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EVALUATION OF THE INSTITUTION OF STRUCTURAL ENGINEERS' PROCEDURE ON CONCRETE STRUCTURES WITH ALKALI-SILICA REACTION IN THE NETHERLANDS

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ABSTRACT

More than forty years ago in 1957, the first publication was published in The Netherlands indicating the possibility of damage due to ASR in a concrete structure. About ten years ago however the first concrete structure in the Netherlands with alkali-silica reaction (ASR) was documented. During the years before it was generally believed that this type of damage was not present in the Netherlands. In 1999, dozens of concrete structures have been proved to suffer from ASR. These structures have ages from 15 to 60 years. The types of structures vary from road bridges, water locks, bunkers, buildings etc. All structures have been made of portland cement concrete or concrete made of portland cement with a low content of blast furnace slag, the so called portland blast-furnace slag cement.

For the evaluation of these structures the procedure of the Institution of Structural Engineers (ISE) has been adopted. The procedure will be modified to Dutch circumstances such as the concrete codes. Further some improvements are made in the draft of the new procedure as well as a partly more strict formulation.

The modified procedure has been evaluated during a project on twenty different concrete bridges in highway A 59 that were suspected of suffering from ASR. It was found that most of the structures have an extremely low uniaxial tensile strength. This observation had a big impact on the maintenance strategy, more than is necessary according to the ISE procedure on basis of the other observations.

This paper covers the different aspects of analysis of the affected structures, laboratory experimental research, structural aspects, and remedial measures taken to re-strengthen some of the bridges, rehabilitation, and monitoring of these structures.

Keywords: ASR, assessment, ISE, maintenance, monitoring, structural safety

INTRODUCTION

Up to the 90's, damage caused by ASR in concrete structures was considered a rare phenomenon in The Netherlands, though the possibility of damage due to ASR had already been reported for the first time in 1957 (Bosschaert 1957). During the first half of the 90's, some structures have been identified to be affected by ASR (Heijnen et al 1996). Before this period a standard committee has been appointed to set up a Dutch procedure to avoid damage by ASR in new concrete structures. The work done for this committee improved the knowledge on ASR and made it possible to diagnose this phenomenon in practice.

In 1995, an advisory CUR-committee (PC 106 'Structural Consequences of ASR') was appointed to study the structural aspects of ASR, and to advise on how a Dutch procedure should be realised on this aspect. CUR stands for Centre for Civil Engineering Research and Codes. CUR initiates research on concrete structures and on hydraulic engineering. CUR-committee PC 106 has advised to adopt the English procedure of the Institute of Structural Engineers (ISE 1992) for the assessment of ASR affected structures. This latter procedure will be referred in this paper as the ISE-procedure.

A new research committee CUR C 106 'Structural Aspects of ASR in Concrete Structures' was appointed to implement this procedure. In co-operation between the Dutch Ministry of Transport and TNO (Organisation for Applied Scientific Research) an assessment project on 20 concrete bridges in highway A 59 in The Netherlands has been performed (Bakker 1999). It had been decided to use the ISE-procedure, and to fine-tune this for the Dutch circumstances. The results of the assessment have been transferred to CUR committee C 106 for setting up the Dutch procedure.

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 prestresssed 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 possibly from various origins. Various contractors have constructed the bridges. The correlation between the 20 bridges is therefore low. Common properties are that all bridges were not waterproofed and had poor water drainage, resulting in a wet environment.

ISE-PROCEDURE

The overall ISE assessment procedure is briefly presented in Table 1. The procedure intends to diagnose the structural effects of ASR and further to give advice on the maintenance strategy to be followed. The essential characteristic of the procedure is that it is simple. Only in the case of severe structural damage, are structural calculations necessary. The low profile is the result of the extended experience with ASR in concrete structures in the UK. In this experience the balance has been found between the positive (such as prestressing due to the restraint expansion, more redistribution of forces due to the lower stiffness) and the negative aspects (such as lower strength, and cracks) of ASR.

An investigation according to the ISE-procedure involves measurements in the field and in the laboratory. The field tests give a general impression of the present condition of the structure. According to the ISE-procedure the initial expansion can be determined by measuring the total crack width per length unit of the structure. With expansion tests in the laboratory the future expansion can be determined. The ISE-procedure does not claim to be very precise. It only aims to get a good engineering judgement of the condition of a concrete structure affected by ASR.

