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THE RILEM GUIDANCE ON APPRAISAL AND MANAGEMENT OF STRUCTURES DAMAGED BY AAR

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Abstract

This paper presents the guidance made by a working group (named team A) of the RILEM Committee TC 219 dealing with the appraisal and management of structures damaged by AAR. The work begun in 2007 and is scheduled to end in 2012; it has a strong connection with a previous work conducted by a RILEM TC 191 group which drafted a guide on the diagnosis of AAR damage to concrete in structures.

This guidance is an excellent opportunity for gathering the various experiences in the field of appraisal and management of structures, and is developed from the few guides published in some countries. Its structure is organized in four main chapters: a chapter on the effects of AAR on material and structural properties, a chapter bridging the gap from diagnosis to appraisal of residual structural capacity, a chapter devoted to the possible solutions of treatment and mitigation, and finally a chapter constituting an aid for the managers dealing with ASR affected structures.

Keywords: AAR, structures, appraisal, management, treatment

1 INTRODUCTION

The RILEM TC 191-ARP Technical Committee “Alkali-Reactivity and Prevention - Assessment, Specification and Diagnosis”, which started work in 2001, included a working group named “Diagnosis and Appraisal of AAR Damage to Concrete in Structures” which drafted a first document on diagnosis and appraisal (designated AAR-6) [1]. This group decided to split the draft into two parts: Part I on Diagnosis (AAR-6.1) was first completed in 2006 and significant improvements to the original draft were agreed in 2008, whilst Part II on Appraisal and Management (AAR-6.2) was started in 2007 under the auspices of successor Technical Committee, TC 219-ACS “Alkali-aggregate reactions in Concrete Structures”. The development of AAR-6.1 and AAR-6.2 has since been undertaken by one of the teams of this TC, team TC ACS-A “Appraisal, Management and Repair of Affected Structures”.

Part I of the "Guide to diagnosis and appraisal of AAR damage to concrete in structures” (AAR-6.1) is devoted to diagnosis and describes the procedures and methodologies used systematically to make diagnosis of damage to concrete in structures suspected to be caused by Alkali-Aggregate Reaction (AAR).

This document has two primary objectives, firstly to identify any evidence of the reaction and its intensity in various members of a structure; and secondly to establish whether or not the reaction is the primary or contributory cause of damage in the concrete. This guide is also designed to include aspects such as field inspection of the structure, sampling, petrographic examination of core samples, and supplementary tests and analyses on cores, including mechanical tests and chemical analysis.

Part II is "Guidance on appraisal and management of concrete structures" (AAR-6.2) and its objective is to provide information, knowledge, methods and tools for laboratories and consultancy firms for assessing the performance of structures in terms of structural capacity, serviceability and durability, and to help the owners of structures to manage their patrimony by taking the best possible decisions. It is developed from several guides published around the world and listed in references [2] to [16], and also on the experiences of the members of the working group. This guidance comprises the four following chapters: effects of AAR on material and structural properties, from diagnosis to appraisal of residual structural capacity, solutions of treatment and aid to the management of ASR affected structures.

This guidance will cover various types of structures: primarily bridges, but also hydraulic structures (dams, reservoirs, sewage works), buildings, open frames and foundation structures (car parks, retaining walls, piles) and also pavements. In due course, AAR-6.2 will also be published as a RILEM Report, hopefully as part of a combined volume with an updated AAR-6.1.

2 EFFECTS OF AAR ON MATERIAL AND STRUCTURAL PROPERTIES

When the AAR develops at a sufficient number of locations within the concrete, a global expansion occurs. Because of the variability of the concrete reactivity, the intensity of the reaction, micro-cracking and macro-cracking will be variable both in terms of distribution inside the structure and with time. These primary features need to be understood so that the effects of AAR on material and structural properties can be determined. This enables the serviceability, the durability or the load carrying capacity of a structure to be assessed. Therefore, this chapter is divided into two parts: the first one describes the effects of AAR on material properties, and the second part on structural properties.

