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A COLLECTIVE EFFORT TO PROPOSE PRACTICAL GUIDANCE ON THE USE OF NUMERICAL MODELS TO RE-ASSESS AAR-AFFECTED STRUCTURES

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Abstract

This communication presents the ongoing work made by a team of the Rilem Committee TC 219 devoted to the numerical modeling of alkali-aggregate reaction (AAR) effects on concrete structures. The purpose of this "TC ACS-M" Team is to propose practical guidance on the use of numerical models as a tool for managing AAR-affected structures. Based on the various experience of team members, this guide is organized in four main chapters: the role of numerical modeling; a tentative typology of models; a compendium of existing numerical tools; practical advices on how to use these models.

Keywords: numerical model, AAR, structure re-assessment

1 INTRODUCTION

Since its discovery in concrete structures, alkali-aggregate reaction (AAR) received attention of several studies, especially in the fields of chemistry, petrography and material sciences. Mechanics and structure engineers' involvement started later but is now an active research field. Several numerical tools, mainly based on constitutive models for FEM-softwares, have been developed to answer urging questions from structures managers: stress-state due to restrained expansions, pathology evolution, relevance and design of treatment solutions.

The large number and variability of these numerical methods require a collective work to list, clarify and evaluate existing tools. This task is presently devoted efforts in the frame of RILEM's Technical Committee 219 on AAR in Concrete Structures: Performance Testing and Appraisal (TC 219-ACS) by a team composed of specialists in numerical modelling and structures management from various countries. The work of this "TC ACS-M" team is strongly connected to the one realized by "TC ACS-A" team, devoted to Appraisal, Management and Repair of Affected Structure [1].

TC ACS-M work will result in writing a guide called "Practical Guidance on Predictive AAR Modelling" (this is a tentative title). The main chapters will be:

- The need for numerical modeling
- Different types of models
- Models compendium
- Recommendations on the use of AAR models

The present contribution presents this work-in-progress in three parts. First, the use of numerical models in the frame of AAR-affected structures management is considered. The second part presents the current state of the models compendium and ongoing discussions about which points meet fair agreement and which ones are still subject to debate. The last part reviews some practical aspects in the use of numerical models, based on the various experience of TC members.

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2 NUMERICAL MODELING FOR STRUCTURES MANAGEMENT

2.1 Managing AAR-affected structures

The growing comprehension of AAR mechanisms and the refinement of diagnosis methods lead to the detection of more and more AAR-affected structures. Dealing with assets in various stages of degradation, with different priority levels and likely to evolve during several years or, on the contrary, in a stabilized state of degradation, structures owners have turned to more or less complex management rules (the reader should refer to [1] for a view of various existing management procedures).

These procedures are often composed of several steps including: detection, diagnosis, in-situ monitoring, assessment of structure's present state, forecast of evolution and, if considered necessary, designing a repair or treatment project. As for tools used to re-assess structure's present state and its long-term evolution, three types of recommandations can be mentioned:

- the ones which do not mention specific tools but put the stress on the importance of re-assessing structural state (for instance [2, 3]);
- the ones which propose to adapt classical methods developed for sound concrete structures, such as engineer methods (for instance [4]) or FEM-numerical models with modified material parameters, such as [5];
- the ones which recommend to use numerical models specifically designed to represent AAR-affected concrete structures behaviour [6, 7, 8].

Hence, numerical models are clearly part of tools proposed to structure owners to manage their damaged structures, as well as in-situ monitoring devices or laboratory analysis techniques.

As often as possible, specifically designed numerical tools will be prefered to re-assess AAR-affected structures: although several models exist for concrete structures, for designing sound structures as well as for assessing residual life-span of decaying structures, AAR presents some features that are worth being taken into account.

2.2 Specificities of AAR

Contrary to other more common pathologies, such as carbonatation, chlorides ingress or frost effects, AAR occuring was not anticipated during design stage (outside rare exceptions; see *infra*). The expansive reaction is often lately discovered when its over-decades evolution leads to visible consequences which alert the structure owner. This delay in identifying then treating the problem often results in difficulties to obtain usefull data for using numerical models (real material characteristics, construction conditions...)

The second difficulty occuring with AAR is its multi-physics characteristics: it involves, at different scales, phenomena dealing with chemistry, diffusion of moisture and chemical species in hardened-cement-paste porous network, heat conduction, concrete granulometry and mechanical properties, often associated to the presence of rebars or other devices.

