MICROSTRUCTURE OF STEAM CURED CONCRETES DETERIORATED BY ALKALI-SILICA REACTION

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ABSTRACT

In order to know the main cause of the cracking of concrete prisms, the deterioration process was reproduced in the laboratory using the same thermal cycle and materials. Model concretes were first steam cured, then examinated for ASR using CSA-A-23.2.14A accelerated test. Linear expansion of concrete prisms were measured and fracture surfaces of concrete after treatment were observed under scanning electron microscope. They showed ASR gels and secondary ettringite. A simultaneous thermal mechanical computation gives the global microcracking of concrete induced by the steam curing. A second computation showed the accelerating role of temperature on the local development of ASR products.
Keywords : Alkali-silica reaction, computations, expansion,scanning electron microscopy, secondary ettringite

INTRODUCTION

Steam curing concretes have exhibited superficial cracks after several years in service on differents sites. They were produced with the same aggregate containing alkali reactive minerals but with various cements which differed from each other mainly in SO_3 contents.

Under the microscope, deteriorated concretes exhibited cracks within aggregates and cement paste. These cracks radiated from aggregates to cement paste in tortuous paths. Ettringite was also found at the cement paste - aggregate interface and in cracks or pores in the cement paste.

In order to clarify the behaviour of these site concretes, model concretes were prepared with the same materials. The influence of temperature during the steam curing in the cement paste and on the ASR was calculated using a computer model.

EXPERIMENTAL STUDY

Model concretes were made with five different cements (table 1). Their behaviour regarding the AAR was tested after thermal treatment and compared to those of standard samples kept at room temperature before the AAR tests. The mix design of the concretes is in the table 2

Table 1 : Chemical and mineralogical (Bogue calculation) composition of cements

Cement	A	B	C	D	E
C_3A	8.1	8.1	10.6	8.2	8.2
SO_3	4.23	3.21	4.21	3.05	4.25
Na_2O	0.860	0.830	0.810	0.369	0.369

Table 2 : Mix design of concretes

Cement : OPC	446 kg/m3
Water	179 l/m3
Coarse aggregates : 5-12 mm	1028 kg/m3
Sand : 0-5 mm	706 kg/m3
Retarder	928 ml/m3
Air entraining agent	77 ml/m3
Water/Cement ratio	0.4

Thermal cycles of steam cured concretes : Two different thermal cycles of steam curing were applied to concrete prisms of 7 by 7 by 28 cm. The maximun temperature was 60°C for the first cycle and 80°C for the second one (fig. 1)

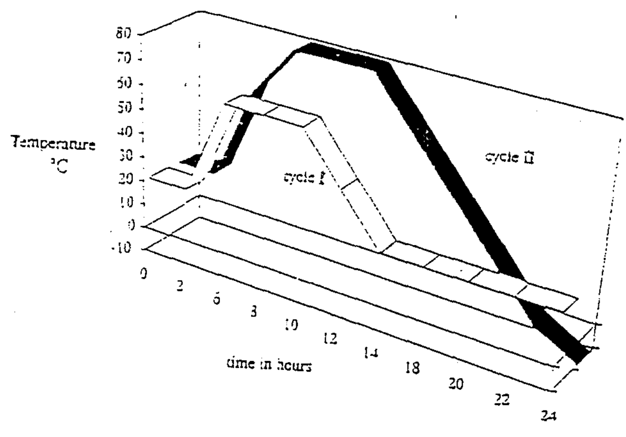

Fig 1 : Thermal cycle used

Alkali aggregate reaction : The alkali-aggregate reactivity was evaluated with a special equipment standardized in France. This equipment maintains the relative humidity at 100% and the temperature at 38°C with a double regulation system (Ranc et al 1990)

Linear expansion : Linear expansions have been measured up to 270 days (table 3). The results show that all the cements behaved in the same way. However, the expansions of cement A, B and D exceed the limit of 0.4%.

Table 3 : Linear expansion (%), 270 days

	A	B	C	D	E
first cycle	0.65%	0.95%	0.74%	0.75%	0.85%
second cycle	0.78%	0.55%	0.28%	0.74%	0.36%
standard	0.48%	0.41%	0.27%	0.41%	0.22%

NUMERICAL STUDIES

In order to simulate the effect of the thermal treatment on concrete elements, we have used two models developed at our laboratory. The first evaluates the predamaging zones induced by the thermomechanical effect due to the cement hydration (Bournazel & Moranville 1994a). The second one evaluates, through a probabilistic approach, the expansion of concrete bars affected by ASR. In this model, the temperature effect on kinetics of reaction is represented by the Arrhenius' function (Sellier et al 1995).

