of silica and penetration of water, to correctly describe the global process. This could account for the shape of the beginning of the swelling curves, often sigmoid (Curtil & Habita. 1994, Bérubé & Duchesne. 1992, Bolton & Wang. 1992, Sibick & Page. 1992, among many others).

Mechanical stresses

Three reactive and one non-reactive specimens are placed in each creep device. The loading of the devices is 5, 10, and 20 MPa. The time-dependency of longitudinal and transverse swelling were measured. The instantaneous loading effect was systematically subtracted for the analysis of the results.

Note that all of these tests are performed at 38°C in saturated air. This modifies the concrete creep which increases with temperature (Neville *et al.* 1983) and decreases with moisture.

Under 5 MPa, the longitudinal expansion is decreased by more than 75 % (see Fig. 4). The creep, directly measurable on the non-reactive specimen, is of the order of -0.006 %. At 10 MPa and 20 MPa, it is nearly no longer possible to distinguish between the longitudinal expansions of the reactive and non-reactive specimens. The creep is larger, of the order of -0.03 % at 10 MPa and -0.09 % at 20 MPa after one year. The bulk of the creep occurs during the first 40 days. After this period, it stabilises at 10 MPa and continues more slowly at 20 MPa.

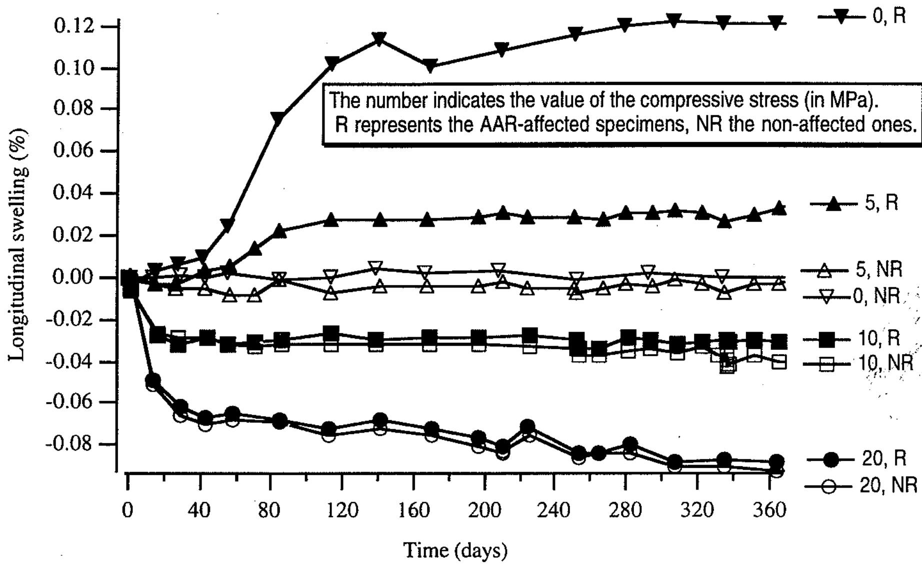

Fig. 4: Longitudinal swelling of specimens under uniaxial stress

Transversely, the effect of the creep is small on the non-reactive specimens (≤ 0.02%). The increase in diameter of the specimens subjected to a stress of 10 MPa is of the same order as that of the specimens in free swelling. That of the specimens at 5 and 20 MPa is greater. This is true both for the reactive specimens and for the non-reactive specimens, but the phenomenon is much more pronounced in the reactive specimens.