TABLE 1: Main Steps in the ISE Procedure

Step	Description	Main Items
1	Need to assess the structure	Determine the type and the amount of damage Judge the structural implications
2	Contribution of ASR to the damage	Assess the following items: – petrographic investigation for ASR – the environment (availability of water) – the reinforcement detailing – the expansion – the stress level in the structure – the amount of damage in the case of structural failure
3	Contribution of ASR to the structural distress	Type and amount of cracking Structural concept
4	Severity rating for the damage	Classification of: – the environment (availability of water) – the reinforcement detailing – the expansion – the stress level in the structure – the amount of damage in the case of structural failure
5	Establish the present and future structural safety	Decision rules based on the classifications (See Step 4)
6	Determine the structural severity of individual elements	Decision rules based on the classifications (See Table 3)
7	Develop proper management	Determine the future expansion due to ASR Reduce the amount of water and de-icing salts Regular inspections / monitoring Reduce loading or improve bearing capacity Determine the effects of other degradations

In general it can be stated that the ISE-procedure is not strictly formulated. The number of tests to be done and the types of tests can for a large extent be determined by the investigator. In Table 2 is an overview given with the basic testing programme to be used for the bridges in the A 59. For the evaluation, the number of tests for the compressive strength in the laboratory have been determined on basis of an existing Dutch recommendation. For the tensile strength, the dynamic modulus of elasticity, and the UPV measurements the same number of tests has been chosen. In practice this meant that 12 cores had to be drilled from the structure. These cores have been taken from the same spots of the structure where the visual analysis, the compressive strength (indicated by the Schmidt hammer) and the cumulative crack width have been measured. The number of cores and measuring locationss had also a practical background. The field investigation could be done, cost effective, within one day by two inspectors and one person for drilling the cores.

TABLE 2: Main Items of the Basic Structural Analysis in the ISE-Procedure Including Extra Measurements for the Evaluation of the ISE-Procedure

Field Tests	Number of Tests	Laboratory Tests	Number of Tests
Inspection of an area of the structure	12	Visual assessment of the cores	12
Schmidt Hammer readings	12	Thin section petrography	3
Cumulative crack width	12	Expansion tests	6
		Compressive strength	6
		Tensile strength	6
		Dynamic modulus of elasticity	6
		Ultrasonic pulse velocity	6

The measurements of the tensile strength, the compressive strength, the dynamic elasticity modulus and ultrasonic pulse velocity (UPV) in the laboratory have been added to provide further information and data to verify the ISE-procedure.

As the ISE-procedure did not give a proper description for the expansion tests it has been decided to do two different types of tests. Half of the tests were carried out in a fog room at 20 ^{0}C. Normally the humidity in a fog room is determined as > 98 % RH. In this case the condition was that the specimens had to be exposed to fog, causing wetting of the specimens. To prevent leaching of the ASR-gel the specimens were covered on the top by a plastic sheet. The other half of the expansion tests have been done by exposing the test cores in a 1 N(ormal) sodium hydroxide solution with a temperature of 40 ^{0}C. The exposure period was 12 months. The two tests represent more or less a moderate test and a severe test.

The specimens that were used for the expansion tests have also been used to do additional non destructive testing. The dynamic modulus, the UPV, and the change in mass (water uptake) have been measured before and during the exposure period.

EVALUATION OF THE ISE-PROCEDURE ON 20 BRIDGES

Field Investigation

The investigations on the twenty bridges were not restricted to the phenomenon of ASR. As it would not be clear from the beginning that ASR would be present in all the structures it had been decided to get an overall impression of the condition of the bridges. For this reason the following observations and determinations have been made:

- the cracking in the structure by means of the pattern, the distances between the successive cracks, and the crack widths
- the presence of damage that has not been caused by ASR
- the concrete cover
- the carbonation depth
- the presence of chloride
- the previous repairs.

With respect to the damage due to ASR the following aspects were additionally determined:

- the deformation of the structure (for example: are the expansion joints open?)
- the presence of a coating
- the environmental conditions
- the drainage of the bridge.

From the field investigation it followed that the bridges were in a generally good condition. Occasionally some damage was present due to the ingress of de-icing salts, causing chloride-induced corrosion. This damage originated in most cases from leaking expansion joints. The overall impression from the investigation was that road decks were typical wet structures. Drainage is often poor, pipes and gutters are blocked, joints are leaking, and drainage water is running over the structure and due to rearranging the lanes on the bridge deck the drainage of the deck is not functioning. This poor drainage has aggravated leaching, frost damage, corrosion, and ASR.