Thermomechanical computations : During the hydration of the cement paste, some phenomena occur (heat generation and volume changes). They can result in the cracking of a concrete structure. From the mechanical point of view, elastic characteristics are involved. Simultaneously, strains appear due to self-dessiccation, thermal gradient, environnemental effects and concrete composition.
Using the thermodynamics of irreversible processes, we have developed a global model capable of describing these main phenomena. The starting point is the free energy potential which can be expressed as (Bournazel 1992) :

$$\rho\psi = \frac{1}{2}(\varepsilon - (\varepsilon^{th} + \varepsilon^{sh} + \varepsilon^{c})) : \Lambda(M)(1-D) : (\varepsilon - (\varepsilon^{th} + \varepsilon^{sh} + \varepsilon^{c})) + \rho\psi_M + \rho\psi_T \qquad (1)$$

where $\rho\psi$ is the free energy potential, $\rho\psi_M$ is the free energy due to maturation, $\rho\psi_T$ is the free energy due to thermal effects, $\Lambda(M)$ is the tensor of elastic characteristics affected by maturity, M is maturity, $\varepsilon^{th} + \varepsilon^{sh}$ are the volumic strains due to thermal variations and autogeneous shrinkage, ε^{c} is the maturation creep strain and ε^{e} is the elastic strain and D is damage considered, as isotropic

It is possible to deduce the expression of stress from the free energy according to the first state law defined by equation (2)

$$\sigma = \frac{\partial\rho\psi}{\partial\varepsilon} = \Lambda(M)(1-D) : (\varepsilon - (\varepsilon^{th} + \varepsilon^{sh} + \varepsilon^{c})) \qquad (2)$$

This model was applied to the case of steam cured concrete ties ; the mesh used is described in figure 2. The numerical computations, realised with the finite elements code (CESAR-LCPC 1987) gave a damage map of the structure due to thermal effects. The results are presented in figure 3 and show that after three days the tie presents, already large damaged zones in its thicker part. There are, however, no external indications of damage. The microporosity and microcracking functions change, thereby modifying the permeability of the material which affects fluid transports (Bary and Bournazel 1995).

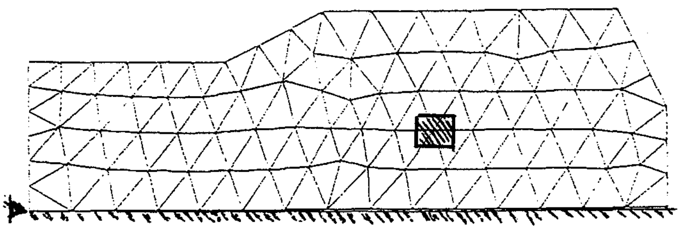

Fig 2 : Mesh used for numerical computation of concrete elements and boundary conditions

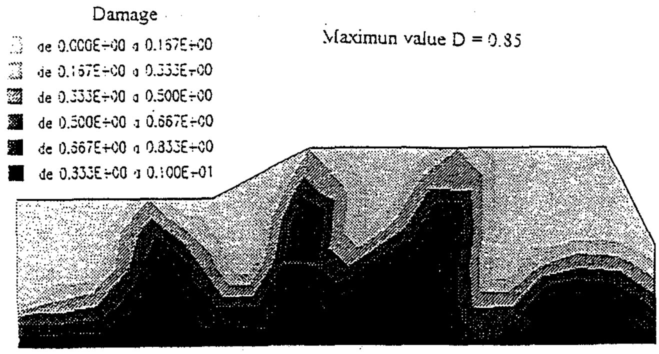

Fig 3 : Damage in concrete tie after three days

Probabilistic computations : The mechanical modelling of AAR is made with a deterministic approach. Usually concrete is considered as homogeneous and chemical reaction as uniform in the volume. However, chemical processes are mainly induced by local supersaturation and not by average value of concentration (Bournazel, Capra, Mébarki, Sellier 1994, Sellier, Bournazel, Mebarki 1995). In our model, the calculation takes into account a random reactive site distribution. The model considers the average values and standard deviation of all parameters (fig. 4)

