Monitoring alkali-silica reaction in structures

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A large number of structures along motorway A59 are experiencing cracking due to alkali-silica reaction, ASR. From recent investigations, it appears that this cracking varies from innocuous to cracking that has led to structurally undesirable situations. For this reason, some structures have been structurally reinforced. With regard to the remaining structures, a range of measures are currently being taken to ensure that the amount of ASR-induced cracking will not increase.

Current experiences of rehabilitation of structures affected by ASR are rather limited. Therfore, the Civil Engineering Division of the Netherlands Ministry of Transport, Public Works and Water Management decided to monitor the structural behaviour of two viadcuts on highway A59. This paper summarizes the final results of this pilot project, which started in 1998.

Key words: alkali-silica reaction, monitoring, structures

1 Introduction

Monitoring is more than just measuring. Before designing a monitoring system, its purpose should be determined. Subsequently, one needs to determine the ways by which that purpose will be achieved. The current pilot project has two objectives. First, it was designed to determine the changes in the behaviour of the structure in the course of time. Second, it was intended to determine the effects of rehabilitation and maintenance practices on the structure.

During the design of the individual components of the monitoring system in 1998, it appeared that very little practical experience existed with regard to monitoring of concrete structures in terms of the relevant properties of such structures. On the basis of a preliminary literature study, it was concluded that no general method was yet available for predicting the structural safety of a concrete structure affected by ASR. For this reason, it was decided to monitor the damaging effects of ASR. Lack of both knowledge and experience limited the possibilities of optimally designing a monitoring system. Choices regarding the measuring equipment, measuring points on the structure and the applied measuring frequency were not trivial with this respect. Therefore, a secondary objective

HERON, Vol. 47, No. 2 (2002) special issue on ASR-ISSN 0046-7316

of the pilot project was to acquire experience with the various measuring and monitoring techniques.

The pilot project involved two structures, the viaducts on motorway A59, Wolput (Fig. 1) and Vlijmen-Oost (Fig. 2). The viaduct Wolput is located near the exit to the village of Cuijk, and is constituted by three sections. ASR had affected part of this viaduct to such an extent that structural measures were deemed necessary. These measures have been in place since 1996, and consist of a supporting portion of the bridgedeck being strengthened by vertical anchors.

Fig. 1. Overview of viaduct Wolput.

Fig. 2. Overview of viaduct Vlijmen-Oost.

The viaduct Vlijmen Oost, located near the exit to the village of Vlijmen, is constituted by four sections. The damage in this viaduct necessitated reduction of the maximum axial load allowed, a measure that has been imposed since 1996. The viaduct had previously been renovated at the end of the 1980's. At that time, a layer of dense asphalt concrete was applied onto the surface of the entire bridgedeck and the joints were sealed from moisture. In addition, the bottom surface of the bridgedeck was protected with a vapour open coating, known as KEIM.

A maintenance programme was planned right from the beginning of the project for both structures. This was based on preventing ingress of mositure into the top of the bridgedecks of both structures, and application of a surface layer permeable to moisture on their bottom sides.

At onset of the pilot, a concrete surface layer with a thin layer of porous asphalt concrete (ZOAB) was present on the top of the bridgedeck of the viaduct Wolput. A layer of so-called Latexfalt was applied as a temporary measure below the porous asphalt concrete layer on the northern driving lane that had earlier been repaired. Unfortunately, inhibiting moisture ingress into the bridgedeck by applying a layer of dense aspalt concrete on top of a layer of Latexfalt was delayed until June 2001, after the second year of the measuring period. A similar measure was applied onto the southern driving lane in 2002. Water from the northern lane is drained to the axis of the structure, where most damage due to ASR has been observed.

In the case of viaduct Vlijmen Oost, the existing layer of asphalt concrete was kept as a water-resisting layer. In order to promote drying of the structure, the coating on the bottom and the sides of the bridgedeck has been removed during the project (end 2000),

2 Design of the monitoring system

The choice of variables to be monitored depends on the damage mechanism, geometry and extent of the damage, and the adopted maintenance strategy. The cause of damage or *damage mechanism* in both structures is ASR. This mechanism (reactions) does only occur if sufficient reactive aggregate, alkalies and water are simultaneously present in the concrete. Both the amounts of alkalies and water available for reaction may vary with time. Variations in water content are presumed to be much larger, and, from point of ASR-induced damage, more important, as swelling of the ASR-gel under consumption of water induces stresses in the concrete resulting in diminishing mechanical properties and failure. Therefore, it was quite obvious to monitor the moisture content in the concrete. In order to follow the future development of the alkali-silica reaction and associated deformations, it was considered necessary to monitor expansions of the structure at different locations.

