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MONITORING OF REINFORCED CONCRETE STRUCTURES AFFECTED BY ALKALI-SILICA REACTION

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ABSTRACT

Recent inspections of 20 bridges in a highway in The Netherlands revealed that ASR had affected the concrete. Until then alkali-silica reaction (ASR) was a rather rare phenomenon. In view of the expected, future importance of the maintenance of Dutch infrastructure, it was decided to start a long-term monitoring program on the decks of two of the bridges. The methods used are essentially non-destructive. The objective of this investigation is to gain quantitative information on the development of the ASR attack over time. Further the monitoring will be used to evaluate the effects of the applied repair and protection measures. The most promising monitoring methods will be used in the monitoring program of the other 18 bridges.

Measurements include internal humidity, internal and external deformations, and temperature. For some measurements new sensors have been developed. A modified multi-ring electrode has been designed to measure the change in concrete resistance as a function of depth. In this way the effect of drying out of the concrete can be followed. Internal deformations are measured by vibrating wire strain gauges which are inserted in drilled holes extending over the full height of the concrete structure. Monitoring will start effectively in the beginning of 1999 and will continue until 2001.

During the preparation stage of this experimental investigation, an extensive literature was executed to obtain an overview of non-destructive methods available to study the effects of ASR and protection methods.

Keywords: ASR, Assessment, Monitoring, Non-destructive testing (NDT), Safety

INTRODUCTION

During the past years it has been found in The Netherlands that dozens of concrete structures suffer from damage attributed to ASR (Heijnen et al 1996 and Bakker 1999). Such damage can have various characteristics and it can influence the behaviour of the structure in various ways. The influence does not necessarily have to be negative. Also positive effects can occur. In practice it will in general be a combination of both.

The Ministry of Transport, Public Works, and Water Management is the owner of the major part of all concrete structures where ASR has been diagnosed. About twenty of these structures are bridges in and over highway A 59 in the southern part of The Netherlands. It has been decided to use these twenty bridges to develop an assessment procedure for concrete structures in The Netherlands (Siemes and Bakker 2000). The basis of this procedure has been derived from a similar procedure from The Institution of Structural Engineers in the UK (ISE 1992). The investigated bridges had ages of about 25 to 35 years. Most of the bridges were made of reinforced concrete. A few of them were made of post-tensioned pre-stresssed concrete. Two types of cement have been used: Portland cement and Portland blast furnace slag cement. The aggregate was apparently coming from the river Meuse, but from various origins. Various contractors have constructed the bridges. The similarities between the 20 bridges are therefore restricted.

From the investigations on these twenty bridges it followed by means of microscopy on thin slices of the concrete that damaging ASR was present. All bridges had moderate expansion due to ASR with typical values of 0.4 to 1.0 $^{0}/_{00}$ ($^{mm}/_{m}$). Locally higher values have been found. Not all of them are representative for the ASR process. Incidentally some other damage has been found such as corrosion and frost damage. This incidental damage was negligible. By coincidence it was however found that in most of these structures an extremely low uniaxial tensile strength is present (Siemes and Visser 2000). The reduction of the low uniaxial tensile strength exceeded in a strong sense the reduction of about 30 %, that could be expected on basis of the measured expansion (ISE 1992). In contrary, the compressive strength and the tensile splitting strength were relatively high.

LOW TENSILE STRENGTH

The low tensile strength had mainly an important effect on the shear capacity of the bridges. No special shear reinforcement was available. The shear capacity was therefore fully dependent on the tensile strength of the concrete and on occasional reinforcement like the vertical reinforcement in the sides of the decks and the vertical steel supports that have been used during the construction to fix the reinforcement.