Moreover, various questions have to be adressed by numerical modeling: it is often necessary to deal with ultimate behaviour (in order to re-assess residual safety or bearing capacity of the structure) and serviceability (a common case in hydro-power facilities is given by the interaction between chemical-induced strains in the structure and low mechanical tolerances of equipment).

Finally, as in other applications of numerical modeling in civil engineering, proposing professional tools adapted to real-case studies and not only prototypes from academic researches is a growing necessity; AAR-devoted numerical models must answer, as expressed by [9], "an increased demand for reliable, robust and - above all - industry relevant analyses"

2.3 Purpose of numerical modeling

One of the main purposes of modeling an AAR-affected structure is the assessment of its real stress-state, in order to determine if the pathology has induced a decrease in structural safety and to quantify it. Hence, numerical models have to take into account:

- overtensions in rebars and tendons which restrain concrete expansion;
- reciprocaly, the compressive stress induced in the affected concrete by rebars resistance;
- the complex stress-states which can result from strain gradients (due to heterogeneous water ingress, such as [10], temperature gradients, various alkali content or dispersion in material properties);
- complexity of multiphysics coupling which influence occuring and development of AAR such as thermal history [11];
- second order effects or occuring of excentricity in compressive forces due to excessive strains in structural elements [4];
- in the case of statistically indeterminate structures, strain-induced redistribution of reactions.

The second purpose of numerical modeling is to answer one of the questions most frequently asked by structure owners confronted to AAR problem: what will be the evolution of the structure if no appropriate measures are taken. This question concerns structural safety [8], serviceability (see for instance real case presented in [12]) and durability.

But there are other cases where numerical modeling can provide useful informations for structures management:

- deciding which locations are the most relevant to equip in order to monitor an affected structure;
- providing help to interpret in-situ monitoring data already available [13];
- choosing a repair technique, as well as designing it [14, 15, 16, 8];
- designing new structures when practical and economic arguments require the use of reactive aggregates [17].

2.4 Different modeling scales

Discussions between the working group members exhibited the various meanings covered by the words "numerical modeling" in the frame of AAR. First, a distinction can be made between modeling the AAR in itself, as a chemical and diffusion phenomenom, and modeling its effects on the concrete, namely stresses, swelling, cracking, etc.

Moreover, the pathology is driven by chemical, physical (especially diffusion and heat transfer) and mechanical phenomena, and these phenomena occur at different geometrical scales in the concrete.

Consequently, the different numerical models can be classified according to the scale(s) at which they represent the material and the structure. Three categories have been distinguished:

- microscopic models, where the characteristic length is far smaller than the largest aggregate, which allows for instance to explicitely represent cracks occuring in an aggregate core due to AAR-gel growth [18] and microstructure of the material;
- material models, where the characteristic length is similar to the aggregates size (for instance [19, 20]);
- structure models, for which concrete is assumed to be a homogeneous continuous media, allowing to represent an entire bridge, building or dam with a limited number of finite elements.

It should also be mentionned that some models [21, 22] can be classified as multi-scale models because they are based on more than one scale at the same time.

3 MODELS COMPENDIUM

The main result expected from the current working group consists in building a list (which will not pretend to be exhaustive) of different existing models for AAR-affected concrete. Hence, a kind of "compendium" is under development. For each enlisted model, the compendium will tend to provide the following informations:

- scope of the model;
- theoretical background;
- description, main equations;
- fitting of the various parameters involved in the model description and, if any, laboratory tests or in-situ measurements used to obtain appropriate values;
- numerical implementation (name of existing FE software in which the model was developped, availability, type of software: commercial, academics, open-source...);
- validation, example on simple test-case.

3.1 Tentative list of models

The models supposed to be considered in the compendium are presented in table 1 (for practical reasons, they are given name based on the litterature; these names are not official). When this information is relevant, the scale of the model is given, as well as the way it represents AAR-effect (prescribed expansion or internal pressure).

In addition to these models which can be considered as concrete constitutive equations specially designed to take into account AAR effects, the two following numerical tools might be considered. They have not been especially developped to manage AAR-affected structures but they are sometimes used in the frame of real-case studies.

Equivalent thermal load: This technique consists in using a classical FEM-software allowing to solve thermo-elasticity problems and to apply an artificial temperature field (or, if the software allows it, a strain field) to represent chemicaly-induced swelling in concrete. It can be used as a structural scale model (see for instance [23]) or at a material level, by prescribing expansion to the sole aggregates [18].

