DIAGNOSIS AND MONITORING OF CONCRETE BRIDGES DAMAGED BY A.A.R. IN NORTHERN FRANCE

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After a brief description of the pathology found in these structures and a rapid survey of the parameters of influence of the alkali-aggregate reaction (concrete formulation, environmental conditions, etc.), the article focuses on 3 methods applied to investigate the behaviour of bridges : monitoring of map-cracking development, monitoring of the evolution of global deformation by infrared distancemeter, and expansion tests on drilled cores. A first judgment is made of the utility of each of these methods.

INTRODUCTION

While the presence of alkali-aggregate reaction in a few French dams was diagnosed at the end of the 1970s, it was not until 1987 that this reaction was identified in several bridges. Surveys were then begun (1), and it now appears that the North of France is the region most affected.

While an inventory of damaged structures is still in process, one bridge has already been replaced in this region, and the others are receiving detailed inspection, a few of them being under monitoring.

INVENTORY OF DAMAGED STRUCTURES IN THE NORTH OF FRANCE

While the inventory by the different operating authorities of structures affected by the alkali-aggregate reaction is still in progress, a first estimate of the number of damaged structures, basically bridges, can be advanced. Table 1 gives the first results obtained for structures built since 1970 :

TABLE 1 - Number of structures built after 1970 and affected by the alkali-aggregate reaction in the North of France.

Department	Number of structures built since 1970	Number of structures affected to various degrees	%	Remarks
Pas de Calais	290	20	7	(1)
Nord	400	100	25	(2)
Somme	80	0	0	(3)
Aisne	90	3	3	(4)

(1) Structures on national and departmental roads built by national authorities (basically

in the mining basin). The structures on the shore were made with aggregates that seem to be non-reactive.

(2) These data are given for information, because some structures built since 1985 are starting to show signs of damage.

(3) In the current state of knowledge (population probably underestimated).

(4) The North of this department is the region most affected.

PATHOLOGY OF STRUCTURES AFFECTED BY THE ALKALI-AGGREGATE REACTION

Description of Damage

The most affected parts are retaining walls, the piers of open frame bridges, and the cross-beams over supports of slab bridges. However, more important parts such as reinforced concrete deck slabs, prestressed beams, and intermediate bearing piers are also found to suffer from the alkali-aggregate reaction.

Several symptoms of the presence of the alkali-aggregate reaction in French structures have already been identified (2). For the structures of the North of France, most of the damage is abnormal cracking of the facings. This cracking occurs in various forms, the commonest of which is a mesh 10 to 20 cm on a side with rather random cracks.

In reinforced concrete structures, the cracks are often aligned on the reinforcements, dividing the facing into rectangular blocks. In prestressed concrete structures, the cracks often favour an orientation parallel to the prestressing forces. Generally, these cracks result from exceeding the principal tensile stress limits through a superimposition of the mechanical stresses already existing in the structure (self weight, prestressing, shrinkage, etc.) and the internal stresses caused by the swelling of the concrete.

The opening widths of the cracks vary considerably. They range from a thread-like opening, 0.05 mm (resembling crazing of the concrete skin), up to an opening of a few millimetres, and can reach the centimetre in a few cases, fortunately rare. Their depth of penetration also varies considerably: from a few millimetres for the finest to several centimetres for the widest open, which can sometimes lead to failure of the whole thickness of the element. The many examinations made have shown that there is no constant relation between crack opening width and depth.

There is rather often a greyish exsudate marking the edges of the cracks and these edges sometimes protrude from the surface of the facing.

On two structures, the formation of small pop-outs straight on the gravels was found; but it is possible that this highly localized damage, located in one case at the outlet of a rainwater pipe (OA 10 under the A21 motorway) and in the other at the foot of a low wall on a poorly drained slab (Footbridge of Sighs at Villeneuve d'Ascq), was caused by winter frost rather than the alkali-aggregate reaction.

