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DIAGNOSIS, TREATMENT AND MONITORING OF A BRIDGE DAMAGED BY AAR

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ABSTRACT

This paper presents the method adopted by SANEF (Northeast France highways) for the diagnosis, analysis, treatment and monitoring of bridges affected by AAR. The different steps of this method are described using a case study.

The reactions affecting the studied bridge concrete (AAR and sulfate attack) are presented using field measurements, laboratory observations (polarizing microscope, scanning electron microscope) and analyses (chemical and mineralogical analyses). Accelerated tests results are also taken into account. These results, combined with the structural analysis and the loading test results, were used to defined a repair solution using a water-repellent surface coating (silane) and a thin cement-polymer coating. The upper deck waterproof membrane of the bridge was also repaired, but no reinforcement was necessary. A monitoring of the bridge with sensors is now being conducted. The first results suggest that the internal reactions have been stopped successfully.

Keywords : Alkali-aggregate reaction, bridge, structural analysis, loading test, treatment, monitoring.

INTRODUCTION

Several bridges of the A26 highway, located in the north-eastern part of France and built during the seventies, are affected at different degrees by AAR and/or sulfate attack (Brouxel and Valière 1992, Prin and Brouxel 1992). SANEF developed since 1990 a surveillance method of all the 224 bridges of the A26 highway based on a cracking index. This surveillance method is used to determine which bridges must be studied in detail. A diagnosis is conducted when the cracking index reaches 0,8 mm/m. Depending on the diagnosis, an adapted treatment is conducted. This paper describes the diagnosis, the structural analysis, the repair works and the monitoring of a bridge affected by AAR and sulfate attack.

DIAGNOSIS

Measurement and Monitoring of the Cracks

The studied bridge showed an intense map cracking of all its piles (Fig. 1a and 2a) and of one deck (Fig. 1b and 2b, the other deck shows no degradations). The evolution of cracks number and opening is described in Fig. 1 with measurements realized in 1982, 1993 and 1995. The cracking index (mean total opening per meter of the cracks measured on three axes, horizontal, vertical and bissector, as defined by Godart et al. 1992) was measured on 14 different parts of the bridge every six months since 1994. The results are described in Fig. 3 with cracking indexes reaching locally 2.20 mm/m. The regular increases of the cracking index with time confirm that an expansive phenomenon is occurring. Measurements, realized on isolated cracks, showed also an opening of the cracks.

Microscopic Study (Polarizing Microscope)

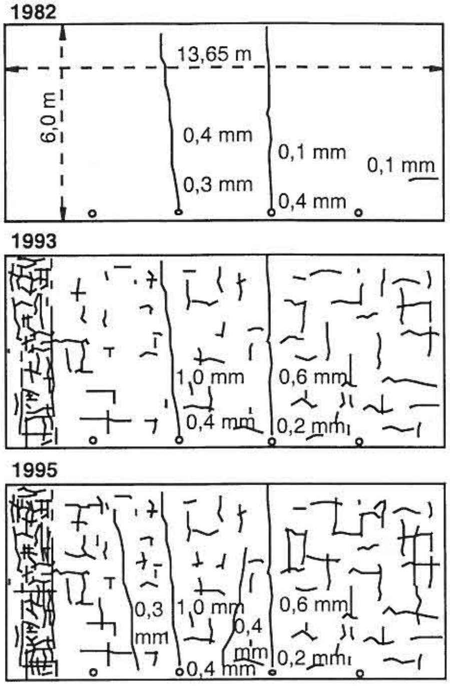
The theoretical concrete composition is not potentially reactive to the alkali-aggregate reaction, taking into account that the Boulonnais marble, also used in channel tunnel, is known as non reactive (Poitevin 1998) :

- portland cement : 400 kg
- sand (0 / 4 mm) : Boulonnais marble 780 kg
- gravel (5 / 12.5 mm) : Boulonnais marble 500 kg
- gravel (12.5 / 20 mm) : Boulonnais marble 540 kg

However, the microscopic observations are not completely in agreement with the theoretical composition. If the majority of the observed aggregates is made of calcareous aggregates (micro-crystallized or fossiliferous limestone), numerous flint aggregates, potentially reactive with a pessimum effect, and altered siliceous aggregates (micro-crystallized quartz), were observed in the gravel fraction. The absence of flint in the non-deteriorated deck must be pointed out. Moreover, nearly 10 to 20 % of siliceous aggregates were observed in the sand fraction. The cement paste also contains systematically disseminated sulfur grains.