The proposed maintenance measures were designed to inhibiting ingress of moisture into the concrete of the structures, aiming to stop the alkali-silica reaction or, at least, swelling of the ASR-gel. By monitoring the moisture content and deformations, the effectiveness of the rehabilitation strategy may be evaluated. As no maintenance measures were carried out during the pilot project, the latter objective was dropped.

Based upon the considerations mentioned above, the monitoring system was designed as follows:

1. *Monitoring of the moisture content in the concrete,* to be carried out using two separate measuring techniques, viz. measuring the concrete resistance, which is dependent on the moisture content of the concrete, and measuring the relative humidity of the concrete directly.
2. *Monitoring the deformations in the vertical cross-section of the bridgedeck (perpendicular to the rein-*

forcement): The observed geometry and extent of ASR-induced damage implied that swelling had predominantly occurred in the vertical direction of the bridgedeck.

3. *Monitoring the deformations in the horizontal dimension (within the plane of reinforcement) of the bridgedeck:* These changes were monitored on both the top and bottom sides of the bridgedecks, using three different measuring techniques.
4. *Monitoring the changes in altitude of the bridgedecks* in order to establish whether or not bending of the bridgedecks had occurred as a result of swelling in the vertical cross-section (thickness) of the bridgedeck.
5. *Monitoring of crack propagation in the concrete.*

In order to determine to what extent deformations were caused by temperature variations in the bridgedecks, additional temperature measurements within the decks were carried out.

3 Measuring sites and frequencies

Geometry and extent of the observed damage implied that ASR had not occured uniformly over the bridgedecks. For this reason, the system was designed to monitor both the overall behaviour of the bridgedecks, and the local behaviour of the smaller parts of the bridgedecks. Consequently, the measurement system was designed as follows:

- *Measurements on bridgedeckscale:* Measurements that were carried out on this overall level were focused on changes in the horizontal and vertical dimensions. To achieve this, measurement studs were applied to the top of the outermost kerbs of both viaducts, above the supporting columns points and halfway the spans.
- *Measurements on local scale:* Measurements that were performed on a local scale were focused on the moisture content, temperature, deformations in both vertical and horizontal dimensions and cracking. Four positions were selected on each structure where all the measurements were grouped within a surface area of 1 x 1 m^2 . These positions were situated on the bottom side of the bridgedecks, so that application of the equipment and control measurements could be performed without obstructing any traffic. The choice for the test positions was based on the accessibility and being representative for the damage.

The following measuring sites were selected in the outermost sections of the bridgedecks:

Viaduct Wolput
Measuring sites A and C: in zones with minor cracking in the western section.
Measuring site B: in a reinforced zone with major cracking in the western section.
Measuring site D: in a reinforced zone with major cracking in the eastern section.

Vlijmen-Oost
Measuring sites A and B: in zones with moderate cracking in the southern section.
Measuring sites C and D: in zones with moderate cracking in the northern section.

The deformation measurements in horizontal and vertical directions in the top of the bridgedeck were performed once a season for a period of two years, producing in total 8 measurements. As ongoing ASR, if any, would have proceeded at a relatively slow rate, the three-month measuring interval was considered to be sufficient to provide information on ongoing processes in the bridgedecks. Similar to the measurements in the top of the bridgedekcs, the deformation and cracking measurements in the bottom part were carried out 8 times during the project period. These were preformed from a scaffolding.

Sensors for measuring other variables in the bottom part of the bridgedecks were connected by means of cables to a central measuring control and readout unit. These measurements were carried out thirteen times during the project.