While cracking of the facings is the commonest consequence of the phenomena of internal expansion of the concrete of structures suffering from the alkali-aggregate reaction, we have nevertheless found, in some especially severely affected structures, that it could also be accompanied by a permanent deformation of the structures caused by weakening of their mechanical properties :

- deflection of about ten centimetres in several spans of the deck of underpass no. 7 under the A22 motorway, a reinforced concrete slab bridge.
- large bulge in the retaining wall of the Carihem bridge at Roubaix.

Since the margin of safety on the stability of these two structures was dangerously reduced, they received extensive repairs involving partial demolition.

Another consequence of the degradation of the structures affected by the alkali-aggregate reaction is bursting of the concrete, possibility accompanied by falling pieces. Footbridge G over the South ring road at Lille presented a risk of falling concrete elements from part of its deck just over heavily travelled expressway lanes, and has been temporarily covered with a flexible reinforced coating designed to retain pieces of concrete that separate from the structure.

Study of the Parameters of the Alkali-Aggregate Reaction

One finds a predominance of damage in zones exposed to infiltration by water: abutment cross-beam (through lack of tightness of pavement joints), sides of deck slab or wall, edge beam, structures that are poorly waterproofed or not at all, etc.

The investigations carried out on the structures, and examination of their records, when usable, revealed a rather constant fact in the composition of the concretes : the presence of primary Tournaisis (Tournai area) limestone gravels; this rule is not however absolute because there are also sometimes porphyries. The other constituents of the concrete are most varied in type and source :

- Portland cements (pure or with additions) from the cement plants of Lumbres, Pont à Vendin, Haubourdin, Cantin, and Barlin. All of these cements, except for the one from Haubourdin, had an Na2O equivalent content greater than 0.6 %.

- Siliceous sand from the Rhine or silico-calcareous sand from the Seine and the Oise.

Another point these structures have in common is their period of construction, approximately from 1970 to 1985. It is indeed remarkable to find that structures built before this period exhibit, to our knowledge, no damage attributable to the alkali-aggregate reaction; the beginning of this period coincides both with the new use of hard limestones (some of them now recognized as reactive) and with an increase of the alkali content of the cements (3). As regards the structures built since 1985, it is to be feared that the absence of pathology is only temporary and that damage will finally appear later.

METHODS OF INVESTIGATION

Evaluation of the condition of the structures to obtain precise knowledge of their level current of degradation and help predict its evolution is a key step. It is for this purpose that the Laboratoires des Ponts et Chaussées has initiated, on a number of structures affected by the alkali-aggregate reaction, the application of three methods that are simple and promising, if not original :

- Measurement and monitoring of cracking.

- Monitoring of total deformation by infrared distancemeter.

- Measurement of residual expansion on cores, using the method recommended by the British Cement Association (B.C.A.).(4).

Each of these methods will now be described briefly, then examined from the standpoint of its utility.

Measurement and Monitoring of Local and Global Cracking

Local cracking. The assessment by an individual of the degree of damage of a cracked concrete facing is obviously highly subjective, since the reproducibility of the observations is completely random. Only measurement of the crack opening widths under specified conditions, with suitable equipment, by the same person, allows reliable monitoring of cracking.

The measuring instrument used here is the crack-meter. One or several reference patterns with three axes (horizontal, vertical and bisector), each covering an area of one square metre, are marked on the facings of the structures suspected of degradation by the alkali-aggregate reaction. The locations of these reference axes depend on the extent of the visible damage (comparison of more or less affected zones), the type of structure, and means of access. In general 2 or 3 reference patterns are sufficient for an ordinary structure. Care must be taken not to place only a single mark in the most affected zone, because any destruction of this zone would cause loss of the monitoring information.

All cracks having opening widths greater than 0.05 mm (threshold of visual detection) and intercepting these three axes are recorded and measured following precise instructions. The record is completed by a photograph printed in a large format (18 x 24 cm).