Scanning Electron Microscope (SEM) Observations

The SEM study showed that the studied bridge concrete is affected by AAR. However, some parts of the bridge (notably the non-deteriorated deck) don't exhibit any gel. Some samples, with no AAR gel, present secondary ettringite crystals, crystallized in an hardened cement paste and characterized by larger sizes and higher sulfur contents than primary ettringite crystals.



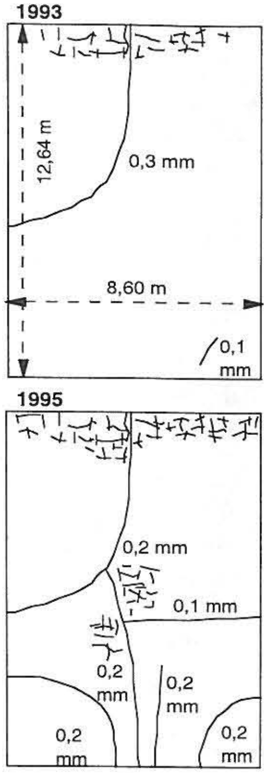
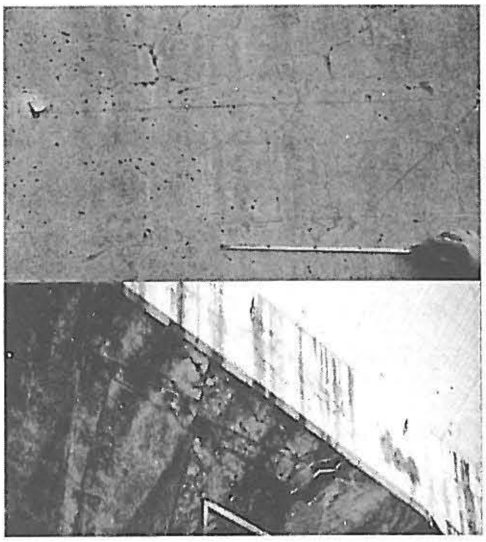


Fig. 1a (above) : Crack pattern evolution of a pile of the bridge.
Fig. 1b (on the right) : Crack pattern evolution of the deteriorated deck.



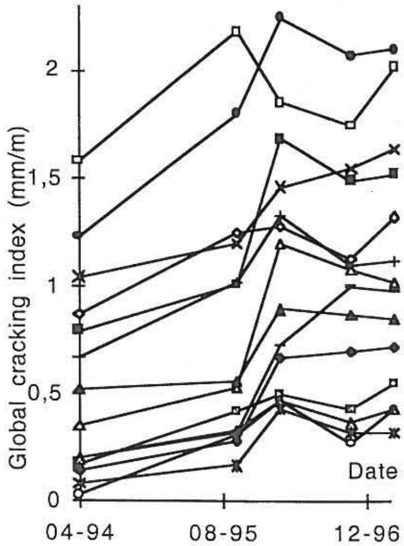


Fig. 2a (top) : Map cracking of a pile.
Fig. 2b (bot.) : Cracks in the deteriorated deck.

Fig. 3 : Evolution of the cracking index between 1994 and 1997.

SEM pictures

Fig. 4 : Massive gel.

Fig. 5 : Massive gel, with crystallized gel on surface.

Fig. 6 : Crystallized gel.

Fig. 7 : Rosette-like gel.

Fig. 8 : Massive “secondary” ettringite not associated with AAR gel.

In most samples, different forms of gel (massive, partly crystallized and rosette-like) were observed (Fig. 4 to 7). The main characteristic of the gel in the studied concrete is the abundance of crystallized and rosette-like gels (Fig. 5 and 7). Large amounts of ettringite crystals were observed in voids and in the cement paste (Fig. 8).

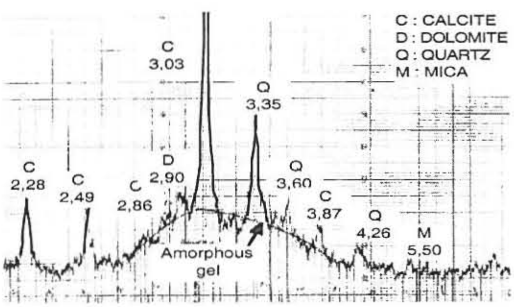
Chemical and Mineralogical Analyses of the Gel

The important amounts of gel present in the concrete allowed us to realize ICP-MS and X-Ray diffraction analyses. It was however not possible to determine if the analysed gel was massive or crystallized. The ICP analyses showed that the gel contains more K than Na (Table 1) reflecting the cement composition.

