A TOOL FOR CONCRETE PERFORMANCE ASSESSMENT FOR ASR AFFECTED STRUCTURES: AN OUTLOOK

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Abstract

This paper outlines a project (namely PAT-ASR) which entails the development of a multi scale material performance assessment model on simulation of alkali silica reaction deployment and its effects on concrete durability. Performance models require a multi scale approach from micro (namely reaction chemistry) to macro level studies (namely structural mechanics). PAT-ASR aims to combine the tasks of guidelines on ASR prevention and control in a comprehensive integrated tool. This project involves experimental studies, among others including the determination of mechanical properties of ASR gel. A computational model, in conjunction with the already developed Lattice Models, will be used for simulating crack patterns in a concrete matrix. A statistical approach to sample data, harvesting from literature, can be used to increase the reliability of such a prediction model. Final integrated support tool will provide a guideline for engineers on ASR conscious design and a full-scale technical report on the subject.

KEYWORDS: alkali-silica reaction, multi-scale modeling, performance assessment

1 INTRODUCTION

Numerous studies have been collected on alkali silica reaction (ASR) in the last decades. These studies mainly focused on chemistry and progress of reaction. It is often very challenging to design durable concrete structure with decades of service life relying on single accelerated test result. Accelerated tests last very long to be practical and provide some what less reliable results lacking a full understanding of the reaction mechanism itself. Recently more studies are undertaken on the cause-effect relation of ASR covering multi-scale approaches to this deleterious degradation process.

Today the reliability and duration of accelerated test setups are questioned. Several variations are observed between laboratory test results and real structure measurements due to discontinuity of material properties, variations in environmental conditions and coupling effects of other degradation processes, are observed. Common practices to mitigate the effect of ASR on structures are to avoid the reactive aggregate, to use low-alkali cement or supplementary cementing materials (SCMs). However, understanding the mechanism of the reaction is core for sustainable and durable concrete design. Today, determination of service life of concrete structures depends on full-scale understanding of such deterioration mechanisms by designers, contractors and clients. International union of Testing and research laboratories for construction materials and structures (RILEM) has been carrying out studies on legitimacy of standard accelerated tests for performance assessment of alkali reactive aggregates. Also, several European funded research projects are executed on aggregate classification for ASR (Wigum, Lindgård et al. 2006).

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2 MODELING ALKALI SILICA REACTION

The alkali silica reaction is defined as the breakdown of silanol bonds in poorly crystallized silica in aggregates [1]. In high alkaline conditions, depolymerisation and solution of reactive silica in aggregate creates sodium hydroxide and potassium hydroxides. Hydrolysis of these oxides produces alkali silica gel in solid form [2]. This product gel expands in the presence of moisture which results in stresses in the microstructure [3, 4]. Expansion in concrete and degradation of mechanical properties may result in malfunction of structure. Prediction of such slow degradation process throughout a service life of a structure constitutes vital importance in durable concrete design, construction and operational issues.

ASR models are generally formulated on material level. Such models mainly base their predictions on curing conditions, temperature, stress and relative humidity effects on free expansion values. However studies on micro structural level are fairly limited. Recently, Comby-Peyrot [5] published their work on three dimensional computational modeling of ASR using finite element model. More recently, Schlangen and Copuroglu [6] proposed a method on modeling ASR expansion using a new test set up. All analytical and computational approaches rely on their degradation mechanisms with underlying assumptions of gel formation, aggregate types, progress of ASR gel towards the cracks and similar attributes assigned for the material. These assumptions are deeply related to the parameters defining the model and predefined performance criteria assigned for the material, itself.

2.1 Material performance assessment

Standards, guidelines and specifications are all aimed to guarantee certain performance threshold for safety, durability, cost and energy issues in a concrete structure. Material performance interpretation must include overall effects on the system. The only way to achieve this goal is to fully understand the structural effects of the degradation process rather than a single uniaxial parameter value. Design limits and conventional testing methods become inapplicable, which strengthen the role of computational methods in design process. Numerical tools, when interpreted correctly, can accelerate the development of new products and their optimization processes.

In 2010, Dutch government initiated a research program on 'Integrated Solutions for Sustainable Construction', namely IS2C. The main aim of this program is to develop advance knowledge management systems for predictive simulation model for service life assessment of concrete structures. Within the scope of this program, this 4-year project aims to develop multi scale material performance assessment tool of ASR development and its effect on concrete durability, namely PAT-ASR. It combines the tasks of the available recommendations in a unique comprehensive integrated tool, and furthermore it covers alternative materials, national and international codes, environmental profiles and structural parameters in the design process of ASR-proof concrete.

Two main work clusters are formed within research scope of this project. The first part focuses on analysis of reactivity assessment of aggregates. Standard accelerated tests and newly developed small scale ultra accelerated tests are used to analyze the effects of varying temperature, aggregate related parameters (such as, gradation, shape, origin, petrographic properties, reactive component, mechanical properties, etc.) and use of supporting cemetitious materials. Second part of the study aims to relate chemical and mechanical properties of ASR gel to stresses in micro structure and fracture formation mechanism. Both parts of the model will be combined in an integrated software interface which enables robust concrete mix design for durable structures.