The monitoring frequency is fixed according to the probable evolution of the cracks, which can be predicted from the past of the structure, and the urgency of the problem. It is once or twice a year in the initial phase or if evolution is rapid, and can be reduced to once every 5 years in a more stabilized phase.

The measurements are made in climatic periods that are as identical and as close to average as possible (spring or autumn), and the temperature and the humidity of the air are recorded. The values obtained are statistically processed in a simplified way and stated, by axis and for all three directions, as follows :

- number of cracks
- total opening per linear metre
- mean opening by crack
- histogram of opening widths

A global indication on the extent of cracking is thus rapidly available, in a numerical and objective form, in the value of the mean total opening per metre, called the "cracking index" (CI). This index can be calculated for each axis, or evaluated for the zone, by taking a mean of the indices along the axes (figure 1).

On the basis of our experience, we have established a scale to characterize the cracking of a structure, as shown in table 2 :

TABLE 2 - Characterization of damage through cracking index CI.

Cracking index CI (mm/m)	Extent of damage
0 to 0.5	negligible
0.5 to 1	low
1 to 2	moderate
2 to 5	high
5 to 10	very high
> 10	considerable

It is obvious that this classification applies only to the visible external cracking of a particular zone of the structure and not to the degree of true damage of the structure, which depends on many other parameters.

This method also makes it possible to track the evolution of the degradations in time. While less global than instrumentation with large extensometers (which it can nevertheless usefully complete) in that it does not take account of the expansion of the concrete located between the cracks, this method has the advantage of requiring only rudimentary, easy-to-use equipment and being very durable.

Global cracking. Global monitoring of cracking uses the method just described and the same means of measurement. But it differs in that it is performed on large bases (for example the whole length and full height of a wall) and so combines all of the differently affected zones of a given wall (figure 2).

The total crack opening per linear metre is processed in the same way; but on this scale it becomes possible to establish relations with the density or possible discontinuities of the reinforcements (ends of bars, fractures, etc.).

For example, in the case of overpass 17 on the A22 motorway at Tourcoing, it was possible to detect :

- the effect of confinement of the wall by its footing,
- zones where the yield strength of the material is likely to be exceeded or the steel-concrete bond is likely to fail.

Monitoring of Global Deformation by Infrared Distancemeter

This technique uses topographical distance measuring equipment based on the time of propagation of an infrared ray between a transmission/reception base and an optical reflector. With a few procedural precautions and the introduction of corrective parameters in the calculation to take account not only of the index of refraction and the relative humidity of the air, but more especially of the temperature of the concrete, the reproducibility and precision of the results obtained are good (of the order of 0.2 mm for a distance of several tens of metres).

The use of this technique calls for the permanent installation on the structure, at the ends of each measurement base, of equipment attachment devices : a support plate on the distancemeter side and a receptacle on the reflecting prism side (photo 1). Since the infrared distancemeter is mounted on a swivelling shaft, several measurement directions can radiate from a single instrument location provided that there are enough reflectors. This makes a rather complete record of deformations possible.

In the North of France, four structures are currently instrumented and being regularly monitored by this method. The information provided is still limited because of the slowness of the phenomena measured, but already seems interesting. An example is the case of the bridge on the RN 50 at Brebières, a bridge 20 years old, one of the two abutment walls of which exhibits extensive internal reaction cracking (CI = 3.02) and the other practically negligible cracking (CI = 0.40). The global deformation measurements show that the expansion of the walls is still continuing, but at a much lower rate (0.024 mm/m/year) than must have existed to reach the current state of cracking of the more affected wall; this rate must have been at least 0.150 mm/m/year, calculated on the basis of the current opening of the cracks, neglecting the expansion of the concrete between the cracks. The monitoring also reveals the difference in expansive behaviour between the two walls : the more cracked is still progressing 0.05 mm/m/year more than the other.