4 Measuring apparatus

Moisture content: concrete electrical resistance measurements

During the initial phase of the project, it was not possible to measure the in-situ moisture content of the concrete by a non-destructive method. There was, however, an indirect measuring method, based on the electric resistance of the concrete; this method makes use of multiple ring sensors. Previously, experience had been gained with the use of these sensors in new concrete, through placing of the sensors in the concrete during casting. The method is based on measuring changes in the alternating current resistance, which gives an indication of the change in the moisture content of the concrete. The method reveals relative changes in the moisture content as a function of time, not the absolute moisture contents. Measurements were performed at an operating frequency of 108 Hz.

Using the multiple ring sensors, the alternating current resistance between stainless steel rings fixed on an isolator is measured. The multiple ring sensors with a diameter of 20 mm were placed within 35-mm diameter holes in the concrete, which were subsequently injected with a cement-based low shrinkage grout (Fig. 3). Whenever the moisture content of the concrete in the structure changes, the moisture content of the material around the metal rings also changes, resulting in a change in the electric resistance.

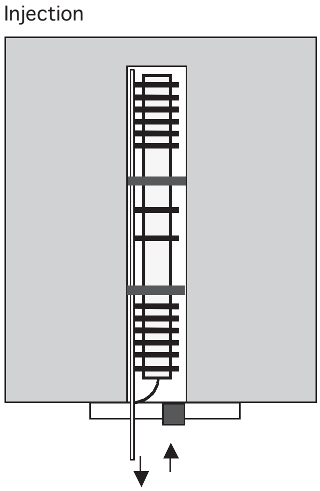

Fig. 3. Schematic drawing of a multiple ring sensor.

The multiple ring sensors used in both viaducts were modified versions of the MRG208 from Sensortec in Aachen. The sensors in both viaducts contained 14 rings. Heart-to-heart distances between the successive rings were chosen in such a way that the distribution of the resistance over the whole cross-section of the bridgedeck could be measured.

Moisture content: measurement of the relative humidity

A second method that was used to gain insight into the moisture content of the concrete is determination of the relative humidity in closed spaces in the concrete. Combined relative humidity and temperature transmitters of the Vaisala HMP 143 type were used, equiped with a Humicap 180 probe and integrated electronics. The sensors derive changes in temperature by measuring changes in the electrical resistance of the sensor, and changes in relative humidity by measuring changes in the specific capacity of the sensor. Sensors are placed in a closed box with a length of about 60 mm. These boxes were thereafter placed in a borehole. The borehole was subsequently injected with a cement-based grout. Owing to the small volume of the holes, it may be expected that equilibrium will be established between relative humidity and temperature in the holes and the surrounding concrete.

To gain insight into the relative humidity distribution in the bridgedeck, two sensors were applied on each measuring site. One sensor was placed at about 70 mm from the bottom side of the bridgedeck, the other about 140 mm from the top surface, in the upper part of the deck.

Vertical deformation (perpendicular to the reinforcement): vibrating wire strain gage

The measurements with the vibrating wire strain gages were carried out in order to obtain insight into any eventual vertical deformation of the concrete. Deformation and temperature were measured simultaneously. The sensors used were vibrating wire strain gages of the type Geokon VCE-4200, with a gage length of 150 mm (Fig. 4).

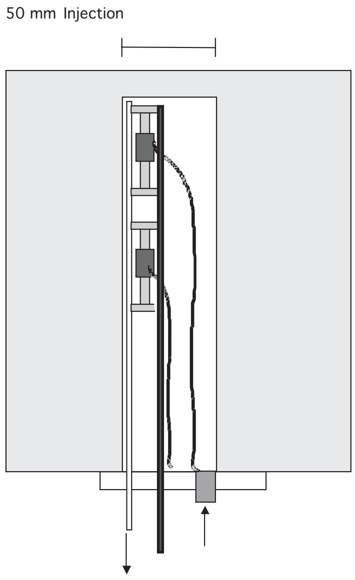

Fig. 4. Schematic drawing of a vibrating wire strain gage.

The measurement principle of the sensors is that changes in dimension of the concrete are determined through changes in the typical frequency of a vibrating wire. A wire under tension is brought into vibrating by a surrounding coil, through which the resonance frequency is subsequently determined. This resonance frequency depends, among others, on the tension in the wire, which is influenced by the deformation in the tube protecting the gage. The strain is then read directly from an electronic readout box.