2.1 Effects on material properties

This section is dealing with the role of water and the effect of stresses on the concrete expansion, the anisotropy of the concrete according to the casting direction, the micro-cracking of concrete, the altered mechanical characteristics of concrete (compressive strength, tensile strength, elasticity modulus, Poisson'ratio,..). It also covers the test methods that can be carried out for a basic assessment of the material (compression, direct tension, splitting, torsion, residual expansion, stiffness damage test,...) as well as the test methods that may be required for a numerical assessment of reaction rate (permeability to water, humidity diffusion, temperature conductivity, …)

2.2 Effects on structural properties

A critical review of various consequences of AAR at a structural level is then presented by focusing on the main effects which have been found in different types of structures, the expansion, the development of cracking, the degree and design of reinforcement, the quality of the bond strength and the effects on member strength. Some other features are also tackled such as the development of internal stresses, the overstresses in steel leading to eventual steel failures, the redistribution of stresses inside structures, the possible delamination of the cover concrete, the movements and global deformations, and the consequences of global deformations on adjacent structures, equipment, machinery and ancillaries.

3 FROM DIAGNOSIS TO APPRAISAL OF RESIDUAL STRUCTURAL CAPACITY

This chapter does a link with the RILEM Guidance Part I and integrates the knowledge coming from the previous chapter to assess the residual structural capacity of a structure, as well as its serviceability and its durability. Three levels of appraisal are considered and introduced according the three following sections.

3.1 Initial review of drawings and site inspection

This section lists the information that has to be gathered from the site environment, from the detailed inspection of the structure, and from the analysis of detailing and prestress. The efficiency of reinforcement and/or prestress (either applied or developed as reinforcement resists the expansion) in maintaining the integrity of the structure depends on the degree of containment it provides to the differential expansion. It is important to identify any parts of the structure which may be classified as highly vulnerable (V3 or V4 – see 5.2) at this stage, so that resources for diagnosis and assessment can be obtained and focussed on them.

3.2 Assessment of severity index and initial sampling and monitoring

This section describes how a severity index may be designed with the help of various tools:

- the expansion index (or cracking index)
- the monitoring of parts of the structure (cracks with the help of a digital camera or Demec gauge, global and local deformations with the help of distance meters, pendulums or optical means).
- different sampling and testing methods (drilling cores, expansion tests, Stiffness Index Method, non destructive methods, full-scale test loading, stress measurement,...)

Of course, the variability inside a pour, between pours, between structural parts, and the non-uniformity in moisture or stresses need to be taken into account. This subchapter allows classify in more detail the critical elements that need thorough investigations and assessment.

3.3 Detailed assessment of critical elements and overall behaviour with models

This section presents the appraisal of the structural strength and ductility of the critical elements or parts of the structure. It deals, for example, with the detection of brittle failure, especially due to the loss of bond between concrete and bars in case of cover delamination, or due to shear cracks. It also presents the tests that are useful for defining parameters for numerical models. This links with another RILEM ACS team that is working on the modelling of structures in order to predict the future behaviour of these critical elements (see paper presented by J.F. Seignol & al. in this conference).

4 TREATMENT SOLUTIONS

Currently, there is no proven universal methodology of treatment which is sufficiently effective to durably repair the structures damaged by AAR, and even to stop the further evolution of the disorders. As long as the ingredients which are necessary for the continuation of the chemical reaction are present in sufficient quantity within the heart of the structures, it appears rather illusory to stop this type of reaction.

Indeed, AAR develops forces from swelling which can be large compared to the mechanical efforts introduced by general structural behaviour.

Four general principles for the treatment of the structures may be considered: to apply mechanical means to confine the expansion or to release the constraints, to avoid the penetration of water or moisture in the structures, to remove water from concrete, and to reduce the contents of alkalis in concrete; each one of these principles having 'side effects'.