Measurement of Residual Expansion on Core

This method, described in a report published by the British Cement Association (3), consists of taking a core in the part of structure to be studied, placing extensometer studs on three generating lines on the core at 120°, and recording the time history of the length of the core while accelerating its possible expansion by storage in a warm, damp environment (container at 38°C and 100% RH). In general, the core is given a diameter of 100 mm and a slenderness ratio of 2.5 so that two measurement levels having 100 mm bases can be placed.

The information so gathered can then be used to estimate, in a reasonably short time - of the order of one or two years - the residual expansion potential of the concrete of a structure.

Having performed this test on about thirty cores from various structures in the North of France suffering from damage caused by internal swelling reactions of the concrete, we can draw the following conclusions:

- Expansion, when it occurs, is in two stages (figure 3) : the first is very fast (1 to 2 months) and intense (up to 1000 µm/m/month), and is superimposed on a weight gain or recovery of the core, while the second is slower (approximately 200 µm/m/month) and declines gradually to reach practically zero after a year and a half.

- The immediate expansion is all the faster if the concrete of the core is microcracked and dry and contains alkali-aggregate reaction gel (an effect analogous to the swelling of a sponge).

- The variability of the expansion within a single core that swells is large, and the measurements recorded between two contiguous bases can even vary by a factor of two. This may be explained by the fact that, in a core (as in a structure, moreover), expansion is not homogeneous but seems greater at the centre than on the periphery, so creating a tension in the skin of the core, which then cracks randomly (cracks are in fact visible).

- We propose interpreting the results of this test on the basis of the expansion Er measured in the course of a year after an initial phase of water recovery lasting 2 months, a mean duration after which water recovery can be regarded as stabilized (since the share of the expansion due to the recovery of water by the core is not considered an integral part of the residual expansion of the concrete of the structure). Table 3 below gives the thresholds selected for the residual expansion Er :

TABLE 3 - Proposed thresholds for expansion test on cores.

Expansion Er on core	Effect on structure
0 to 100 µm/m	negligible
100 to 500 µm/m	moderate
> 500 µm/m	high

CONCLUSIONS

While the visual identification of damage due to the alkali-aggregate reaction constitutes a fundamental first step in the identification of diseased structures, taking samples of concrete and analyzing them in the laboratory is a second step that is currently essential in diagnosing the presence of the alkali-aggregate reaction in structures that exhibit symptoms of it. This methodology may be modified in the future if techniques such as impregnation with uranyl acetate (5) make possible effective in-situ recognition of the presence of alkali-aggregate reaction gels in structures.

While the three methods of investigation examined in this article are a precious aid to diagnosis, they are, more particularly, useful means of management of diseased structures, making it at least possible to determine the order of urgency of possible actions. The first two methods are used in particular to track the evolution of the structures and check the effectiveness of the treatment applied to them. The localized record of cracking (on 1 square metre) yields, simply, an objective numerical value for the visible state of cracking of a facing, while the measurement of global deformation, more expensive and more cumbersome in use, determines dimensional variations of all origins very precisely.

The third method is a step towards the evaluation of the residual bearing capacity of structures. It remains however to determine to what extent the final expansion value of the sampled cores represents the potential expansion the part of the structure concerned will undergo in the future.

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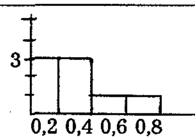
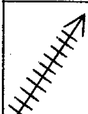
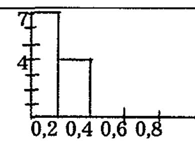
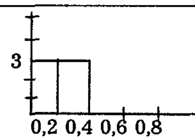
Axes	Intercepted cracks (mm)	Number of cracks	Cracking Index CI (mm/m)	Mean opening (mm)	Histogram of opening widths (mm)
 1 m	0,3 0,2 0,7 0,4 0,05 0,05 0,1 0,2	8	2	0,25	
 1 m	0,1 0,05 0,1 0,05 0,1 0,05 0,3 0,2 0,1 0,2 0,2	11	1,45	0,13	
1 m	0,1 0,2 0,2 0,05 0,2 0,05	6	0,8	0,13	
Global		25	1,42	0,17	