TABLE 1 : ICP-MS Major and Trace Elements of the Collected AAR-Gel.

SiO_2 (%)	40.03	K_2O (%)	9.37	Co (ppm)	14.8
Al_2O_3 (%)	0.40	TiO_2 (%)	0.02	Cr (ppm)	6.67
Fe_2O_3 (%)	0.26	P_2O_5 (%)	0.05	Cs (ppm)	20.1
MnO (%)	traces	S (%)	0.04	Rb (ppm)	454
MgO (%)	0.18	L.O.I. (%)	28.10	Sr (ppm)	644
CaO (%)	18.63	Total (%)	99.72	Zn (ppm)	17.9
Na_2O (%)	2.65	Ba (ppm)	144	Zr (ppm)	16.8

(L.O.I.) : Loss on ignition = mostly water



The X-ray diffraction analysis confirms the amorphous composition of the gel (Fig. 9). Small amounts of crystallized phases were also observed (calcite, dolomite, quartz and mica). No crystallized form of gel, like rhodesite (De Ceukelaire 1991) was detected.

Fig. 9 : X-Ray diffraction pattern of AAR gel sampled in the deteriorated deck.

Accelerated Tests

Accelerated tests were performed on cores obtained from different structural members in order to determine the concrete residual expansion. Two different tests, specific to AAR and sulfate attack, were conducted. The test specific to AAR is derived from the autoclave test described by Tang et al. (1983). The samples are autoclave-treated at 120°C in a water environment for 24 hours. Five to ten cycles of 24 hours are realized. The result presented in fig. 10 showed that the residual expansion is lower than the threshold (0,11 % expansion).

The test specific to the sulfate attack is the test described by Garbowski et al. (1992). In this test, the concrete cores are immersed in distilled water at room temperature for one month following a thermal cycle (heating up to 82 °C for 24 and 72 hours). The thresold is 0,1 % expansion after 21 days of immersion in distilled water. The results presented in fig. 11 show no residual expansion due to sulfate attack. However, the presence of numerous sulfur grains in the concrete implicate some precautions. Indeed, oxidation of these sulfur grains may, in the long term, liberate sulfates which can participate in a sulfate attack.

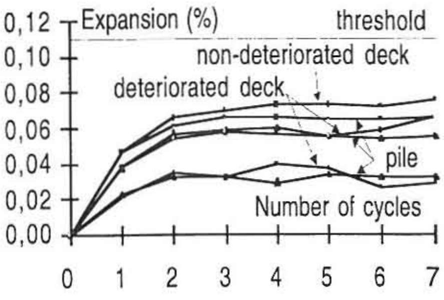


Fig. 10 : Residual expansion due to alkali-aggregate reaction.

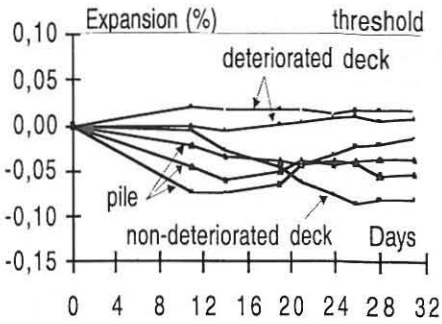


Fig. 11 : Residual expansion due to sulfate attack.

STRUCTURAL ANALYSIS AND LOADING TEST

A structural analysis based on a loading test was performed on both decks supporting the highway. The main goal of this test was to compare :
- the displacements measured in 1980, just after the bridge was built and the displacements measured during the loading test.
- the displacements measured on the deteriorated deck and the non-deteriorated deck.

The concrete compressive strength range between 34 and 41 MPa ; while the tensile strength range between 2.86 and 3.82 MPa. The concrete elasticity modulus of the non-deteriorated bridge is 37 200 MPa, compared to 31 680 MPa for the deteriorated deck.

The loading test was performed with three 48 T trucks with a geometry similar to the geometry of the trucks used in 1982. Five sensors were used to measure the displacements, in the middle and the borders of the deck (Fig. 12). Five invariant metal cables supporting small weights were fixed on the deck. Sensors fasten to tripods measured the vertical displacement of the weights during the loading test. The different loading cases and the displacements results are presented in fig. 13 and in table 2.

TABLE 2 : Loading Test Maximal Displacements in mm.