The vibrating wire strain gages are placed high in a 50 mm-diameter borehole in the deck, and the borehole subsequently filled with a cement-based injection grout. The fixing of the devices at the required heights in the borehole is achieved by securing the vibrating wire strain gages at the suitable height on a 4 mm-diameter rebar.

To obtain insight into possible differences in vertical deformation across the thickness of the deck, two vibrating wire strain gages were applied at each measuring site: one sensor halfway the vertical cross-section of the bridgedeck, the other in the top of the deck.

Horizontal deformation of the bottom of the bridgedeck: cracking

All cracks crossing the sides of squares of the four sites of 1 x 1 m^2 on the bottom side were traced on a map. Location and width of each crack were determined manually. The angle between the crack and the side of the measuring square was rounded off to 30, 45, 60 or 90°.

Horizontal deformation of the bottom of the bridgedeck: strain gage

Horizontal deformation (displacements) measurements and monitoring of the cracking were performed using a portable strain gage. The measuring device used here was a strain gage placed on an invar rod with a length of 1 m, which was used to measure the distance between two reference studs in the deck. The measured lengths were expressed relative to the distance between two reference studs on a rod made of invar steel.

To facilitate the measurements, reference studs were placed at the four edges of the measuring squares. These studs were placed on anchors; on the outside tip, a small ball was placed to enable docking of the strain gage. The length of all four sides of each measuring site was determined.

Accuracy of the strain gage on a reference rod of 1 m is about 0.004 mm. In practice, this accuracy is not met, because measurements were taken from a platform. Field accuracy is estimated at 0.04 mm. In order to enhance the accuracy, measurements were performed in duplo. The average of both measurements was taken.

Structural deformations: horizontal displacements

In order to evaluate overall deformation of the bridgedeck, horizontal displacements were measured using a Sokkia MonMos 3D system. Brass reference studs were applied to the top of the kerbsides and abutments of the viaducts to facilitate measurements. Reflective tape was placed on the studs. Measurements of both angle and distance were obtained from two standard positions and recalculated to coordinates in a x-y grid. The x-axis is projected through two reference studs situated on the abutments. The origin of the grid is situated at the first reference studs. Accuracy of the individual measurements is about 1.2 mm. To enhance this accuracy, measurements were taken in duplo from two different positions

Structural deformations: vertical displacements
Measurements regarding the vertical dimensions of the bridgedeck were preformed in order to trace any bending or buckling of the bridgedeck in response to anisotropic deformations. Measurements were obtained using a digital leveling instrument, Leica NA 3003, and were obtained from two standard positions by reading the altitude of a beacon placed on top of the same reference studs as used to measure horizontal displacement. One measurement is the average of five individual readings, excluding the lower- and highermost readings. Performing the measurements takes about one minute each.

Accuracy of the individual measurements (i.e. the average of three readings) is about 0.2 mm. To enhance this accuracy, measurements were taken in duplo from two positions.

5 Results

Visual inspection of the bridgedecks: Viaduct Wolput
Below the northern driving lanes, the bottom of the bridgedeck displays major cracking, especially below the left driving lane. This part of the bridgedeck has been strengthened by vertical anchors through the deck. Since onset of the project, part of the cracks were carrying water, especially in the thicker parts of the deck located above the supporting plates on the abutments. On measuring locality, minor efflorescence was observed once (March 30, 2001).

Measuring sites B and D are situated in the most intense cracked part of the northern driving lanes; site C is situated north of this area; site A is situated below the southern driving lanes, in an area with minor cracking only.

Visual inspection of the bridgedeks: Viaduct Vlijmen-Oost
The bridgedeck shows cracking over almost its entire bottom. At onset of the project, cracks were dry. Cracks remained dry after stripping of the coating in October, 1999.
All measuring sites were situated in cracked areas, A and B on the southern section, C and D on the northern section.