In the mean time maintenance measures have been taken to assure the safety of the structures for the time being and for the future (Siemes and Bakker 2000). The main measures to assure the safety of the bridges were:

- the redesign of seven critical bridge decks
- the strengthening of a very weak part in one of the bridges
- the application of additional supports under one of the other bridges
- the reduction of the payload on two of the bridges
- the replacement of a bridge; this has been done on one of the bridges where replacement already had been decided in advance; this replacement has been speeded up

- the research on the shear capacity of parts of bridge decks with relatively severe ASR; this research showed a reduced shear capacity (Den Uijl et al 2000).

After measures have been taken to reassure the safety of the bridges, all bridges had to be secured for the future. A rehabilitation project has recently been started, aiming to stop the ASR expansion, in an attempt to dry out the concrete. The ingress of water will be arrested. The water already present in the structure should evaporate gradually. To meet these goals a waterproofing membrane will be applied on top of the concrete deck directly under the asphalt road. On the remaining surfaces of the concrete a hydrophobic treatment will be applied. As the crack propagation is related to the bulk deformation drying out is of vital importance for the success of the operation. The drying is a long-term process.

The expansion due to ASR is rather unpredictable. Expansion tests showed inconsistent results (Siemes and Bakker 2000), even for individual bridges the expansion tests results could differ from total disintegration to a little shrinkage. Despite all investigations the amount of damage, the structural effects of the damage and the especially the progress in time remained uncertain. This implies that the structural reliability might become insufficient. To prevent this, monitoring was considered to be necessary.

The rehabilitation strategy may induce a new risk. Due to drying the ASR expansion may be lost together with the favourable 'pre-stressing effect' in the concrete due to restraint caused by the reinforcement. Calculations have however shown that this effect will be not more than 3 to 5 percent of the structural capacity (Den Uijl et al 2000).

NEED FOR MONITORING OF STRUCTURES WITH ASR

According to the ISE-procedure (ISE 1992) several maintenance measures can be taken after structural damage has been established in a concrete structure. Depending on the amount of damage this can vary. In the case of very severe damage it is recommended to demolish and to replace the structure. In case of very moderate damage it is recommended to monitor the behaviour of the structure. The aim is to establish that the condition of the structure will not reduce too much. Monitoring can relate to:

- structural behaviour, like deformations, deflections, cracking and the safety level
- degradation process due to ASR
- the environmental conditions related to ASR
- the effectiveness of curative measure or if no measures are taken to control the overall behaviour.

In the assessment of damage due to ASR both positive effects and negative structural effects can occur. Whether an effect is positive or negative is often dependent on the type of structure and its loading. The following negative main aspects should be taken into account:

- reduction of the strength of the concrete;
- reduction of the modulus of elasticity;
- map cracking and delamination;
- increasing eccentricities; the expansion of the concrete is in general not homogenous, the same applies for the restraint; the resulting forces will therefore in general not work centric and may lead to instability (such as buckling);

- increasing stresses in the reinforcement steel; due to the restraint of the expansion the reinforcement will get as a reaction an additional tensile force.

There are however also some positive effects, such as:
- additional compressive stresses in the concrete due to the restraint of the ASR expansion; these stresses can cause that the concrete will transfer forces through (former) cracks;
- reduction of the modulus of elasticity; this can contribute to the redistribution of cracking; this has a similar effect as cracking and delamination.

On basis of the positive and negative effects of damage due to ASR, the following list of possible monitoring parameters can be established:
- environment (temperature, relative humidity, moist loading, and the presence of alkali)
- presence and development of the ASR
- reactivity (formation of gel)
- moisture content in the concrete
- concrete quality and integrity
- strength and stiffness (compressive, tensile, shear, torsion, bond)
- cracking: pattern, width, length, distance and depth
- structural behaviour, like stresses, strains, deformations, displacements and integrity.

Monitoring can further be done to establish the chemical degradation process or to evaluate the effect of repair and protection measures.

Giving the present situation at highway A 59 it was found necessary to get an insight in the possibilities of non destructive testing (NDT) for monitoring the condition or the environment of concrete structures with damage due to ASR. For this purpose a survey has been made with respect to:
- the possible measuring techniques; it has been decided not to restrict this overview to purely non destructive techniques, techniques with a restricted amount of damage were also taken into account
- the technical description of the methods including indications of the restrictions of it
- the relevance of the measuring techniques and a selection of the most relevant methods.