Statistical models: Instead of explicitly modeling AAR-effects in concrete, it is possible to base a structure analysis on monitoring results [24, 25]. Thanks to statistical tools, measured displacements and strains are explained as functions of respectivelly external-load, temperature and creep in order to exhibit the residual part which is supposed to be generated by expansive reaction. Once this last component is described by a set of equations (based on regression methods), prognosis can be performed by mean of extrapolation techniques.

3.2 Agreements between models

The study of these different models allows to emphasize some agreements between them. A consensus is observed on the following points:

- Most of the models consider a latency period when the reaction starts, during which little or no expansion is observed at a macroscopic scale. It can be modeled by a simple translation of the expansion curve (for instance [26]), a very low strain rate (see [27]) or else by representing AAR-effects as an internal pressure which does not apply to the material until the initial porosity of concrete is filled by reaction gel (see [28]).
- Concrete temperature influences AAR kinetics through Arrhenius law. This coupling is observed both in material scale models such as [20] and in structure scale ones, e.g. [11].

- Available moisture influences swelling amplitude, and two features are often observed in the coupling models: first, there exists a threshold value below which expansion does not exist (or remain very low); second, expansion quickly grows with moisture as soon as threshold value is exceeded. Several coupling relations exist (see for instance [29, 30, 31]), but they often lead to similar results when applied to structures re-assessment [32].

- Stress-state can lower and even totally prevent expansions in the most compressed directions. Once again, different coupling equations have been proposed for the models based on prescribed chemical strain [33, 34, 35], whereas models based on internal pressure naturally lead to similar behaviour [36, 28].

3.3 Ongoing discussions

There are no agreement in all features of AAR-models, and some points are still debated. Amongst them, the shape of the expansion-versus-time curve is given strong interest. Several models are based on an S-shape curve [37] or a similar shape [26], which leads to an asymptotic expansion for sufficiently large value of time. This is the mathematical translation of the idea of a closed system where reactants are consumed by AAR and this is in fair agreement with free expansion laboratory tests performed on sample cores. But the monitoring of some real structures, especially large ones such as dams, pushes for a continuous expansion at constant rate without any sign of slowing down [8]. Asumptions of alkalis resupplied by release from certain aggregates or indefinitely recycled in the AAR-processus have been proposed [38].

Other points, of lesser importance, are also treated in different ways by various numerical models (or simply ignored by some of them):

- Triaxial compressive stress-state: does it induce a global decrease of volumic expansion, or shall we consider that only deviatoric stress-state does influence chemical swelling anisotropy?

- It is generally agreed that AAR is responsible for a decrease in concrete Young's modulus as well as its tensile strength. But experimental results are not so conclusive when considering compressive stress [35].

- Several models take into account long-term strain to represent concrete creep, but there is no clear agreement about the interaction between AAR and creep characteristics. Some models (for instance [33, 22]) consider a creep function independent of AAR-development whereas other [39] binds both phenomena.

Reaching a conclusion for these different debates will imply further discussions amongst model-makers, but also acquiring new knowledges from experimental tests, real-case studies and, more generally, a deeper understanding of AAR-mechanisms.

4 PRACTICAL ASPECTS IN THE USE OF NUMERICAL MODELS

The last part of the ongoing guide will be devoted to some practical recommendations concerning the use of numerical models as tool to re-assess and manage AAR-affected structures. It is composed of two main parts, the first one dealing with choosing a model and the second one with some considerations about correctly fitting the models. Additional parts also adress questions such as results interpretation, precisions, link with field monitoring, etc.

4.1 How to choose a model?

Readers' attention is drawn to the fact that choosing a numerical model (amongst the ones presented *supra* or others) first requires a precise definition of the question(s) to be answered, and, especially, on the physical phenomena to be taken into account and the ones which can be neglected. The size of the problem (a complete structure, a single element, etc.) also has to be considered, since it influences the scale at which the model will operate.

The correct choice implies a good balance between necessary sophistication (to achieve a fair simulation of the complex physical, chemical and mechanical interactions occuring in AAR-affected concrete) and limiting the complexity of the model, unless it could be impossible to correctly fit it due to the lack of available data.