Loading case	Deck	Sensor 0	Sensor 1	Sensor 2	Sensor 3	Sensor 4
1	not deteriorated	0.255	0.22	0.215	0.19	0.13
	deteriorated	0.31	0.32	0.275	0.265	0.20
2	not deteriorated	0.47	0.40	0.385	0.30	0.30
	deteriorated	0.515	0.53	0.41	0.32	0.37
3	not deteriorated	0.70	0.595	0.59	0.50	0.40
	deteriorated	0.765	0.76	0.605	0.52	0.47
3	not deteriorated	**0.6**				
1982	deteriorated	**0.6**				
4	not deteriorated	0.68	0.56	0.54	0.42	0.44
	deteriorated	0.735	0.68	0.58	0.44	0.52

The behaviour of the AAR non affected deck showed to be conform to the theoretical model. The behaviour of the AAR affected deck showed a local and limited loss of its stiffness (approx. 10 %) in the most deteriorated part of the deck (sensors 1 and 2 were supposed to have a symmetrical behaviour). However, the overall stiffness of the entire deck compensate the local loss. No reinforcement of the deck was therefore necessary.

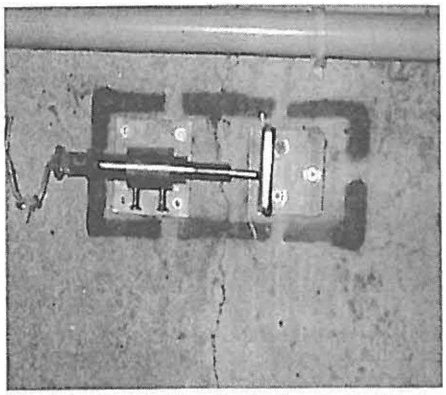


Fig. 14 : Sensor monitoring an individual vertical crack.

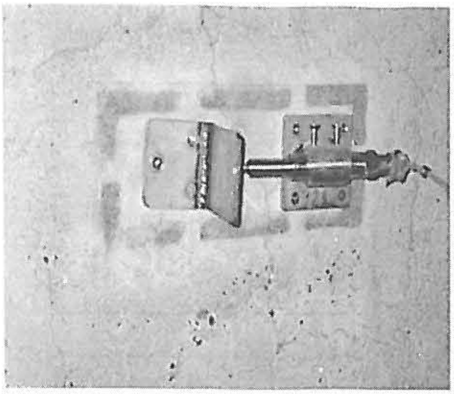


Fig. 15 : Sensor monitoring an individual crack in a map-cracked area.

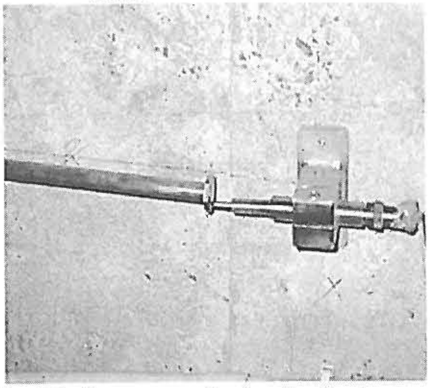


Fig. 16 : Sensor monitoring the displacement of a 12 meter long bar.

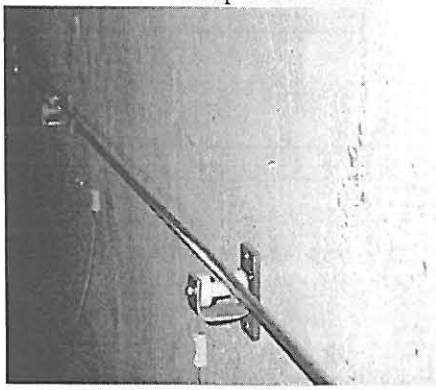


Fig. 17 : Supporting system of the 12 meter long metal bar.

TABLE 3 : Minimal and Maximal Opening of the Monitored Cracks.