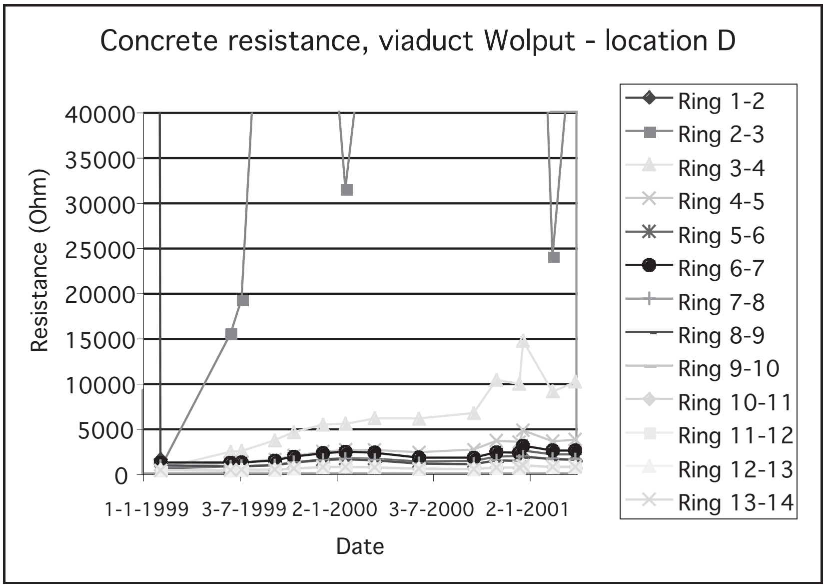

Fig. 5. Concrete resistance at site D, viaduct Wolput.

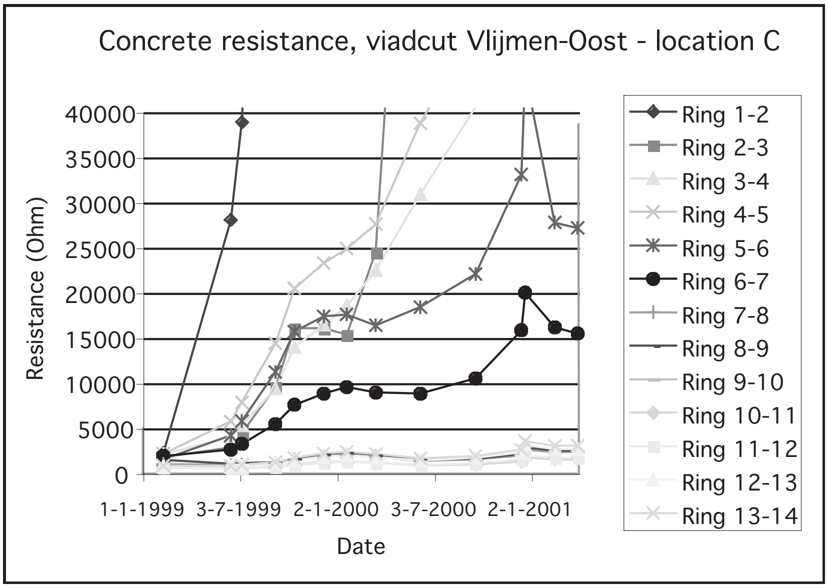

Fig. 6. Concrete resistance at site C, viaduct Vlijmen-Oost.

Concrete resistance measurements using multiple ring sensors

Concrete resistance measurements (for examples, see figs. 5 and 6) show that:

- The lower rings of the multiple ring sensors indicate an increase in concrete resistance with time at most sites. This is probably due to drying of the injection grout surrounding the sensors, possibly combined with detachment of the grout from the surrounding concrete due to shrinkage.

- For the rings yielding realistic values in viaduct Wolput, those at sites B and D are lowest. Concrete resistances measured at site C are slightly higher, those at A are highest. A lower resistance for concrete of similar composition indicates higher moisture contents, viz. for sites B and D. This is in agreement with field observations.

Rings yielding realistic values in viaduct Vlijmen-Oost show comparable values for concrete resistance at all sites. Resistances are comparable with those at site C in viaduct Wolput Rings yielding realistic values in both viaducts show an increase in concrete resistance with time in the bottom part of the bridgedecks. This might be explained by some extent of dessication, which is, however, considered unlikely. For most of the timespan during which measurements were performed, both structures had not yet been rehabilitated. Nevertheless, a systematic increase of concrete resistance is measured. The question arises whether this increase should be explained by other processes than dessication.

Moisture content: measurement of the relative humidity

Relative humidity measurements indicate that, within both viaducts, relative humidity decreases with time from about 90 to 95 % down to 85 to 90 %. Results are comparable for all measuring sites on both viaducts, with the exception of sites B and D on viaduct Wolput. Here, relative humidity does not decrease below 95 %. At these sites, vibrating wire strain gage measurements indicate the largest expansions. Results from relative humidity measurements agree reasonably well with those of concrete resistance measurements using multiple ring sensors and field observations.