Monitoring of structures with damage due to ASR is very complex because it can relate to a great number of different aspects, as has been shown before. It has therefore been expected that many measuring techniques were relevant. For each individual structure an evaluation has to be made of the most proper and effective technique. The review has however not been directed to straightforward methods such as standard measurements of the deflection, the crack width, and so on.

Comprehensive monitoring of existing structures with damage due to ASR has seldom been performed. In a literature search hardly any papers have been found. The reason is not quite clear. Possibly this is a consequence of the fact that monitoring of civil engineering structures in general is not popular. Further the interest in structural aspects in relation to ASR gets little attention. Less than 10 % of all publications on ASR relate to structural aspects. Once structural damage has been established in concrete structures, it will in general be very difficult to predict the future behaviour on basis of materials research (for example expansion tests or microscopy). The only reliable method however to establish the reliability of a structure with damage due to ASR seems to be monitoring. This has to be done in a indirect way, as no reliable non-destructive method has been found that predicts the safety level directly.

Monitoring the rehabilitated structures is considered of great importance, both to monitor the effectiveness of the chosen rehabilitation strategy, as well as to evaluate the safety of the structures. For the bridges in the A 59 the following topics are considered of major interest:

- What kind of structural deformations are caused by the continued or reduced ASR expansion?
- Will the concrete actually dry out after repair and how long does this take?
- Is the bridge safe?

Due to the low concrete tensile strength and the lack of proper shear reinforcement in the A 59 bridges the last point is of major interest. Shear failure will most likely result in a brittle collapse (the bridge either fails or does not fail). No proper warning system can be used yet for monitoring this process.

LITERATURE REVIEW

Considering the list of possible parameters for monitoring it can be concluded that the following main parameters are of special interest:

- the humidity of the concrete (see Table 1)
- the change of elastic parameters (see Table 2)
- the cracking process of the structure (see Table 3)
- the deformations of the structure (see Table 4)
- the displacements of the structure.

In Table 1 to 4 an overview has been given (Visser and Siemes 1999) of possible measuring techniques that can be used for monitoring. The tables also give information on the advantages and disadvantages of the various methods. This may sometimes be a little subjective, as objective considerations are not always available. Besides it must be realised that the development of these techniques is still going on and disadvantages may disappear in the course of time. For measuring the displacements standard methods like surveying, pendulum, and infrared techniques are available.

From literature it follows that until now only a restricted number of techniques, like UPV (ultrasonic pulse velocity), AE (acoustic emission), and vibration methods have been applied. These methods will have the best possibilities with starting ASR, when the material and structural changes are relatively big. These methods have not been applied simultaneously. It is therefore difficult to decide upon the best method. Besides it should be realised that monitoring of concrete structures is seldom be done. The practical experience is therefore little. It has therefore recommended for the monitoring of the bridges in the A 59 to start with a pilot project where relatively simple methods should be applied.

For the measuring methods that can be selected on basis of the development stage (radar and radiography) it has been advised to extend the study to establish their practical perspective. This can be done in a study where the methods are engineered for a practical application of a concrete structure with ASR. It is however very important to test these methods for their practical application in a simulation in the laboratory.