Most of the measured cracked areas had cumulative crack widths of less than $1\ {}^{0}/_{00}$. According to the ISE procedure, these expansions should be related to the reinforcement configuration and the possible consequences of failure. For most of the structures this lead to the classification 'mild ASR damage'. Locally the cumulative crack width was far in excess of $1\ {}^{0}/_{00}$, giving the impression of a more severe ASR damage. This has been observed in the sides of the bridge deck. The cracking in these regions is apparently not representative of the ASR process in the whole structure. The cumulative crack width should therefore only be measured on spots where the cracking pattern can be fully developed.

The ISE procedure does not relate the number and direction of cracks to the amount and orientation of the reinforcement, which makes this interpretation questionable. Especially in this case where most of the bridge decks had no shear reinforcement, and the potential consequences of failure were considered as very severe. It is not clear from the ISE-procedure how it deals with other phenomena that can cause cracks, such as shrinkage and bending. If cracks are already present in the structure, drying shrinkage could cause an additional cumulative crack width of approximately $0.2\ {}^{0}/_{00}$ under Dutch environmental conditions. In regions with high bending stresses, it is even possible to have a cumulative crack width of more than $1\ {}^{0}/_{00}$ (for example distances of 0.2 m between the cracks and widths of 0.2 mm). The cumulative crack widths have to be corrected for these effects. Some of the cores from the bridge decks were horizontally de-laminated, obviously because expansion in vertical direction was not prevented by vertical reinforcement. Some of the cores leaked gel after they had been exposed in a humid room for some time.

Microscopic Investigation

By means of thin section petrography ASR has been established in 17 bridges. The reaction occurred mainly in the coarse aggregate grains. In the remaining 3 bridges the ASR followed from the gel that was present in the bridge or became visible in the test cores. In case of a moderate amount of ASR the thin sections are too small to find reaction products in all the structures. The diagnosis of ASR damage cannot be restricted to thin section petrography. It has to be made by combining observations on various levels. On a microscopic level the presence of potential reactive aggregates has to be proved. Further evidence of reacting aggregates is necessary. The reaction should have caused damage to the material. This damage must be visible in cores (for example: gel and reaction borders on the coarse aggregate, these might however have been present from the beginning in the case of gravel). Further it must be clear that the structure is damaged due to the ASR.

In all structures the following indication of potentially reactive materials have been found by means of PFM (a detailed geological investigation has not been carried out):

1. porous chert (flint)
2. sericitic sandstone, chalcedony and opal are presumably the reactive materials
3. micro- to cryptocrystalline quartz in quartzite
4. chalcedony.

Porous chert had reacted in all structures and in most of the structures also the sericitic sandstone. In a few cases the third mineral had reacted. Chalcedony did not react.

Laboratory investigation

The cores taken from the structure have been used to measure the compressive and tensile strength of the concrete. Further the remaining expansion has been measured including the change in elastic modulus and the ultrasonic pulse velocity (UPV). During the exposure period expansions with values of 0.2 – 0.4 $^{0}/_{00}$ have been measured on the cores in the fog room, and 0.2 - 2.0 $^{0}/_{00}$ (in a few cases the cores were completely disintegrated) on the cores in the sodium hydroxide solution. A part of the measured expansion may be caused by the reversible drying shrinkage of the concrete. In the outdoor Dutch climate the concrete will shrink about 0.2 $^{0}/_{00}$. After exposition to water in the test, this will disappear and be measured as an apparent expansion. This effect will occur relatively fast. The baseline for the further expansion should be established after this effect has occurred. The correlation to the expansion in the structure was poor. On basis of the test results it was not possible to select the most reliable expansion test. The sodium hydroxide solution test seems to exaggerate the remaining expansion.

In most cases UPV increased instead of dropped (typical values of 4200 to 4900 m/s). Also the dynamic E-modulus increased instead of dropped (typical values of 30 to 50 kN/m_). This may be the effect of water absorption in the cores or precipitation of secondary products in cracks.

Conclusions from the Investigation

The ISE-procedure will give in the first instance a so-called structural severity rating, ranging from negligible to very severe structural damage. Most of the bridges had a rating mild or moderate damage. In the procedure the rating is the result of classification of various relevant aspects (expansion, reinforcement, environment etc.) and the application of decision tables. No redesign has been made. For this reason we have changed the term ‘structural severity rating’ into ‘maintenance strategy rating’ with new descriptions according to Table 3.