With respect to the used equipment itself, it is noted that unrealistic values were indicated several times; this is probably due to the presence of moisture on the sensors itself. This phenomenon has previously been reported in the literature. This implies that measurements become unreliable on the longer term..

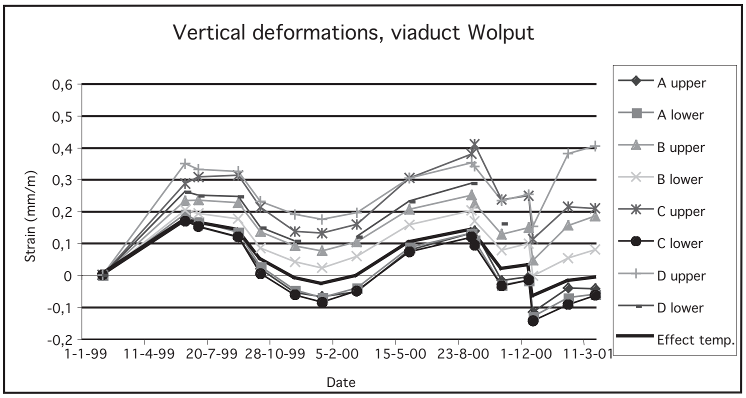

Fig. 7. Vertical deformations in viaduct Wolput, as determined using vibrating wire strain gages. Letters indicate measuring sites, 'lower' and 'upper' indicate the lower and upper sensors at each site, respectively.

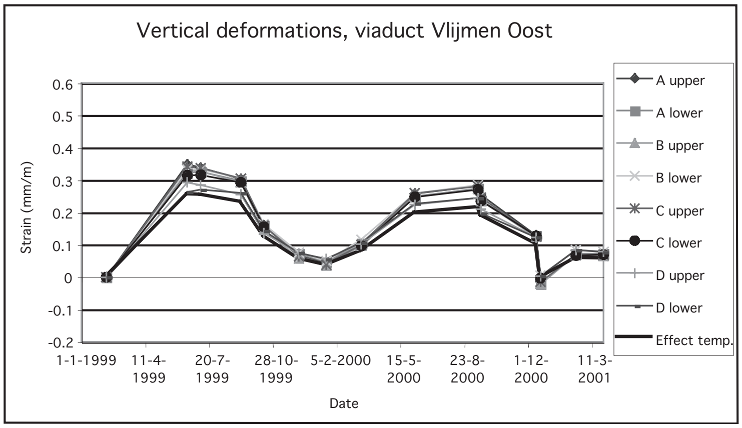

Fig. 8. Vertical deformations in viaduct Vlijmen-Oost, as determined using vibrating wire strain gages. Letters indicate measuring sites, 'lower' and 'upper' indicate the lower and upper sensors at each site, respectively.

Vertical deformation (perpendicular to the reinforcement): vibrating wire strain gage

Deformations perpendicular to the bridgedecks were measured on two depths for each site. Results for viaducts Wolput and Vlijmen-Oost are given in figures 7 and 8, respectively. The figures also show displacements with time as result of temperature relative to the first measurement (Effect Temp. curves in figs. 7 and 8), using a thermal expansion coefficient of 12 x 10^{-6} m m^{-1} °C^{-1}.

It appears that results for all sites in viaduct Vlijmen-Oost and sites A and the lower part of site C in viaduct Wolput agree reasonably well with deformations resulting from variations in temperature. On sites B and the upper part of site C in viaduct Wolput, vertical deformation (expansion) is considerably larger than the temperature effect. This indicates, possible, that expansion due to ASR continues.

Horizontal deformation of the bottom of the bridgedeck: cracking

At sites B and D on viaduct Wolput, cracks widened on some measuring days, in agreement with results from vibrating wire strain gage measurements. Widening of the cracks possibly indicates local expansion of the bridgedeck.

At all other sites on viaduct Wolput as well as those on viaduct Vlijmen-Oost, no changes in width of the cracks have been observed, indicating that no deformations larger than those imposed by temperature variations occured.