TABLE 1: Measuring Methods to Determine the Humidity in Concrete

Method	Advantages	Disadvantages
electrical resistance	• well developed • simple and cheap	• unambitiousness is only possible in homogeneous materials (no cracks or reinforcement) • profiles are only possible in the cover zone
multiple ring sensors (electrical resistance)	• reasonably developed • relatively simple and cheap • reasonably unambigious	• indirect method, the measurement is done in the injection grout instead of the concrete • restricted unambigiousness
di-electrical constant	• imaginary and real signal can be measured	• still under development • interpretation still needs a model for concrete
micro-wave sensors	• reasonably developed • relatively quick and simple • not sensitive for salt and inhomogeneities	• inaccurate with high humidity • measurement restricted to 25 mm • commercial equipment not yet available
radar	• reasonably developed • continuous profiles • simultaneous image of the internal part of the concrete	• very specialised • high initial costs • restricted depth • interpretation problems
radiography Röntgen/Gamma	• see radar	• see radar • requirements with respect to safety
NMR (nuclear magnetic resonance)	• less sensitive for salt and cracks	• under development • in-situ application yet experimental • high initial costs • restricted depth (yet)
infrared reflection	• well developed • measurements of large areas	• only superficial measurements • relationship between humidity and cracks unclear
humidity of wooden dowels	• simple	• relative humidity between 85 and 100 % • relationship between humidity wood and the RV is not unambitious • humidity wood is less than 30 % or rot will occur • each individual probe has to be calibrated

TABLE 2: Measuring Methods for Determining Elastic Parameters in Concrete

Method	Advantages	Disadvantages
UPV (Ultrasonic Pulse Velocity)	• well developed • quick and simple • sensitive to local changes	• influences of compression zone and reinforcement difficult to eliminate
SASW (Spectral Analysis of Surface Waves)	• gives more information	• under development • difficult interpretation • high initial costs
vibrations	• well developed • very sensitive to changes	• difficult with complex geometry
mechanical impedance	• see vibrations	• see vibrations

TABLE 3: Measurement Methods for Cracking

Method	Advantages	Disadvantages
radar	• reasonably developed • internal structure can be determined	• resolution • very specialised
radiography	• see radar	• see radar • use of contrast fluid
active acoustic emission	• see radar	• see radar.
infra red reflection	• well developed • quick and simple • low costs	• only superficial cracks • variations in humidity are unclear
video-records	• well developed, simple • low costs	• only crack patterns and gel
passive acoustic emission	• see radar • cracking is determined	• see radar • pre-loading necessary

TABLE 4: Measuring Methods for Deformations

Method	Advantages	Disadvantages
mechanical gauges	• well developed • quick, simple, and cheap	• local measurement
vibrating wire gauges	• see mechanical gauges	• see mechanical gauges
inductive gauges	• see mechanical gauges	• see mechanical gauges
strain gauges	• see mechanical gauges	• see mechanical gauges
glass fibre (multiple reflectors)	• many simultaneous measurements	• experimental and under development • expensive equipment
Moiré method	• 2D technique • stress type is determined	• only elastic deformations • overruled by computer simulations
photogrammetry	• 3D-technique	• under development
holographic interferometry	• 3D-technique	• under development • relatively expensive equipment • specialised • accuracy still unclear
speckle correlation	• see holographic interferometry	• see holographic interferometry

MONITORING THE DAMAGE PROGRESS IN THE A 59

A pilot study was set up for two bridges with relatively severe ASR damage, to monitor deformations and moisture effects after repair. The goal was to gain experience on limitations and implications of the test methods selected and on appraising and evaluating the test results. It was decided to do the monitoring on parts of the structure with relative moderate and severe damage due to ASR.

However a reliable evaluation can only be achieved after a long period of monitoring, as the behaviour of the structures depends to a large extent on time dependent loading effects and influences temperature and moisture. To distinguish between these effects and the effects of ASR requires the long period, as temperature and moist variations differ from day-to-day, but also form one season to another.