Figure 1 - Example of a calculation of the Cracking Index CI

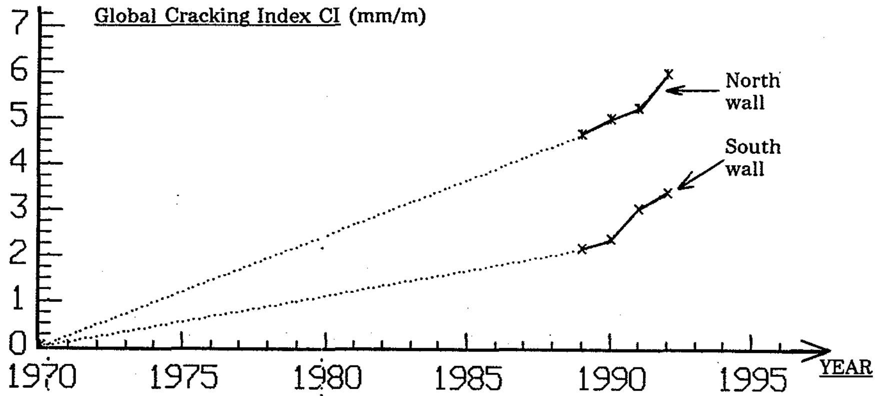


Figure 2 - Evolution of the global cracking of two walls of the overpass 17 of A 22 at Tourcoing

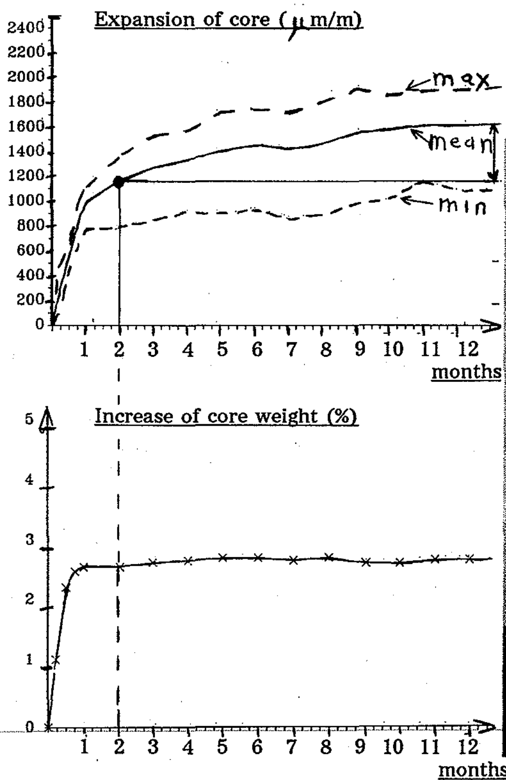


Figure 3 - Longitudinal expansion and weight increase of cores during expansion test according to the BCA procedure.

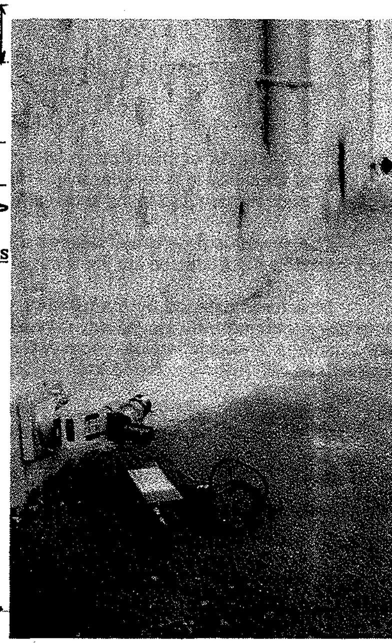


Photo 1 - View of the infrared distancemeter and ofits reflecting prism.