EVALUATION OF THE RELATIONSHIPS BETWEEN SWELLING, CRACKING, DEVELOPMENT OF GELS

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ABSTRACT

The fluorescence of alkali-silica reaction products under ultraviolet radiation has been used as a diagnostic method to detect the presence of the alkali-silica reaction in damaged concretes. With the help of image analysis, the fluorescence of gel zones may be used to monitor the evolution of the reaction. In the experiment presented in this paper, the authors compare the evolution of the reaction measured through the growth of reactive surfaces with time with measurements of longitudinal expansion and with the development of cracks. Such an approach makes it possible to compare two distinct characteristics, on the one hand the chemical aspect of the reaction, which is revealed by the development of gels, on the other the mechanical aspect, characterized by the outbreak of cracks. For a given concrete, it then becomes possible to specify the stage of progress of the reaction, from which the concrete is damaged by the outbreak of cracks.

Key words: alkali-aggregate reaction, gel, fluorescence, swelling, cracking.

INTRODUCTION

The results presented in this article originated in thesis work currently being done at the L.C.P.C. by C. Larive on the macroscopic modelling of phenomena related to the alkali-aggregate reaction. This work required the production of a very large quantity of test objects, and we thought that it might be used as an opportunity to test a new technique of quantification of the reaction gels revealed by fluorescence of uranyl ions, a technique already tested and used for a few years both in the U.S.A. (K. Natesaiyer and K.C. Hover, 1988, 1989, 1990) and in France (J-S. Guédon and F. Martineau, 1991, 1992). Quantification was the logical sequel to this test; the L.C.P.C. therefore acquired image processing and analysis software for the purpose of quantifying the phenomenon. The percentages of distribution of the gel in some specimens taken from the batch were compared with measurements of longitudinal swelling and with percentages of cracking.

WORKING METHOD

Type of samples

The formulation of the concrete was deliberately chosen to give a rapid alkali-aggregate reaction; for this purpose, the gravel used was a limestone with scattered silica, a gravel regarded in France as an archetypical reactive material. The formula was doped to 1.25% potash to reproduce the standard conditions of alkali-aggregate reaction tests. The conditions of preservation were also those closest to the standards currently used to qualify the potential reactivity of aggregates, in other words 38°C and 100% relative humidity.

The cylindrical concrete specimens 13 cm in diameter and 24 cm high were systematically broken by shear without water into 8 slices. Both sides of each slice were examined and photographed, except for the bottom of slice 1 and the top of slice 8, which are pouring surfaces, giving 14 images for each specimen.

L.P.C. test number. 36 (1992)

Principle

The amorphous products of the alkali-aggregate reaction are revealed by a method based on the fluorescence of uranyl ions, developed in the United States (K. Natesaiyer and K.C. Hover, 1988, 1989; K. Natesaiyer et al, 1991), and since used in France (J-S. Guédon and F. Martineau, 1991, 1992). The products most characteristic of the alkali-aggregate reaction are found in the material concrete in the form of a gel containing variable proportions of negatively charged amorphous silica and Ca^{2+}, K^+ and/or Na^+ ions. The uranyl ion $(UO_2)^{2+}$ has exchange capacities (K. Natesaiyer and K.C. Hover, 1988), and replaces preferentially the cations in the gel; its own fluorescence in the yellow-green hues under hard ultraviolet excitation serves to distinguish the pathogenic zones, occupied by the gel, from the sound remainder of the concrete. What had to be done was therefore to quantify these zones revealed by fluorescence, so as to determine the percentage of the area occupied by the reaction products.

Course of the test

This test must be performed on fresh fractures, for example those produced by the "Brazilian" test, so as to eliminate the problems inherent in carbonation. After spraying of the reagent and illumination by hard ultra-violet excitation, the image can be produced, using two light sources 90° apart to avoid any shadows from surface irregularities of the sample of concrete.