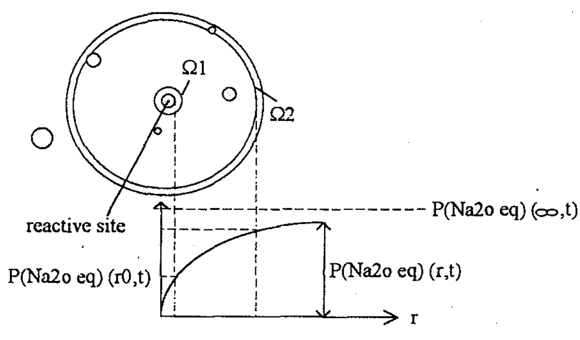

Fig 4 : Evolution of the probability of Na_2O_{eq} versus r, size of reactive silica particle

The computation (fig 5) showed that increase of temperature accelerated the expansion of concrete. A temperature of 70°C induced the onset of expansion ten times faster than a concrete kept at room temperature. This numerical simulations are in agreement with experimental results by Ong and Diamond (Ong & Diamond 1995)

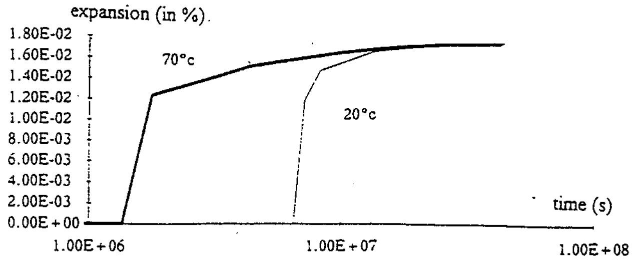

Fig 5 : Simulated expansion of two concretes cured at different temperatures (20°C and 70°C)

The model proposed and presented at this conference by Sellier et al (Sellier, Bournazel, Mébarki 1996) has been applied to this case study. Some parameters values have been obtained from SEM analysis, the others ones, when there were not available, have been chosen in litterature. The results are reported on figure 6

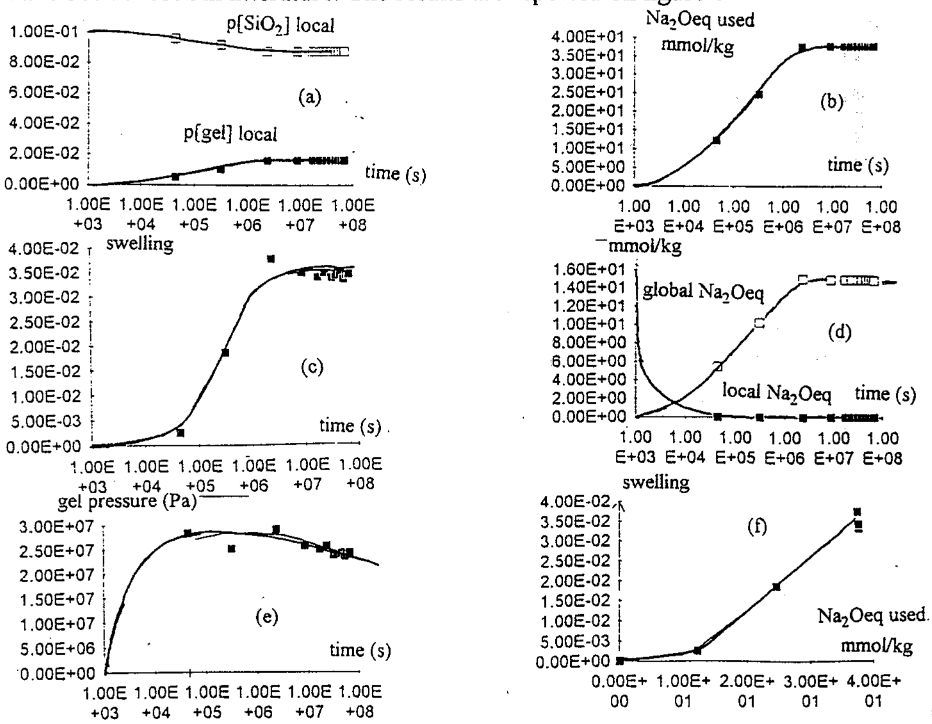

Fig 6 : (a) Evolution of probabilities of reactive silica and gel versus time, (b) Evolution of Na_2Oeq used versus time, (c) Evolution of swelling versus time, (d) Evolution of total and local Na_2Oeq versus time, (e) Evolution of the gel pressure versus time and (f) Evolution of swelling versus Na_2Oeq used (in %)