One of the problems with the interpretation of the results is the fact that for one concrete elements different ratings can be found. The expert giving the rating has to make a decision for the rating of the whole element or the whole structure. Even if ASR damage is present in a structure it is possible that parts of the structure do not have any damage. In the ISE-procedure this situation will lead to the rating ‘negligible’. In the draft CUR C 106 procedure this situation is rated as ‘no ASR damage’.

TABLE 3: Rating for the Maintenance Strategy

Original ISE Description 'Structural Severity Rating'	Description according to CUR C 106 'Rating for the Maintenance Strategy'
negligible	no measures necessary
mild	preventive measures
moderate	monitoring and preventive measures
severe	general structural investigation
very severe	detailed investigation

During the investigations some additional measurements have been made to provide for an objective evaluation of the ISE-procedure. In Table 4 the results of the compression and the uniaxial tensile tests are given as mean values and the characteristic values. The characteristic value is in this case equal to the lowest measured value of the six specimens. This is similar to a Dutch recommendation for measuring the compressive strength in existing structures. Such a recommendation is not available for the tensile strength. The values given in Table 4 are therefore only indicative. The values in Table 4 are also indicative because many cores from the bridge deck were broken due to the horizontal cracks in the decks. Formally the strength is thus 0 MPa. Further we must realise that no distinction has been made between regions in the structure with and without damage.

The compressive strength is for all bridges in line with the expectation for concrete of this age and made of coarse grained portland cement and portland blast-furnace slag cement. The bridges were constructed with concrete grade 25 to 35. Due to the ongoing hydration of the cement it is not unusual that the compressive strength increases to more than the double 28-day value. Any reduction due to ASR is than no longer significant. The ISE-procedure assumes that always a reduction will take place.

The uniaxial tensile strength (according to Rilem CPC 7) for all bridges is dramatically lower (mean values ranging between 0.7 and 3.2 MPa) than can be expected on basis of the measured high compressive strength. Mean values of 3.5 to 4.5 MPa would have been normal. These latter values were indeed found in a restricted number of tensile splitting tests. The value for the uniaxial tensile strength points to an extremely high scatter. The measured values are in principle too pessimistic because the uniaxial tensile test is very sensitive for eccentricities. In this case eccentricities are due to:

- inaccuracy in the test set up; such as test platens that are not in line or not plan parallel
- eccentric big gravel grains or mortar spots in the test specimen
- local damage or compression stresses due to AAR
- anisotropic microcracking.

These eccentricities can be fully responsible for the low uniaxial tensile strength. In that case it would be better to use the term apparent tensile strength. During the microscopic investigation some strong indications have been found for a low tensile strength:

- poor bond between the cement paste and the aggregate
- a high amount of micro cracks;
- crack width of these microcracks is 0.1 to 0.2 mm
- the (apparent) water-cement ratio (w/c) varies on a microscopic scale from 0.45 to 0.65
- the damage due to AAR.

These indications are not strictly related to ASR and can also occur without ASR.

Based on the considerations with respect to both eccentricities and micro damage we must assume that the real tensile strength lies between the measured uniaxial tensile strength and the tensile splitting strength. The load bearing capacity for tensile dependent mechanisms (shear, bond, torsion etc.) will be reduced. In the mean time testing beams, taken from existing structures with damage due to ASR has showed, that the shear capacity is indeed reduced.

TABLE 4: Indicative Values for the Compression and the Uniaxial Tensile Strength of the 20 Investigated Bridges

No	Bridge	Compression Strength [MPa]		Uniaxial Tensile Strength [MPa]	
		Mean	Characteristic	Mean	Characteristic
1	Hambaken	69	56	1.7	0.6
2	Hedelseweg	72	65	2.0	1.2
3	Rietvelden	58	50	2.6	1.1
4	Den Bosch W.	73	59	2.5	1.7
5	Vlijmen-Oost	63	56	1.9	0.8
6	Heidijk	55	46	1.3	0.6
7	Kennedy	65	44	2.4	1.3
8	Wolput	50	33	2.1	1.2
9	Wolfshoek	69	49	2.4	0.7
10	Elshoutseweg	57	50	2.0	0.6
11	Drunen West	61	53	1.6	0.4
12	Labbegat	64	46	2.3	1.9
13	Capelsche H.	67	56	2.5	2.1
14	Schoutstraat	59	29	2.7	1.6
15	Zijlweg	62	53	2.2	0.4
16	Heemraads.	62	43	1.6	0.8
17	Hespelaar	72	55	2.8	0.8
18	Haasdijk	69	60	3.2	2.6
19	Houteind	58	51	3.0	2.6
20	Rode Weel	63	48	2.6	1.0