	Period of time	Cracks minimal opening (μm)	Cracks maximal opening (μm)	Cracks opening (μm)
pile	07/98 to 12/98	3	34	31
	12/98 to 04/99	9	40	31
deteriorated deck	07/98 to 12/98	-164	-149	15
	12/98 to 04/98	-145	-120	25
pile	07/98 to 12/98	-120	3	123
	12/98 to 04/99	-44	-10	34
non-deteriorated deck	07/98 to 12/98	-125	219	344
	12/98 to 04/99	-110	125	235
pile	07/98 to 12/98	-1	6	7
	12/98 to 04/99	-25	10	35
pile - 12 m bar	07/98 to 12/98	-1828	1700	3528
	12/98 to 04/99	-1821	501	2322
deteriorated deck - 6 m bar	07/98 to 12/98	125	142	17
	12/98 to 04/99	104	150	46

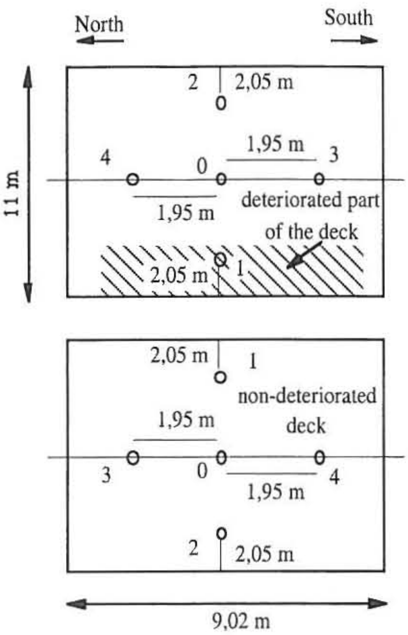


Fig. 12 : Position of the sensors.

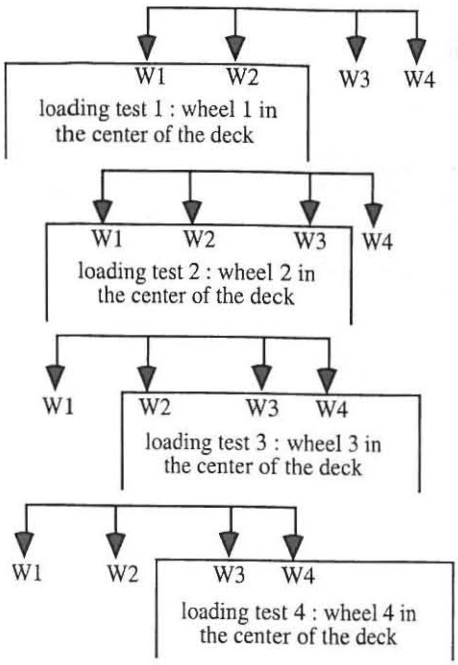


Fig. 13 : Loading cases.

TREATMENT AND MONITORING

To stop the reaction in order to prevent further deterioration, it was decided to repair the bridge using a water-repellent surface coating (silane) and a thin cement-polymer coating (3 mm thick membrane). The main characteristic of this commonly used waterproofing membrane are its flexibility (35 % elongation before rupture), its good bonding on concrete (2 Mpa) and its resistance to de-icing salts. The upper deck waterproof membrane of the bridge was also repaired. No reinforcement being necessary, the goal was to avoid water circulation (with de-icing salts) in the deck numerous cracks.

Knowing that this kind of treatment does not stop definitively the AAR, a monitoring device was installed. Eight LVDT sensors and two temperature gages are monitoring the bridge piles and decks. Before the surface coating was put on, « windows » have been marked with paint to avoid coating in the measurement areas. Sensors were installed on selected cracks (Fig. 14 and 15). Six sensors are measuring directly the opening of six cracks. Two sensors, related to 6 and 12 m long metal bars with dilation coefficients similar to the rebar are measuring the opening of all the cracks affecting 6 and 12 m long concrete elements (Fig. 16 and 17). Measures are taken every 30 minutes.

The bridge monitoring results during the fall of 1998 are presented in table 3 and in Fig. 18 and 19. All the measured variations are temperature related. In order to detect any variation not related to temperature, the minimum and maximum crack openings are recorded for each 6 months period and compared every year. Part of the results are presented in table 3. No significant increase can be detected after one year. However, this surveillance must be conducted over several years taking into account the low kinetics of the reaction, especially in a concrete protected from water circulation.