Horizontal deformation of the bottom of the bridgedeck: strain gage

At each site, horizontal deformation was determined in four directions using a strain gage. These results too, should be corrected for temperature effects in order to reveal any continuing deformation due to ASR. Figures 9 and 10 show the average displacements for each direction at each site, as well as the calculated temperature effect.

For all sites, it appear that horizontal displacements agree reasonably well with those expected from measured variations in temperature. No significant differences between different sites have been observed. There are no indications for continuing deformation due to ASR.

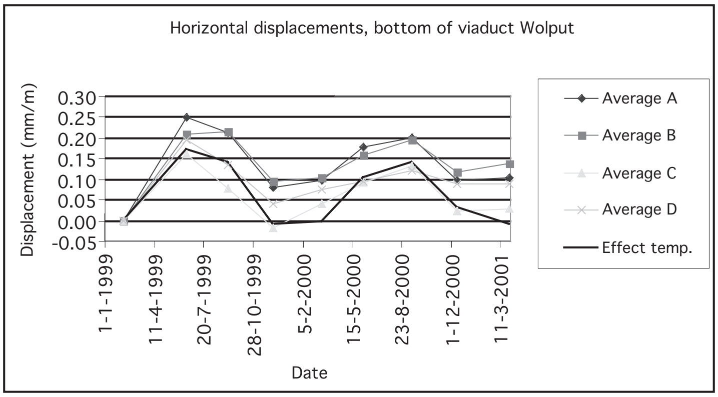

Fig. 9. Average horizontal displacements and calculated temperature effect on the bottom of viaduct Wolput.

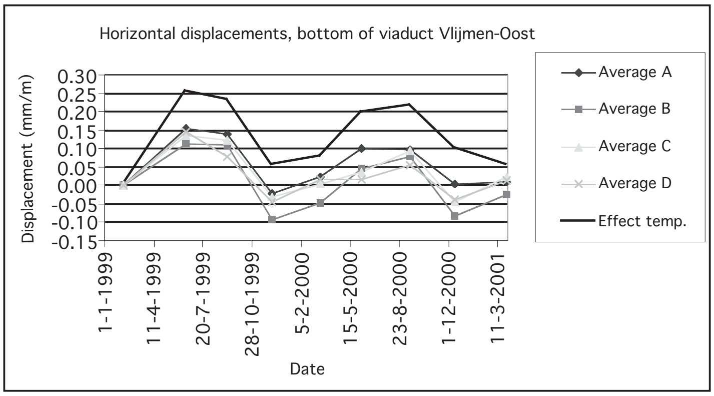

Fig. 10. Average horizontal displacements and calculated temperature effect at the bottom of viaduct Vlijmen-Oost.

Structural deformations: horizontal displacements

Structural deformations have been measured by determining displacement between successive reference studs on the top of the bridgedecks. Results and the temperature effect are given in figures 11 and 12. The average displacements at all sites correspond with those expected with those calculated from measured variations in temperature. There are no indications of continuing horizontal structural deformation due to ASR.

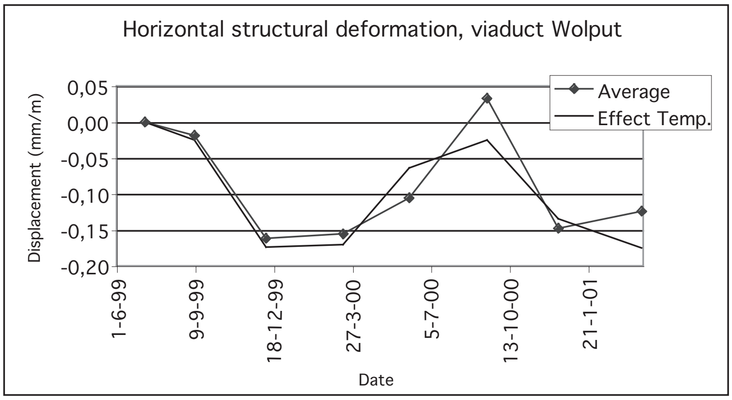

Fig. 11. Average horizontal structural deformation and calculated temperature effect ('Effect Temp.') for viaduct Wolput.