The low uniaxial tensile strength has been found in this project more or less by chance. Testing the tensile strength is not a formal part of the ISE-procedure. Adding compression and tension tests to the ISE-procedure is however strongly recommended. The extra costs for the total investigation will increase slightly. Having data on the compressive and tensile strength will improve the decision made on basis of the ISE-procedure, especially in the case of more severe damage due to ASR. The measured tensile strength is significantly lower than the reduction of about 25 % indicated in the ISE-procedure.

MAINTENANCE STRATEGY

The purpose of the ISE-procedure is to determine the maintenance strategy for a concrete structure that is affected by ASR. The maintenance strategy can in principle be found by classification of a couple of relevant aspects. On this basis the maintenance strategy can be determined. As ASR will only occur in wet conditions, the ISE rules can be simplified by assuming that the outdoor condition is always wet. In Table 5 the decision rules are given.

TABLE 5: Classification for the Structural Severity Rating in a Wet Environment

Expansion $^0/_{00}$	Consequence of Failure	Reinforcement Detailing Class		
		1	2	3
< 0.6	slight	mild	mild	mild
	significant	mild	mild	moderate
0.6 – 1.0	slight	mild	moderate	moderate
	significant	moderate	severe	very severe
1.0 – 1.5	slight	mild	moderate	severe
	significant	moderate	severe	very severe
1.5 – 2.5	slight	moderate	severe	very severe
	significant	severe	severe	very severe
> 2.5	slight	moderate	severe	very severe
	significant	severe	very severe	very severe

Table 5 shows that in the most common case, reinforcement detailing class 3 (three-dimensional reinforcement), the basic rating is predominantly 'very severe'. For class 2 the rating is predominantly 'severe'. This means that knowing the reinforcement detailing, only an impression about the amount of expansion suffice to determine the severity rating and as a consequence the maintenance strategy. In case the expansion shows that ASR plays an important role (expansion > 1.0 $^0/_{00}$) the structural severity rating nearly always either 'severe' for reinforcement class 2 or 'very severe' for reinforcement class 3. The specific information coming from the investigation of the structure and the laboratory tests have hardly any influence on the decisions.

In the case of the 20 investigated bridges the structural severity rating has been determined for the various parts of the structure. From this structural severity rating the maintenance strategy has been derived (Table 3). An overview of this is presented in Table 6.

TABLE 6: Scores for the Maintenance Strategy of the 20 Bridges

Type of Measure	Percentage
No measures	44
Preventive measures	24
Monitoring and preventive	16
General structural investigation	4
Detailed investigation	12

According to this table only in 16 % of all measured locations of the 20 bridges a structural investigation has been advised. If the whole bridge is considered than the outcome looks different. For 14 bridges (70 %) a detailed investigation has been advised and for 6 bridges a general investigation. The measured low uniaxial tensile strength raised additional questions about the safety of some of the bridges. For the most severely attacked bridge decks structural redesigns have been made, focussing on the shear capacity. These proved that some of the structures had a too low shear capacity. Actions have been taken for the safety on these bridges, varying from reducing the payload, adding local reinforcement, complete close down for traffic, and replacement of one bridge. After taking these measures, all bridges had to be secured for the future. A rehabilitation project has been started, aiming to stop the ASR expansion, by an attempt to reduce the moisture content of the concrete.

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.

CONCLUSION

The ISE-procedure proved to be a relatively good guidance for the practical part of the assessment of 20 concrete bridges in the Netherlands that were affected by ASR. It was however found that the information from the investigations has no big influence on the final decisions with respect to the maintenance of the structures. An essential part of the information is not used.

On the other hand, according to the ISE-procedure no strength testing is required. The experience in the Netherlands has shown that such tests, and especially uniaxial tensile tests, should be done. In older concrete structures the uniaxial tensile strength can be very low. The effect of this low uniaxial tensile strength was more dominant for the maintenance decisions than the other damages caused by the ASR.

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