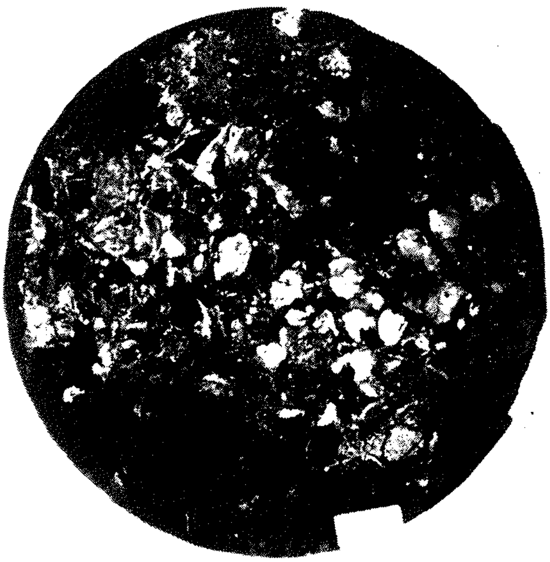

Fig. 1 The reaction gel appears in yellow-green against the dark blue background of the sound concrete.

The reaction products may develop either at the paste-aggregate interface, or by filling pores and cracks, or in the paste. These various localizations entail different degrees of precision in the delimitation of the zones to be quantified.

Optimization of image production

Given the type of light source needed to cause uranyl ions to fluoresce, which has a wavelength of 254 nm, and given the low intensity of the radiation emitted, several techniques were tested with a view to optimizing production of images of the phenomenon. The camcorder and 3 CCD camera were rejected on the grounds of insufficient sensitivity for close-ups; scanning a photograph on paper gave acceptable results, but there is a risk of drift of the colors when printing. The solution chosen was to scan a transparency. As for the taking of the pictures, the parameters of film sensitivity, exposure time, and diaphragm opening were fixed after many tests on concretes giving as wide a range of fluorescence responses as possible.

Acquisition and processing of the images

The image acquisition and processing software used is OPTILAB. It runs on a Macintosh platform. It allows the acquisition of images in black and white (8 bits), and of images in color (24 bits). The advantage of 24-bit acquisition, in three planes, is to be able to select the plane yielding the maximum of information necessary for the processing. There are two possibilities:

RGB: Red-Green-Blue

HSL: Hue-Saturation-Lightness

For polychrome images, there is no hard-and-fast rule; the operator chooses the plane according to the objects to be "isolated". The images taken under ultraviolet lighting are in two colours (blue and yellow-green); the difficulty comes from the fact that between these two hues there exists a multitude of shadings. In the case of interest to us, it is the H (hue) plane that turns out to be the most selective. To quantify only the fluorescence that corresponds to the gel, it is necessary to determine selection thresholds. The yellow-green level was calibrated using a sample of synthetic gel, in the form of a pellet set into a mortar brick. In this way, a set of values specific to the fluorescence of alkali-aggregate reaction products was determined, yielding a very selective threshold. It then remained only to use the functionalities of the software to quantify in percentage the area occupied by the destructive products.

Validation of the method

The surface area of the specimen processed is 84 cm^2 and takes the form of a rectangle inscribed in the circle representing the slice of concrete. Given the fineness of the results obtained, the acquisition system was calibrated using millimetre-ruled paper of which 1 mm^2 was tinted using the software; after a setting of thresholds and an automatic quantification, the error proved to be 0.04%.

In addition, the wavelength of the emitted fluorescence was measured using a monochromator, on other samples of concretes from structures exhibiting alkali-aggregate reaction phenomena. The range of values extends from 522 to 528 nm, which proves the small spectral span, in the yellow-greens, of the phenomenon in question.

Other tests

Measurements of longitudinal swelling:

The thesis work of C. Larive has led to the collection of a large number of measurements concerning, in particular, the longitudinal swelling, making possible a comparison with the percentages of areas occupied by the reaction gel found by image processing. This swelling is measured along three generatrices 120° apart on the concrete cylinder. The 100-mm measurement baseline is represented by stainless steel balls crimped onto lugs bonded to the specimen in advance. The measurement is made using a ball extensometer (Pfender type) precise to one micrometre.

Measurements of skin cracking:

As a second element of comparison, we chose a percentage of cracking obtained from a tracing on which the cracks distributed on the perimeter of the cylindrical specimen are drawn; only cracks visible to the naked eye are taken into account. When highlighted with a felt pen, they show up in black against the white background of the tracing paper. This is not really a percentage of cracking as it is normally understood. Quantification is then performed by image processing.