All computations have been realized in an external temperature of 70°C. The figure 6a shows that in this case only a few reactive silica is used by ASR, the swelling is around 3 to 3.5% (fig 6c) for a non confined concrete sample. This value largely exceeds the limite of 0.4%. Such a swelling can induce important cracks in a concrete piece. One can also remark that at the local level all alkalies are used in the chemical reaction (fig 6d). A further reaction needs a new local inflow of alkalies. The figure 6e shows that the gel pressure can reach 25 MPa. This value is largely over the tensile strength. In this case we find an induction period for ASR (fig 6f)

MICROSTRUCTURE OF MODEL CONCRETE

After 250 days of the AAR accelerated test, all concretes with the reactive aggregate presented the same external signs of alteration (pop-outs, gel exudations, cracks). In all concretes which expanded, ASR gels and ettringite were observed on surface fractures under SEM, whatever the type of cement or the thermal cycle, as follows : coexistence of ASR gel and ettringite (fig 7), ettringite as a thin layer on aggregate surface, in fibers (fig 8).

Same observations were already published (Regourd, Hornain and Poitevin 1981, Shayan and Quick 1992). The redistribution of SO_4^- ions in the pore solution forms ettringite through solution, possibly as microcrystals in the C-S-H , where the cement paste expands, ettringite recrystallises in the cracks (Taylor 1993).

Fig 7 : Cement A, cycle I, 100d at 38°C. Coexistence of AAR gel (+) and secondary ettringite (o)

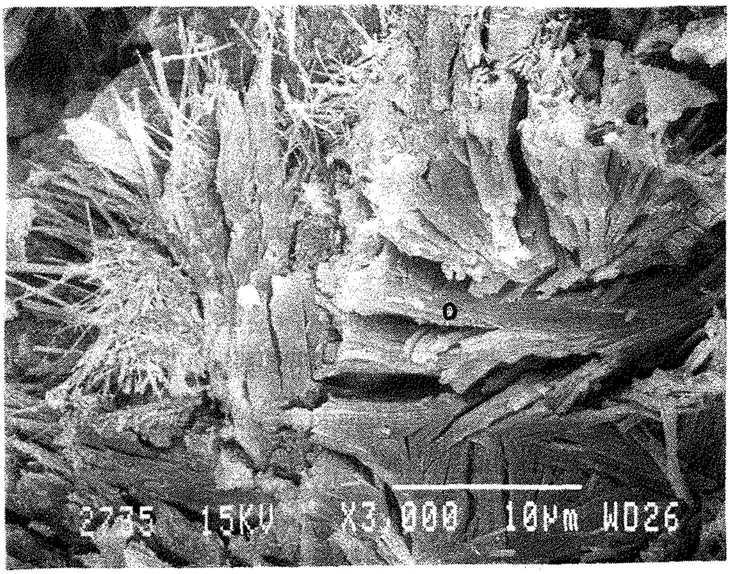

Fig 8 : Cement B, 2d at 20°C, 100d at 38°C, secondary ettringite (o)

DISCUSSION

The results of computations show that the steam curing treatment (temperature > 60°C) damages the concrete and accelerates the ASR and its resulting expansion.

The SEM observations of site and model concrete are similar : both clearly show ASR product and secondary ettringite. In cement A the ASR gel existing even at 20°C developed a grainy texture related to an increase in Ca^{++} ions as observed at three months (Bournazel and Moranville-Regourd 1994b). The cement D and E contained only 1.65 Na_2O_{eq}/m^3. With this low amount of Na_2O_{eq} no ASR usually occurs. The aggregate was treated chemically for evaluating an eventual solubilisation of alkalies. It was found that the aggregate was a source of alkalies in the concrete.

The same concretes made with a non reactive aggregate (limestone) did not expand either after the first cycle or after the second cycle of steam curing followed by the AAR accelerated tests.

The ettringite occurred as massive aeras coexisting with ASR gels at the cement - aggregate interfaces or in veins in the matrix. This ettringite which appears as a secondary ettringite was observed in all the concretes whatever the amount of SO_3 in the cement used in this study.

CONCLUSIONS

The alkali-aggregate reaction was the main cause of cracking of concrete prisms made with alkali reactive aggregates. The deterioration process is reproducible.

- Steam curing damaged the cement paste and accelerated the ASR.
- The ettringite coexisting with ASR gels was a secondary ettringite, able to enhance expansion.
- The same deterioration occurred for cement low and high SO_3 (3.05 - 4.25%).

- There was no expansion and no visible cracks when alkali reactive aggregates were replaced by inert aggregates, whatever the type of cement.

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