A fifth principle has been suggested which relates to the carbonation of lime in the concrete to prevent it from reacting with alkaline silicates to form alkali-silica gel. Unfortunately, carbonation lowers the pH of the concrete and can cause corrosion of steels. This method is to be reserved for thin unreinforced concrete parts, because it appears improbable to succeed in injecting enough carbon dioxide within the core of the massive parts to carbonate all the lime.

4.1 Mechanical actions

Three principles ought to be distinguished:

- if a simple strengthening is needed, then an additional reinforcement is added;
- if any swelling of the concrete is to be prevented, then a confinement has to be applied with a high compression;
- a by-pass of the affected element of a structure can also be done.

The strengthening may be done by enclosing, ringing, or inserting reinforcements which are called active or passive according to whether they are tensioned or not when installed. These reinforcements are primarily made of steel, but one can use passive reinforcements made of composite materials. It is thus possible to strengthen a structure while fixing on its facings reinforcement steels and by embedding them with shotcrete. Under the effect of the structure expansion which continues, the reinforced shotcrete cracks and the reinforcement bars take again a part of the overstresses generated by the expansion of the concrete.

The experience gained in the laboratory and in the field shows that, in a prestressed concrete structure, the concrete expansion (and thus its cracking) are developing preferentially according to the least constrained directions. It is thus recommended to implement a three-dimensional reinforcement with the objective of confining the expansion. Taking into account the considerable forces generated by the alkali-aggregate reaction, it seems that it is necessary to apply constraints which are in a range of 3 to 10 MPa, with a reasonable value of prestressing being about 5 MPa. However, applying a 3D prestressing on a structure is difficult; it is possible to apply a 3D prestressing in some particular elements like the buttresses of a dam or a box girder bridge, but often there is a direction where it is impossible to apply a prestress.

The experience shows also that, if the concrete expansion continues, the presence of passive or active reinforcements creates an additional prestressing of the concrete because of additional elongations undergone by the steel reinforcements which are obliged to follow the concrete expansion. It is however not advised to rely on this prestress in the dimensioning of the strengthening because it can be considered as artificial.

Another problem that needs to be checked is the strength of the concrete under the anchorage of the prestress. A risk of crushing is possible and this problem may be solved by the interposition of a concrete or steel anchoring block (or plate) in front of the damaged structure in order to allow a sufficient dispersion of the prestressing force.

Finally, another type of active mechanical treatment consists in releasing the stresses by sawing whole or part of the structure (slot cutting). The first attempts were made on dams. This operation, already practised successfully in some countries (USA, Canada, France,...), has a short-term effectiveness, but it often requires reapplication as it releases restraint of expansion but does not influence the continuation of the reaction. It can be an effective solution in quite particular cases, such as concrete structures that are not reinforced.

4.2 Avoiding the penetration of water or moisture in the structures

The control of water and salts ingress is a normal procedure for enhancing the durability of concrete structures, especially bridges and pavements, and these requirements are particularly fundamental for AAR. Simple methods of maintaining and upgrading drainage and waterproofing, for example bridge decks, should be applied as soon as AAR is suspected rather than delaying action till investigations are complete.

The guidance reviews the various methods of treatment that have been used, to try to "repair" structures damaged by alkali-aggregate reaction, on the basis of some example existing in various countries. It gives some conclusions on their limits and their effectiveness. These methods of treatment are the waterproofing and water drainage, the injection of cracks, the application of painting or silanes, the application of a watertight coating and cladding.