ANALYSIS OF THE RESULTS

First of all, before the percentages of gels obtained, specimen by specimen, are compared. This method of quantification, slice by slice, gives most often larger quantities of gel at the bottm than at the top. This is particularly notable in the specimens at 12 months, for example, where specimen 301 exhibits means of 14.6% on the two bottom slices and 8.7 on the two top slices (but these values are highly dispersed between slices).

One factor that might explain this is the quantity of water, often larger at the base of the specimen, another one is that the gel is affected by gravity. This observation may be related to the finding in a dam, where the quantity of gel was larger at the bottom than at the top, and on the upstream face, in contact with the water, than on the downstream face.

All of the results are presented in the form of a summary table of the data and various graphs showing the selected specimens that underwent the three tests described earlier. It must be borne in mind that these three types of measurements are compared for the purpose of validating the method of quantifying gels by image processing, but the comparison has no statistical value, since a point represents only one specimen. For the evaluation of the percentages of gel, the figure obtained is the mean on 14 images of a single specimen. Again, the result obtained should be regarded as precise to the nearest unit, even if the table states it in tenths.

The table below gives the values obtained by image processing after the test revealing alkali-aggregate reaction gel by uranyl ions (L.P.C. draft testing method no. 36), plus the longitudinal swelling measurements and the cracking measurements.

Specimen no.	Time	Quantification of gel after L.P.C. test no. 36 in %	Longitudinal swelling in %	Cracking in %
428	1 month	2.2	0.008	0
14	2 months	5.4	0.055	0
430	3 months	1.9	0.030	0
375	4 months	3.4	0.150	2
432	**5 months**	**1.2**	**0.001**	**0**
77	6 months	3.4	0.060	0.8
285	9 months	9.7	0.140	2.4
19	**12 months**	**13.8**	**0.240**	**2.1**
86	12 months	8.6	0.190	1.2
301	12 months	8.0	0.210	1.6
288	18 months	3.9	0.193	2.4

Fig. 2 Summary table of data obtained after the quantification of reaction gels by image analysis (column 3), longitudinal swelling measurements (column 4), and cracking measurements (column 5).

What does this table show?

There are two major anomalies in the percentages obtained by quantification of the zones of gel:

- a low anomaly represented by specimen 432, which has an abnormally low percentage of gel for its age of 5 months, 1.2%. This minimum is confirmed by two other minima, in longitudinal swelling and in cracking. When this specimen is re-situated within the range of values obtained for all other specimens (figure 3), it is found that specimen 432 is one of the specimens in the batch exhibiting abnormally little swelling.