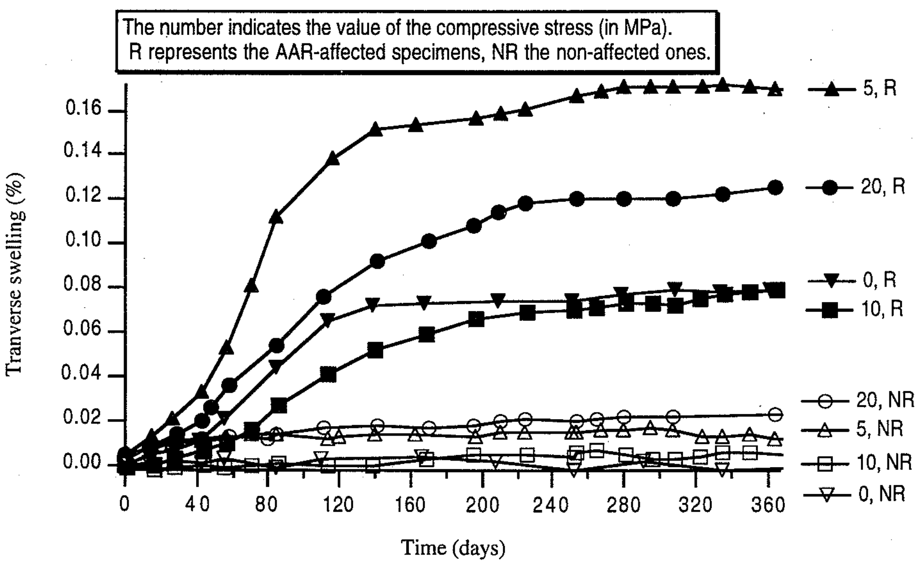

Fig. 5: Transverse swelling of specimens under a uniaxial stress

On Fig. 4 and 5, the curves representing the reactive concrete are the average of three specimens (with a dispersion less than 0.01%), there was one non-reactive specimens in each creep device and three in free swelling.

Assuming that the specimen remains cylindrical, the formula $\frac{\Delta V}{V} = \frac{\Delta L}{L} + 2 * \frac{\Delta D}{D}$, where V is the volume of the specimen, L its length, and D its diameter, leads to a volume swelling of the reactive specimens under 5 MPa of approximately 0.37 %, *i.e.* 32% more than that due to free swelling (0.28 %). It is 0.16 % at 20 MPa (-43%) and 0.12 % at 10 MPa (-57%).

The coupling between the stress and the alkali-aggregate reaction is therefore complex (increase of volume change at 5 MPa but reduction at 10 and 20 MPa, greater at 10 than at 20). Two opposing phenomena may explain this: the reduction of the porous space of the concrete may interfere with the diffusion of the reactants and make the reaction more difficult; in return the products formed cause more swelling since the space available is limited.

It was found that a 5 MPa stress does not decrease the volume swelling but increases it. This shows that any repair by addition of prestress must necessarily be three-dimensional.

Isotropy of free swelling

On 16 cylindrical specimens kept at 38°C and 100 % R.H., without any external mechanical stress, the longitudinal expansion clearly exceeded the transverse swelling. This is consistent with the prevailing transversal crack orientation. However, our measurement methods do not distinguish the origin of the dimensional variations (pure swelling or cracking). On the longitudinal measurement, the sum of the crack openings is added to the swelling, whereas, for the transverse measurement, it is added to the circumferencial swelling. Its influence on the diametrical expansion must hence be divided by π.

For these 16 specimens, the ratio between the length and diameter increases ranges between 1.5 and 2. It is practically constant in time for a given specimen (Fig. 6).

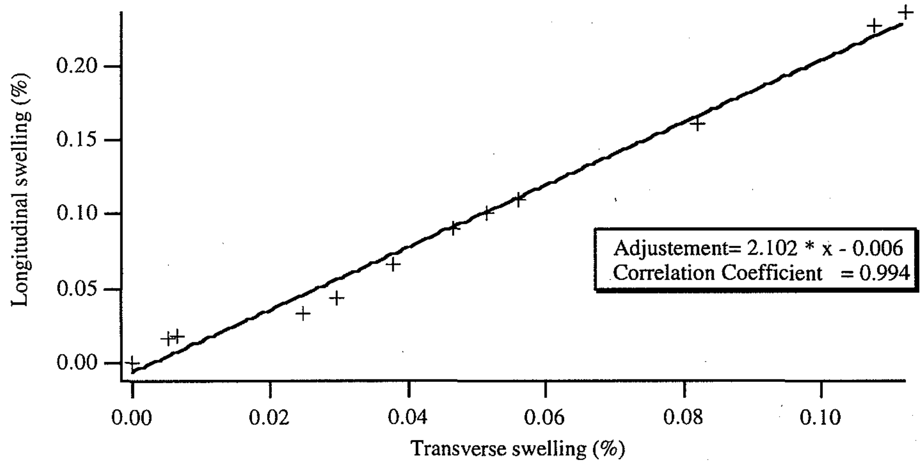

Fig. 6: Ratio between the longitudinal and transverse swellings

It is therefore found that the swelling is not isotropic. Since the same phenomenon is observed in a specimen stored horizontally, this anisotropy can not be related to the storage position. Additional tests on cubic specimens have been undertaken to better understand the origin of this anisotropy, and in particular the possible influence of the shape of the specimens or of the casting and vibration directions.

Mechanical properties

In the model proposed (Larive & Coussy. 1996), a linear elastic concrete behaviour was assumed. This assumption needs to be verified with respect to experimental data. An investigation of the Young's modulus (E) of damaged concrete shows that the behaviour of the material remains elastic, at least up to 30% of the compressive strength. However, the value of the E-modulus decreases more or less substantially with time, depending on the specimens (see Fig. 7).