4.3 Removing water from concrete

Removing the water inside the concrete by drying is another solution. Drying can be forced (e.g. active drying) or natural (e.g. when a protection from further water ingress is provided). But, is a drying really achievable ? Perhaps for easily accessible thin parts of structure, but certainly not for massive structures like dams, or for part of structure in contact with water or grounds like the foundations. Those parts of structures under water can benefit from the migration of the alkalis, but it is a slow process with massive structures. In some conditions, active drying may even have for effect to accelerate the reaction by introducing moisture gradient inside concrete and concentrating the alkalis where there remains water. Therefore an active drying can cause an increase of the content of alkalis locally. In every case, the effectiveness of drying depends on the speed of transfer of water within the structure, and thus on the permeability of the concrete. Indeed, this solution seems to be unrealistic and its implementation is facing technical and economical obstacles.

4.4 Other techniques

Lithium has been used experimentally as an admixture in concrete in order to prevent ASR, provided that it is used in sufficient quantity. The amount of lithium required increases as the amount of alkali in the concrete increases. For existing structures, it is not evident that this can be effective. Some laboratory testing has shown that concrete specimen can be treated using lithium-based compounds to slow down the rate of expansion, but the main problem is with achieving deep penetration of the compound, especially if the porosity of the concrete is low. In the USA, many structures have been treated with lithium using either topical application or electrochemical or vacuum impregnation techniques to increase lithium penetration, but up to now, there is no evidence of any success with such techniques.

4.5 Conclusions

On the basis of examples presented in the guidance, it appears that the most suitable method of treatment in the majority of cases is initially to restore the systems of drainage if those are failing, and in a second place to implement a watertight coating. Even if it fails to constitute a final treatment, this method makes it possible to slow down the progression of the disorders. This type of treatment which aims at extending the lifespan of the structures presents the disadvantage of masking cracking, and thus obstructing the monitoring that is essential to implement on the structures damaged by AAR. One can however note that the methods of monitoring the total deformations remain applicable in the presence of these coatings.

In more specific cases, treatments of mechanical nature may be applied on an experimental basis, but for the most serious cases partial or total demolitions may become necessary.

5 AID TO MANAGEMENT OF ASR AFFECTED STRUCTURES

The initial presumption of the existence of an internal swelling reaction of concrete in a structure is generally founded on the presence of visual symptoms detected at the time of a visit or an inspection. Among the most known signs, cracking is often quoted; it appears in the form of a grid which is more or less dense according to the degree of evolution of the reaction, or is oriented when compressive forces are opposed to the internal swelling (case of the prestressed structures, or the columns for example). A swelling reaction can also generate many other forms of apparent disorders on a structure such as movements, deformations, small craters (pop-out), etc. Based on these symptoms, this chapter proposes two methods of management, a traditional one that is applied extensively but various owners of bridges damaged by AAR, and a more sophisticated method based on risk analysis.

5.1 Traditional method of management

Principle of the method

The diagnosis of a structure affected by an internal swelling reaction calls upon two great types of investigation techniques, the in situ monitoring of the expansion of the structure and its cracking with time, and the analysis in the laboratory of samples taken from the structure.

Considering the cost of these various techniques, and knowing that swelling is a phenomenon which develops in general rather slowly, at least under the climatic conditions prevailing in most temperate countries, it is not good value to implement all of them, systematically and in an identical way, on all structures of a patrimony damaged by a swelling reaction of concrete.

On the contrary, it is advisable to adopt a progressive methodology according to the apparent condition of the structure and the speed of the evolution of its disorders. Except for the case of the very damaged or vulnerable structures where all the investigation methods are simultaneously applied, the suggested methodology prioritises the monitoring of the structures dimensions which is relatively easy to realize, non destructive and allows the evolution of the phenomenon to be accurately monitored with time, rather than the extensive systematic use of destructive cores for expensive analyses in the laboratory.

This methodology can therefore be divided into 5 stages: prioritization, initial assessment, monitoring, search for the causes of disorders, forecast of the evolution, then followed by a sixth stage which is the decision to apply solutions of treatment or mitigation of the consequences of AAR on each structure. In this process the interaction of AAR with the range of other structural and deterioration problems which may also be present need to be considered.