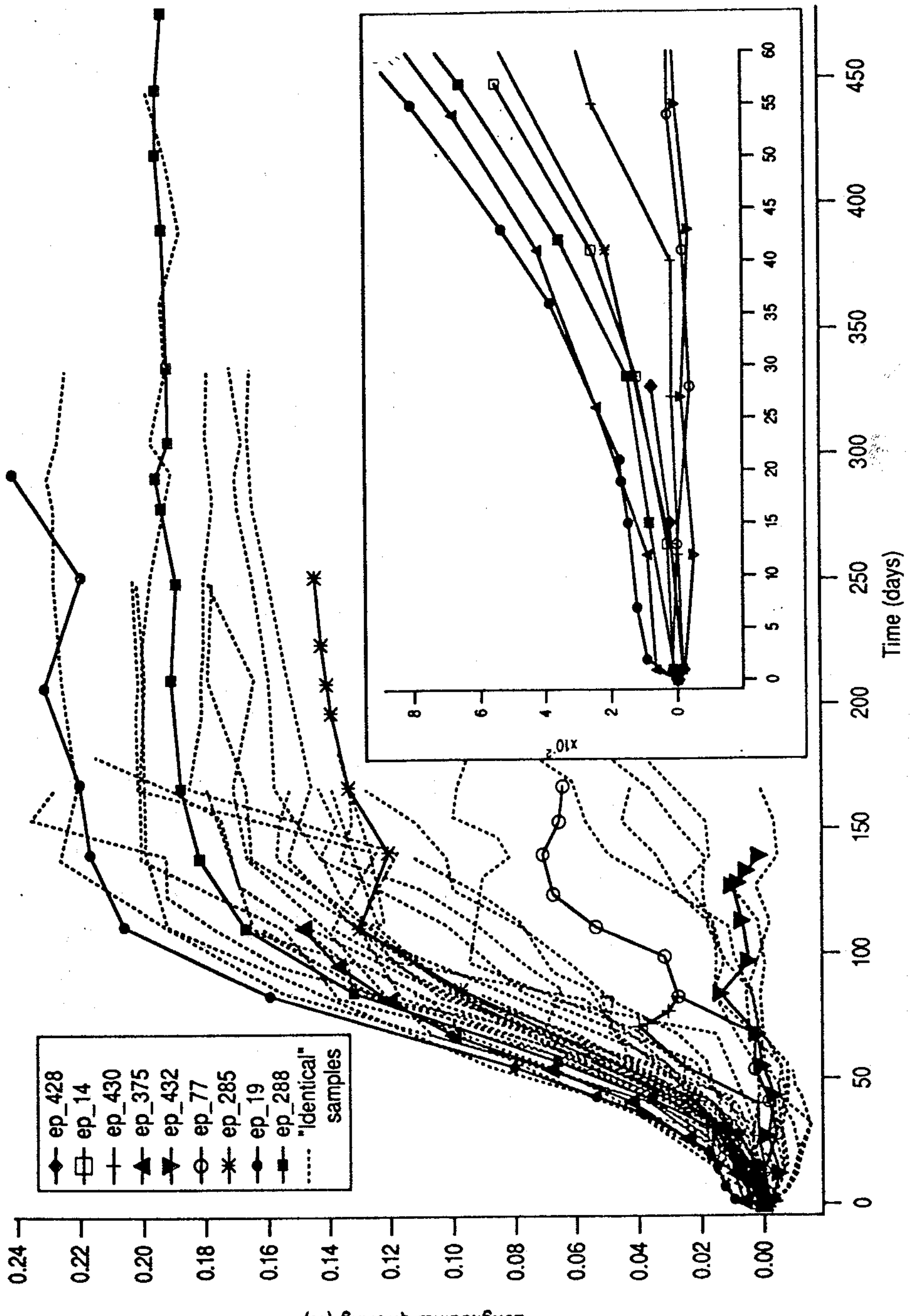

Fig. 3 Graph grouping the longitudinal swelling curves versus time of a set of specimens (shown by a dashed line) within which are re-situated the specimens used in the test (solid lines with symbols).

- a high anomaly represented by specimen 19, which has a percentage of gel of approximately 14% at 12 months, confirmed by a swelling rate that is among the highest. This specimen represents the upper limit of the range. Chance had it that these two specimens were chosen for inclusion in this validation test. In addition to the fact that this choice turned out to be unfortunate, it proves that with the same composition and identical conditions of mixing and preservation, there are very large variations in the measurements of longitudinal swelling. Even so, these differences are detected by quantification of the gels, as can be seen in figure 4 (from which we have dropped specimen 19 to leave only no. 301 at 12 months).

On the strength of these findings, two twelve-month specimens were selected for their proximity to one another in the range, to test the precision of the percentages of gel. These specimens, 301 and 86, are very similar in terms of longitudinal swelling (see the table of figure 2). The values obtained for the quantification of the gel are very close, 8 and 9 %.

Another anomaly was detected, specimen 375, 4 months old, which exhibited a visible anomaly in longitudinal swelling, confirmed by the cracking and reflected in the percentage of gel present (see figure 5).

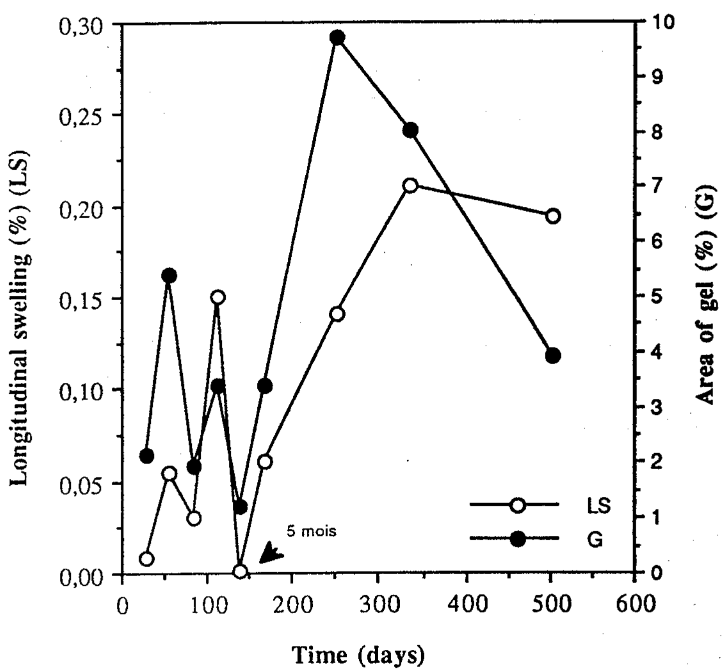

Fig. 4 Graph of longitudinal swelling vs. surface area occupied by gel (%).