As a corrolary, there is no point in deciding whether there are "good" and "bad" models. For each real case-study, some models are adapted, other are not. To evaluate each model with regards to precise requirements, a short list of basic model features concerning AAR has been established:

- isotropic stress-free expansion srain as a given function of time;
- expansion strain-rate expressed as a function of local alkali content;
- expansion and its rate related to local moisture;
- chemical strain rate considered as temperature-dependent;
- anisotropy of expansion with regards to the vertical (or casting) direction;
- expansion adjusted with the local stress-state, inducing strain anisotropy and global expansion reduction with triaxial compressive stress;
- influence of AAR-development on material stiffness and tensile strength
- influence of AAR-development on long-term behaviour, such as creep;
- influence of reinforcement and prestressing.

4.2 Models fitting

Choosing the appropriate model is a required condition of success but is not sufficient. Adjusting it with adequate parameters is essential to make it able to correctly represent the studied structure and its evolution. These parameters can be obtained through laboratory tests performed on samples, data from the structure files...

Several guide pages are devoted to share working group members experience about this complex and essential matter, as well as putting the stress on the main difficulties which may occur during this step.

Choosing sample cores: AAR often presents a strong heterogeneity and intrinsic anisotropy. This is why the number, the location and the direction of sample cores drilled out of the structure strongly affects their representativity when used to fit parameters dealing with AAR-modeling.

It also affects the determination of classical mechanical parameters (Young's modulus, strength and others) since these properties can vary wether the samples are drilled out from sound parts of the structures or AAR-affected ones.

Representativity and size effect: Several models are based on parameters acquired from laboratory tests performed on sample cores, the dimension of which is about 3 to 5 times the diameter of largest aggregate. Field experiments, especially in the case of large structure (dams, for instance) has shown some discripancies between behaviour of sample cores and behaviour of concrete in the structure. Different explanations can be proposed [38], such as size effect, alkali leaching during laboratory tests, recycling of alkalis from gel to CSH...

From residual expansion to total expansion: To use numerical models in order to forecast structural behaviour, various accelerated expansion tests are performed on sample cores drilled out of the structure a long time after the AAR started. Hence, these sample cores have undergone an unknown "swelling history" before the begining of the residual expansion test. Different techniques to find out the "missing part" of the expansion curve are mentionned:

- inverse-problem techniques [12];
- relation between AAR-development and Young modulus decrease;
- evaluation of micro-cracking due to previous AAR.

The feasibility of re-creating an equivalent virgin concrete on which an accelerated expansion test is performed is also discussed.

5 CONCLUSION

This paper reviewed the ongoing work in the frame of the "Modeling Team" of the Rilem Technical Committee TC-ACS. Its aim is to provide practical guidance on the use of numerical models for AAR-affected structures. The results of the Team work should result in a Rilem Report, hopefully published in 2012. The main points this guide deals with are:

- the role of numerical modeling in the general frame of managing AAR-affected structures;
- the different types of numerical models;
- a (non-exhaustive) list of existing models with their major properties;
- practical advices about how to choose, use and fit numerical models to study real AAR-affected structures.

The discussions in the frame of this team give the opportunity to exhibit converging opinions about some aspects of AAR numerical modeling and also point out topics where diverging opinions exist, from which new research themes may be driven.

The authors would like to thank Rilem Technical Committee on Alkali-aggregate reaction in Concrete Structures members, especialy its Chairman Philip Nixon, its Secretary Ian Sims and all the participants to the TC-ACS "Modeling" team.

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Table 1: Alphabetically sorted list of models to be included in compendium. Scales are denoted by μ (micro), M (material) and S (structure); AAR-effects can be represented by P (pressure) or E (prescribed expansion); *nr* stands for "not relevant".

Name	Scale	AAR-effect	References
Bažant *et al.*	M	E	[40, 41]
Comby *et al.*	M	E	[19]
Comi *et al.*	S	P	[11]
Curtis *et al.*	S	E	[15]
Dunant *et al.*	μ	E	[18]
Farage *et al.*	S	P	[36, 42]
Gomes *et al.*	S	E	[33]
Gonzalez *et al.*	μ	nr	[20]
Grimal *et al.*	S	P	[28, 39]
Léger *et al.*	S	E	[29]
Li *et al.*	S	E	[37, 27]
Meghella *et al.*	S	E	[43]
PAT-ASR project	M	nr	[44]
Poyet *et al.*	M/S	P	[21, 45, 22]
Saouma *et al.*	S	E	[35]
Winnicki *et al.*	S	E	[26]