Prioritization of structures

In its first step, the suggested methodology consists of carrying out a classification between on the one hand, structures presenting advanced disorders which affect a vital zone of the structure (structures classified in priority level 1), and on the other hand, structures presenting less marked disorders or disorders which do not affect a vital part (structures classified in priority level 2).

Initial assessment

For the first structures (level 1), it is necessary to engage the monitoring on site and the analysis of cores in laboratory simultaneously. For the most serious cases of particularly damaged structures, it will be advisable to examine the serviceability and, if necessary, to implement safeguard actions.

For the second ones (level 2), it is enough to initiate at first a monitoring of the structure with the help of both dimensional monitoring and cracking surveys. It is only if the evolution of the expansion or cracking with time proves to be fast that coring must then be carried out for analyses.

Monitoring

The frequency of measurements to be made during the monitoring of the structure is related to its cracking condition at the time when the monitoring is installed (initial state). The more significant the initial cracking of the structure is, the more the recommended frequency of measurements is high. Where the pattern of cracking indicates that AAR is interacting with structural behaviour to produce combined cracking which is not controlled by reinforcement, this needs priority in monitoring.

If during this period, the evolution of the cracking index and the opening of possible isolated cracks already widely opened, and the evolution of the expansion remain limited, the structure falls back in the normal cycle of inspections and visits. On the contrary, if the evolution of cracking or expansion exceeds targeted thresholds, fuller investigation must then be carried out in the structure.

Identification of the causes

Indeed, it is the analysis in laboratory which allows to determine the origin of the expansion (AAR and/or ISR) and in the latter case to specify if it is an internal or an external reaction. Part I of the guidance is a basic document to conduct this stage.

Forecast of the evolution

After the diagnosis of the cause of the pathology has been confirmed and the evolution of expansion has been measured on site, the problem is then to know if the structure will still continue to expand, and if its serviceability is likely to be affected. For that, tests of residual expansion can be realised on cores in order to estimate whether, under environmental conditions favourable to swelling, the concrete is still likely to expand and in which proportions. Such tests exist for the alkali-aggregate reaction and are under development for the sulphate reactions.

If it is proved that the concrete still has a high potential of expansion, it may be necessary to carry out a specific calculation of the structure taking into account the effects of the swelling, in order to forecast the load carrying capacity of the structure. Generally, this type of calculation requires a numerical model based on the finite element method. The model used must consider the whole information collected during the monitoring of the structure as well as the results of the tests of residual expansion, and must take into account information on the thermo-hygrometrical environment of the structure, as well as information on its thermal and hydrous history.

5.2 Method of management based on a risk analysis

The application of this method supposes a good knowledge of the structure, of its cracking pattern, of the foreseeable severity of the pathology (forecast expansion at local and global level, consequences of the expansion of individual elements on the structure,…) and of the advancement of the swelling reaction. All these parameters should have been observed or deduced from the inspection campaigns, from the monitoring (cracking index, dimensional monitoring,…), from the complementary investigations (cores and residual expansion measures, possible recasting of concrete and expansion measurement,…), and eventually from a numerical modelling of the damaged element and structure.

These elements completed by the geographical location and the strategic role of the structure define the conceptual context of the methodology. At this stage, two situations may occur: the expansive reaction (whenever its severity) is stopped, and the expansive reaction is still active.

In the first case, the condition of the structure is stabilised and it is advisable to go to a repair of the structure (if necessary) and to restore its serviceability or to improve its durability. In the second case, the condition is evolving and the choice of the treatment depends on a great number of parameters (potential of residual expansion, environmental conditions of the damaged elements, sensitivity of the structure to the expansion of these elements, socio-economical impact of a reduced serviceability of the structure, …). This complex situation whose evolution is uncertain necessitates an approach based on a risk analysis.

Principle of the methodology

In this methodology, we propose to define the internal expansion as the hazard. The vulnerability of the structure regarding this hazard is characterised by its sensitivity to the expansion of a damaged element. The criticality of the structure is defined by the crossing between the hazard and its vulnerability ; schematically we represent this by: Criticality = Hazard x Vulnerability.