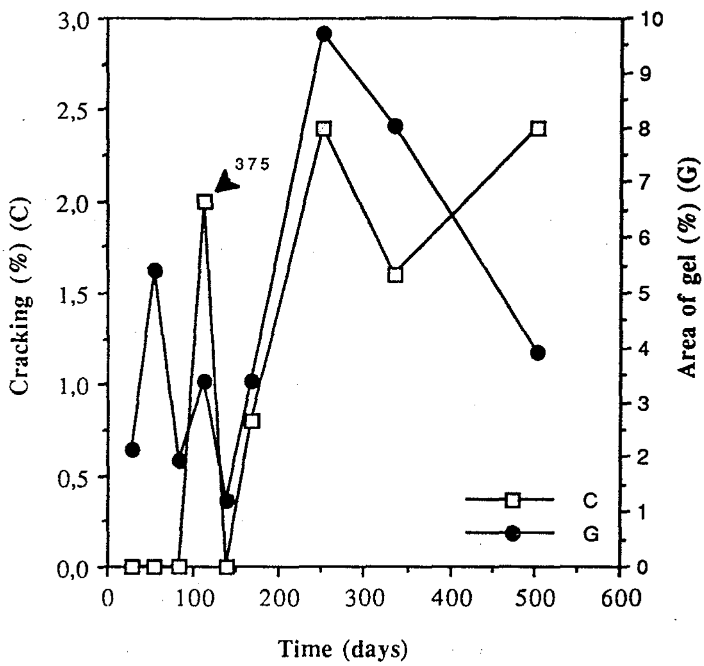

Fig. 5 Graph of cracking vs. area occupied by gel (%).

The cracks start to appear, on the perimeter of the specimen, from 3 months, whereas an increase of the swelling values and of the quantity of gel was already measured before this time.

CONCLUSIONS

- This type of gel quantification measurement by image analysis detected the same anomalies as were recorded in longitudinal swelling and in cracking.
- The repeatability found for two swelling measurements at the same age (n°86 and n°301 at 12 months) is also confirmed by quantification of the zones of fluorescence.
- There is also a relation between the quantity of gel, on the one hand, and swelling-cracking, on the other (figures 4 and 5). This becomes particularly evident for times between 6 and 10 months.
- This series of tests served to show that there is perhaps an effect of gravity within a specimen, with a larger quantity of gel at the bottom than at the top.
- On the other hand, comparing figures 4 and 5 reveals an anomaly between the three types of measurements between the 12 and 18 months; in effect, the slope is positive for cracking, slightly negative for swelling, and highly negative for the quantity of gel. The point concerning the percentage of cracking was checked for the time of 12 months (three values were taken into account for the same time). The reduction of the percentage of fluorescence at 18 months might be explained by a crystallization of the alkali-aggregate reaction products, attenuating their fluorescence.

It would therefore seem that it is not possible to relate swelling and quantity of gel systematically, as many authors think.
Similarly, it is impossible to correlate a percentage of gel with a percentage of swelling, not even within a single concrete (because of the very large dispersion of the quantity of gel measured from one slice to another), much less between concretes having different compositions and/or aggregates. The percentage of gel obtained by this method of quantification, is strictly valid only for the sample of concrete in question.
Any notion of a threshold beyond which a concrete is regarded as pathologically affected by the alkali-aggregate reaction must be ruled out in the current state of the tests.
The method of quantification of alkali-aggregate reaction gels by fluorescence of uranyl ions already had the advantages of rapidity and selectivity in the detection of the destructive amorphous products of the alkali-aggregate reaction (localization of gel in core or in skin, in bubbles, or at the binder-aggregate boundary). Quantification of the gel by image processing, currently being developed at the L.C.P.C., is a rapid way of tracking the evolution of the gel over time.

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