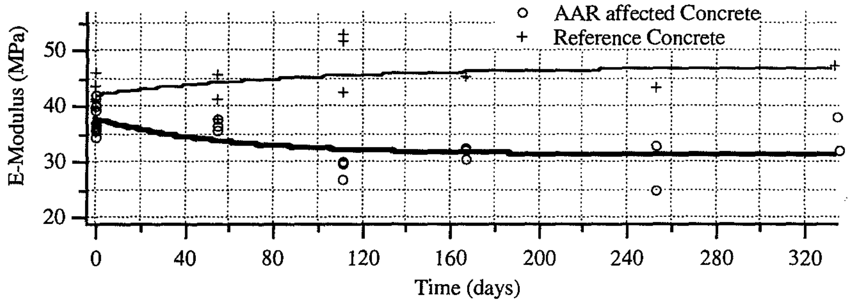

Fig. 7: Evolution of the Young's modulus versus time

The interpretation of these tests is complicated by the fact that the main crack orientation due to AAR is perpendicular to the loading of the specimens. The influence of the reclosing of these cracks in a cyclic E-Modulus test is therefore a maximum. On the other hand, in the case of a prestressed beam, the cracks are horizontal and the bending behaviour of the beam will most likely remain unchanged (Jones *et al.* 1994).

Surprisingly, the compressive and tensile strengths (measured by a splitting test) do not decrease, even on cracked specimens that have reached swellings of the order of 0.2 % (Fig. 8). Nevertheless, when synthetic AAR-products are formed between two pieces of clinker, it is impossible to separate them. Further tension leads to failure inside the clinker (Dron. 1995). Concrete is thus damaged by cracking due to AAR and not by the presence of the reaction products.

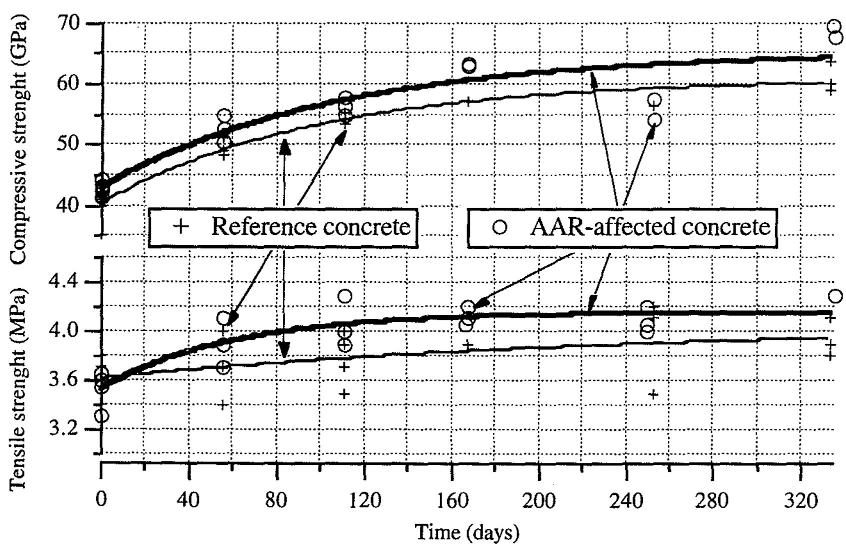

Fig. 8: Compressive (upper) and tensile strength (bottom) versus time

CONCLUSION

- Water plays a fundamental role in the swelling of concrete affected by alkali-aggregate reaction. A model must take into account both the transport of water in the material and the dissolution kinetics of the reactive silica.
- The influence of mechanical stresses is complex. Under 5 MPa, the strains confined in one direction are transferred to the unstressed directions. The volume swelling is even larger than that due to free swelling. It is clearly decreased under 10 and 20 MPa; but no simple rule seems to govern this phenomenon.
- On cylindrical specimens 13 cm in diameter and 24 cm high, a notable anisotropy of the free swelling is observed. Correlatively, the prevailing crack orientation is perpendicular to the axis of the specimens. By contrast, as is found in prestressed structures, cracks are exclusively parallel to the compressed direction for specimens under uniaxial stress.
- In saturated air at 38°C, the compressive and tensile strengths increase with time, slightly more in AAR-affected specimens than in the non-reactive reference ones.
- The Young modulus decreases, but the behaviour of AAR-affected concrete remains linear elastic under the test cycling stresses. The reduction of the modulus seems not great enough to let down the assumption of linear elasticity in the previously proposed model (Larive & Coussy. 1996).

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