In this method, the hazard is estimated from the results of the residual expansion test on cores extracted from the considered element, or from concrete specimen fabricated on the base of the information found in the structure documentation (concrete composition, cement type, thermal history of concrete,…).

Vulnerability

The vulnerability of the structure as regards the expansion of the damaged element explains the severity of disorders occurring in the structure and their influence on the serviceability and the durability of the structure (see Table 1). The vulnerability can be determined, as a function of the damaged element and the design of the structure, either by a simplified qualitative analysis (in simple cases) or by a numerical model integrating a chemo-mechanical coupling. The vulnerability may be classified, in this method, in four levels V1, V2, V3 and V4, according to the fact that the expansion of the element :

- has no influence on the safety, the serviceability or the durability of the structure
- has only an influence on the durability of the structure, without endangering the safety and the serviceability of the whole structure
- has an influence on the serviceability of the structure, without endangering its safety
- has an influence on the safety of the structure.

Criticality

The criticality of the structure depends on both the hazard importance (based on thresholds on residual expansion) and the vulnerability of the structure regarding the expansion of an element (see Table 2). As a function of the strategic importance of the structure (for example in the case of a bridge: the traffic intensity, the operational constraints, the possibility of limiting the weight, the possibility of detour, the patrimonial value,…), the manager should define his goals or specifications in terms of durability, serviceability and safety. Therefore, it is not the size or the cost of the structure that are always the main parameters, but the character of the structure to be essential, useful or minor in its context. The criticality can be defined according to table 2.

Levels of treatment

Then the levels of treatment are proposed according to table 3, by crossing the criticality of the structure with the issues.

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TABLE 1 : Vulnerability of the structure regarding the expansion of an element			
Level	**Vulnerability**	**Examples**	**Consequences**
V1	Null	■ Non structural elements whose expansion and deterioration has no consequences on the durability, the serviceability or the safety of the structure ■ Easy to replace elements, etc.	No consequences on the structure
V2	Low	■ Structural elements or non structural elements whose expansion and deterioration has no consequences on the safety or the serviceability of the structure ■ …	Consequences on the durability of the structure
V3	High	■ Structural elements or non structural elements whose expansion and deterioration affect the serviceability of the structure ■ …	Consequences on the serviceability of the structure
V4	Very high	■ Structural elements or non structural elements whose expansion and deterioration affect the safety of the structure	Consequences on the safety of the structure

TABLE 2: Criticality as a function of Hazard and Vulnerability

Hazard / Vulnerability	Low potential and dry environment	Low potential and humid environment	High potential and dry environment	High potential and humid environment
V1	C0	C0	C0	C0
V2	C0	C1	C1	C2
V3	C1	C2	C2	C3
V4	C1	C2	C3	C4

Example of classification of criticality:
C0 : very low impact of hazard on the structure
C1 : low impact of hazard on the structure
C2 : medium impact of hazard on the structure
C3 : high impact of hazard on the structure
C4 : very high impact of hazard on the structure

TABLE 3: Levels of treatment as a result of crossing the criticality with the issues

Criticality / Issue	**C0**	**C1**	**C2**	**C3**	**C4**
I0 (structure with low issues)	T0	T0	T1	T1	T2
I1 (structure with moderate issues)	T0	T1	T1	T2	T3
I2 (structure with high issues)	T1	T1	T2	T2	T3
I3 (strategic structure)	T1	T2	T2	T3	T3

Example of classification of treatment:
T0 : no treatment or a slight and local treatment on the damaged elements
T1 : slight or local treatment to get a correct durability of the structure
T2 : preventive or corrective treatment to prevent the loss of serviceability and/or durability
T3 : heavy treatment against the loss of serviceability and/or temporary or definitive substitution of the structure. An urgent treatment to secure the structure could be necessary…