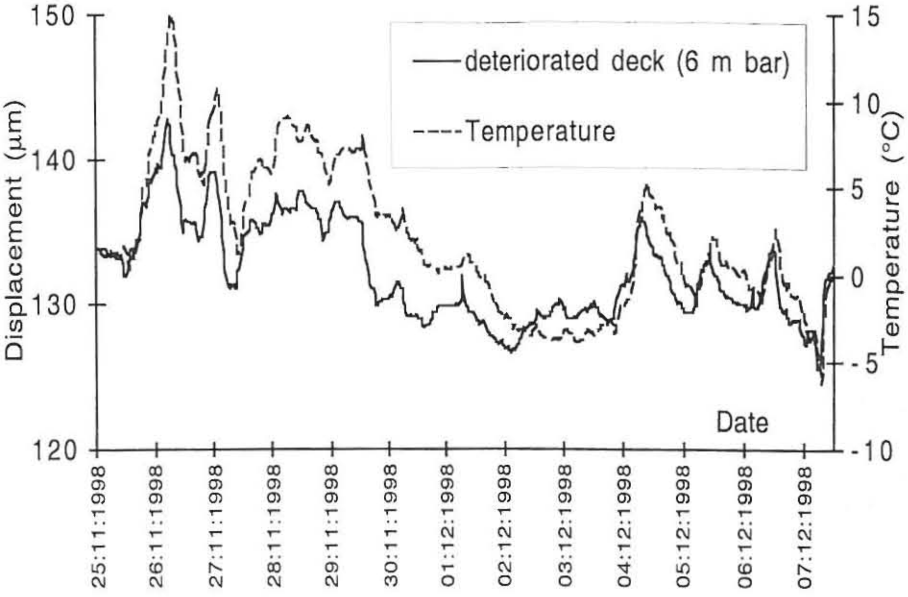


Fig. 18 : Displacement and temperature variations of the 6 m long bar installed under the deteriorated deck.

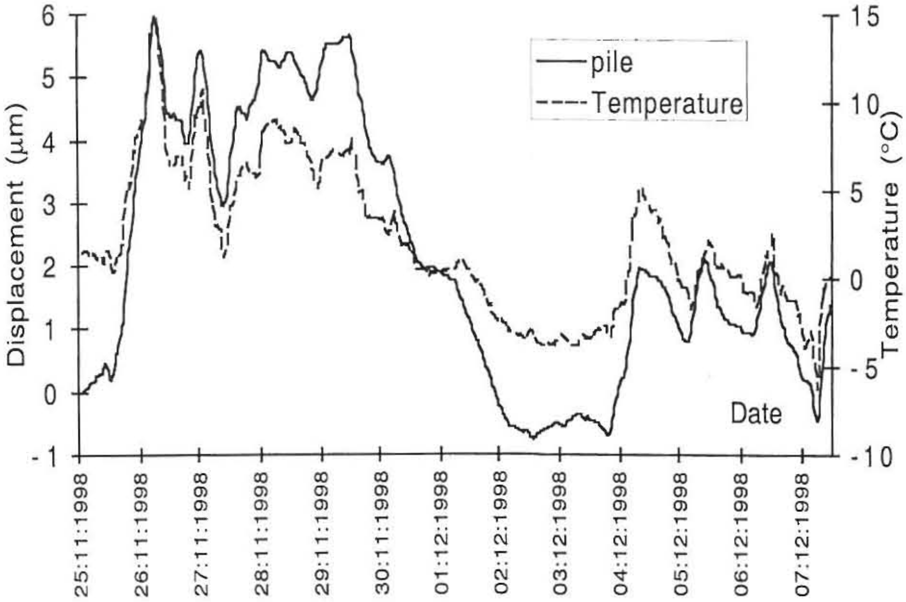


Fig. 19 : Displacement and temperature variations of a sensor installed on a crack of a pile.

CONCLUSION

The methodology presented in this paper permits to monitor, diagnose, analyse, and repair a large number of bridges (224 bridges are inspected), knowing that only a few percentage will need a diagnosis (9 bridges) and that a fewer percentage will need repair and monitoring (7 of the 9 bridges). Adapted to one bridge, this methodology gave the following results :

- the cracks monitoring of the piles and decks between 1994 and 1996 showed a regular increase.
- detailed diagnosis of the concrete (the cracking index was higher than 0,8 mm/m).
- the microscopic study confirms that the concrete is affected by AAR associated with the development of secondary ettringite crystals.
- the accelerated tests conducted to determine the residual expansion showed that only a limited residual expansion is likely to occur in the future.
- the loading tests indicate a local and limited loss of one deck stiffness (10 %) ; but the overall stiffness of the entire deck compensate the local loss.
- based on the accelerated tests and on the loading tests results, it was decided that if no reinforcement was necessary, it may be necessary to avoid water circulation into the concrete (with de-icing salts).
- a water-repellent surface coating (silane) and a thin cement-polymer coating were put on the concrete surface.
- to monitored any residual expansion of the bridge, sensors were installed on the piles and decks.
- measurements taken every 30 minutes show no significant increase after one year indicating that the reactions have been successfully slowed down significantly.

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