The monitoring program consisted of the following aspects, partly overlapping each other to give an opportunity for evaluation of the results:

- *Measuring deformations in the (horizontal) plane of reinforcement*
  Four measuring spikes were mounted in a square of 1 x 1-meter, at the undersides of the bridge decks at places with and without ASR damage. By measuring the distance between these points, small expansions can be measured. The measurements are performed manually, working above the head. As a result the accuracy is less than was anticipated, but sufficient for the evaluation.
- *Crack measurements*
  Cracking at the surface can either be a result of drying shrinkage or bulk expansion due to ASR. Relating this measurement to the before described square, can help to understand the cause of the measured deformations.
- *Vertical deformation measurement (perpendicular to the reinforcement)*
  ASR expansions will be most severe in the unreinforced vertical direction in the road deck. Vibrating wire gauges were fixed in vertical holes in the deck, two in each hole. The holes were injected afterwards with grout, so the displacement of the gauge is compatible with the concrete. A gauge consists of a tube with a wire under a certain tension placed in it. A coil around the wire causes the vibration during measurements. The strain can be measured by the resonance frequency response of the wire.

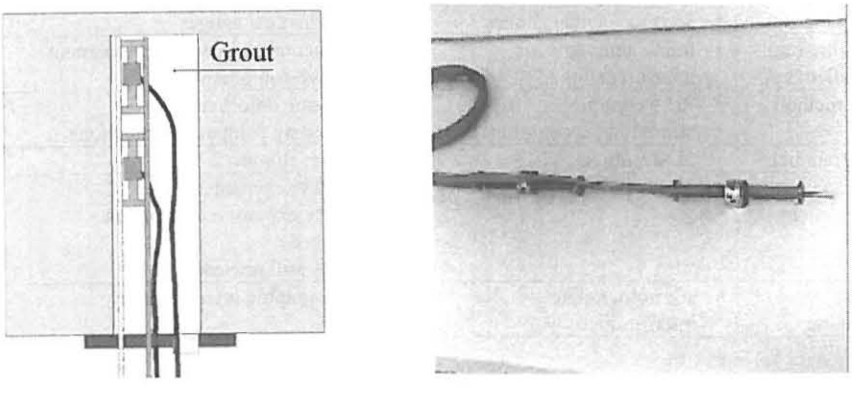

Fig. 1: Principle and picture of a vibrating wire gauge with cables and mounting

- *Structural deformations*
  Using a surveyor, horizontal and vertical displacements can be measured, in the middle of every span, and at each support. These measurements give global deformations and expansions of the decks.
- *Relative humidity and temperature*
  Fifty to hundred millimeters from both the top and bottom surfaces as well as in the middle of the bridge decks, combined temperature/relative humidity sensors are placed.

This measurement must be related to the deformation measurements, to distinguish between temperature, relative humidity and ASR related effects.

- *Multiring electrodes*
  To evaluate the effectiveness of the rehabilitation strategy, moisture profiles in the concrete are monitored. An indirect indication of moisture content in concrete is its electrical resistance. Although no exact values of moisture content can be obtained, the measurements will provide information on the development of the moisture profile in time. The multiring electrodes consist in this case of three sets of metal rings; 6 at the bottom, 2 in the middle and 6 at the top. The electrode is placed in a vertical hole, and injected with a mortar with a lower resistance than the old concrete. Measurements are made between two successive rings. The injection mortar, which has known properties, will be in equilibrium with the surrounding concrete. Measuring in the mortar should therefore be an indirect measurement of the surrounding concrete. The thickness of the grout layer should be as small as possible, this will however cause workability problems. Assessment of the grouting process is difficult.