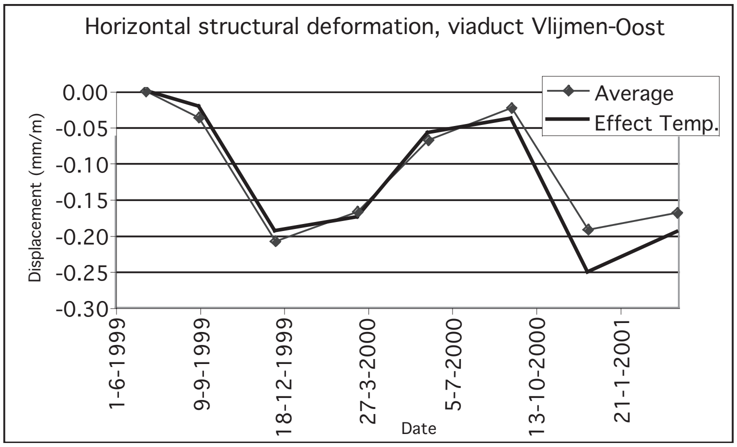

Fig. 12. Average horizontal structural deformation and calculated temperature effect ('Effect Temp.) for viaduct Vlijmen-Oost.

Structural deformations: vertical displacements

Fluctuations in altitude are limited to about 1 mm. There are no indications for bending or buckling of the bridgedecks.

6 Conclusions

6.1 Structural behaviour of the bridgedecks

Viaduct Wolput

Visual inspection, concrete resistance measurements using multiple ring sensors and relative humidity measurements indicate the concrete at sites B and D on viaduct Wolput remain humid. Simultaneously, vibrating wire strain gage measurements indicate continuing deformation (expansion) at these sites. This is probably due to continuing ASR expansion. Both sites are situated in the strengthened part of the bridgedeck.

Viaduct Vlijmen-Oost

Monitoring of relevant variables on viaduct Vlijmen-Oost indicates no deformations other than those derived from varying temperature. The concrete appears to be less humid than that of viaduct Wolput. There are no indications for continuing ASR expansion in the bridgedeck over the measuring period; neither is new development of ASR expected from the measurements, provided that no conditions are changed.

Summarizing, only humid sites on viaduct Wolput show continuing deformations (other than those derived from varying temperature). Viaduct Vlijmen-Oost shows considerably cracking, but appears rather dessicated and shows continuing deformation. This might be due to rehabilitation during the late 1980s.

6.2 Monitoring techniques

The pilot project involved several monitoring techniques, in order to evaluate their performance. With respect to the individual techniques, the following is concluded:

Concrete resistance measurements using multiple ring sensors

Only part of the measurements was satisfactory. This part demonstrated the presence of more and less dessicated sites. It was, however, not possible to obtain a (qualitative) insight in the dessication behaviour of the bridgedecks. The technique has to be improved, in order to be applied on existing concrete structures. Values obtained may be due to other effects than more or less dessication

Measurement of the relative humidity using a Vaisala sensor

Measurements of relative humidity using a Vaisala sensor demonstrated the presence of more and less dessicated sites. The long term performance of these sensors is, however, doubtful. Values obtained on the longer term may be due to other effects than relative humidity in the concrete.

Measurements using (vibrating wire) strain gages

Measurements were satisfactory. Local deformations due to ASR could be detected and distinguished from those imposed by variations in temperature.

Measurements of local and structural horizontal deformation

Measurements yielded a relatively large range of values. Average values, however, agree reasonably well with deformations calculated from measured variations in temperature. Both types of measurements are, however, rather labour intensive.

Measurements of vertical structural deformation

Measurements indicate no significant displacements. Accuracy is probably too small to reliably detect minor deformations due to ASR.

Monitoring of cracks

This technique has only a limited resolution with respect to different behaviour at different sites with time.

6.3 Future research

For Civil Engineering Division of the Netherlands Ministry of Transport, Public Works and Water, the results of the pilot project were reason to:

- partly prolong monitoring of both structures involved in the pilot project; local measurements of moisture content, temperature and vertical deformation will be continued for one more year, after which it will be decided whether to stop;
- start monitoring 16 other ASR-affected structures in motorway A59; these structures have been or will be rehabilitated; also in these cases, it is important to verify whether deformation still continues and what is the effect of the rehabilitation strategy.