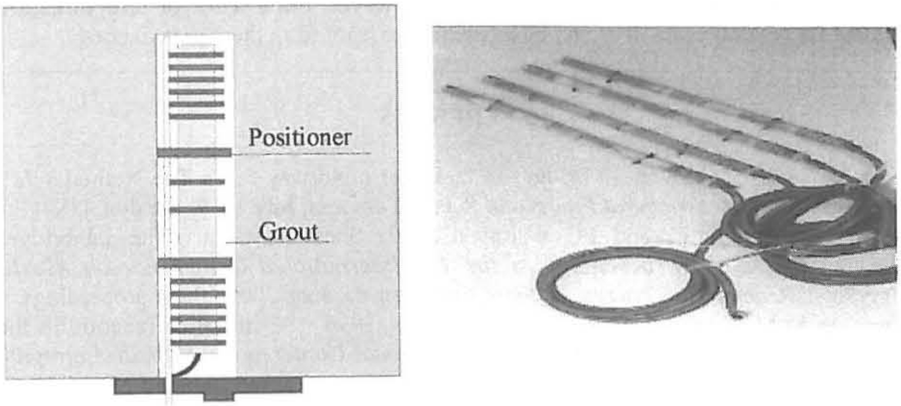

Fig. 3: Principle and picture of multiring electrodes with cables

CONCLUSIONS

The first results have only recently become available, therefore it is too early to evaluate the measured values. Yet, some conclusions can already be drawn:

- Non automatic measuring is time consuming. It should be evaluated whether the costs balance the costs of automation.
- Expansion in the plane of reinforcement: measuring above the head leads to inaccuracy but the results are still useful. Measuring in a laboratory or in practice is different.
- Further research is needed to establish a reliable relationship between the resistance values measured with the multiring electrodes and the moisture content in the grout and the surrounding concrete. Important parameters are the geometry of the electrodes, the thickness of the grout layer, the resistance of the grout and the concrete, the quality of the grouting process, the temperature and of course the moisture content.

- Measuring structural deformations only makes sense, if the measurements are performed during the same period as the temperature and humidity are measured. Further these monitoring should be extended over a long period of time to allow for an unambiguous interpretation of the results. The influence of the temperature, the moist and the loading regime prior to the measurements should be filtered out.
- Measurements of relative humidity and temperature sensors can possibly be corrupted due to condensation of moisture in the measurement devices.

These remarks make clear that each measurement method has disadvantages. Coming to a good monitoring program takes a lot of discussion and evaluation. The lessons drawn from the pilot will help to get to an improved monitoring plan for the other bridges.

Monitoring of structures is part of the complete maintenance strategy and plan for a structures. Knowing that a concrete structure suffers from ASR means that the whole strategy and the resulting maintenance plan have to be re-evaluated. In this way it will be possible to implement and evaluate the results of the monitoring process.

Little has been published about in situ monitoring of concrete structures in general and especially on concrete structures with ASR. However, quite a lot of structures are monitored for several years. It would be interesting to learn form these experiences.

REFERENCES

Bakker, J.D. 1999, "ÁSR in 20 bridges in and over motorway 59 in The Netherlands", *Proceedings of the Structural Faults and Repair* Congress, July 1999, London, UK.

Den Uijl, J.A., Kaptijn, N., and J.C. Walraven, 2000, "Shear resistance of flat slab bridges affected by ASR", *Proceedings of the 11th International Conference on Alkali-Aggregate Reaction in Concrete*, Québec City, Canada, June 2000, these proceedings.

Heijnen, W.M.M., Larbi, J.A. and A.J.M. Siemes, 1996, "Alkali-silica reaction in the Netherlands', *Proceedings of the 10th International Conference on Alkali-Aggregate Reaction in Concrete*, August 1996, Melbourne, Australia, (ed. Ahmad Shayan), pp. 109-116.

ISE - Institution of Structural Engineers, 1999, "Structural effects of alkali silica reaction; Technical guidance on the appraisal of existing structures", London, UK.

Siemes, A.J.M. and J.D. Bakker, 2000, "Evaluation of the ISE Procedure on Concrete Structures with ASR in the Netherlands", *Proceedings 11th International Conference on AAR*, Québec City, Canada, June 2000, these proceedings.

Siemes, A.J.M. and J.H.M. Visser, 2000, "Low tensile strength in older concrete structures with AAR", *Proceedings 11th International Conference on AAR*, Québec City, Canada, June 2000, these proceedings.

Visser, J.H.M. and A.J.M. Siemes, 1999, "Monitoring van kunstwerken met schade door ASR: literatuurstudie naar monitoring-technieken" (Monitoring of civil engineering structures with ASR: Literature review to monitoring techniques), *TNO report 98-BT-MK-R1645/01*, Delft NL (in Dutch).