2.2 Simulation and material models

ASR has long term effects on durability, serviceability and safety of concrete structures. Maintaining affected structures and designing ASR-proof structures is only possible by comprehending the reaction mechanism and its effects under various loading conditions. Such knowledge requires analysis of chemical reaction parameters in micro level and observations on physical effects at structural level. Multi-scale models use micro level information for chemical reaction parameters and meso level deformation analysis. Figure 1 summarizes the flow diagram of this particular tool.

Software initially requires chemical and physical properties of materials and concrete mix design parameters to be defined. This information will be provided from/to data warehouses serving available and commonly used values for concrete mix design and available aggregate sources. This information is then used to calculate reactive silicate component of aggregates, required for initial threshold values dictated by the standards and guidelines. The tool provides several national and international threshold values for comparison and best practice purposes. The mix design properties are later checked with workability and strength requirements enforced by the project design and functional use of the structure. There are several tools enabling prediction of concrete microstructure and resulting porosity/pore solution products. Micro structural information combined with environmental/external conditions/classification may be used to identify potential ASR gel formation in a concrete matrix. In theory, material properties, environmental and external factors can be utilized for the estimation of expansion values for concrete sample at a given time (t). Association of expansion values to mechanical properties of ASR gel formation is proved to be challenging task. Schlangen and Copuroglu [7] introduced a new method for identification of gel properties and proposed a method to use this information in expansion simulation. This method will be further tested with enhanced petrographic analysis of reacted specimen. Verification of the model will be done through a statistical tool harvesting accelerated test results in the literature, case studies from real structures and carrying out experiments in Delft University of Technology (TUD) materials lab.

Parameter Studies

Parameter definition is crucial on several levels: functionality of tool, compliance of the model with real life experience. This process requires reviewing and optimization of the parameters defined in the literature. Studies are mostly focused on the basic parameters that initiate the ASR. However, there are still relatively fewer studies on the stresses and damage mechanism formed due to reactions' effects. Concrete consists of natural constitutes which exhibit heterogeneous mechanical and chemical properties.

Factors affecting ASR are commonly categorized into three main groups: sufficient alkali content, Silica content and high relative humidity [8]. Many scholars provided parameter analysis of factors affecting ASR and accelerated testing procedures [9, 10]. This study covered the parameter studies in the literature and classified according to our needs (see details in Figure 2). Expansion results can be classified according to simplifies rock classifications. Location, test type, test conditions relating to temperature and several variables, which can be used for comparison or early expansion fittings for new concrete mixes. Published reports and results from literature are used as the basis for this analysis. This research currently in collaborations with research institutes on national and international level (Netherlands, Norway, Iceland and Turkey). We are currently in touch with technical committees (RILEM TC 219-ACS), test institutions and industry partners, to exhibit our case and mature objectives for further studies with experts/ international leading scientists' opinions on the issue.

Aggregate reactivity and guidelines

Rock type cannot be solely used as a criterion for potential reactivity of an aggregate. Reactivity of an aggregate is strongly related to reactive mineral content of the aggregate. Although most rocks are capable of containing reactive forms of silica, the number of types of silica that exhibit reactivity is quite small. Studies [2, 9, 11, 12] confirmed that around 2 to 4 % reactive silica content is enough to initiate this degradation process. Yet, many aggregates with high reactive aggregate content do not expand in accelerated tests. Due to economical concerns, inert aggregate is used in concrete to reach higher volume. However, this assumption is not entirely true since most of the aggregate react with surrounding cement paste to certain extend [3]. Although this can be advantageous because partial dissolution of the aggregate particles improves bonding, in extreme cases the chemical reactions can lead to detrimental expansions putting the integrity of concrete in jeopardy.

Petrographic analysis and rock classifications form the basis for threshold/limiting values for ASR control in national/international codes. In The Netherlands, the first reference an engineer could consult for an ASR-proof structural design is Civil Engineering Centre for Execution of Research and Regulation (CUR). Since 2000, they published two separate guidance documents ASR monitoring and outlined the necessary measures for prevention. These documents are based on the Canadian standards (CSA A864-00, 2000). The parameters involved are cement type and alkali content, aggregate type and results of accelerated tests. These recommendations were later followed by CUR recommendation 102, which deals with inspection and evaluation of concrete structures with symptoms of ASR damage. However the propagation of the ASR mechanism and the consequences for the structure is not part of the evaluation with CUR recommendation 102. Therefore it lacks a precise recommendation on what the modification methods entail and the possible consequences of modifications such as effect of limestone fillers or SCMs. In United Kingdom, Concrete Society Working party published Technical Report No.30, in 1999 which summarizes the measures to be taken against alkali-silica reaction. The Norwegian Concrete Associations publication No.21 (1996), gives guidelines for handling AAR in Norway which was revised in 2006.

Material and Damage Modeling

Hydraulic structures, bridges, tunnels and strategically vital buildings are designed to withstand potential durability problems and ASR is no doubt one of the most important of them. Contractors, clients, research institutes and consultancy companies are aimed as the main audience of the project outcome. From an engineers' point, prediction of how much expansion may occur throughout a service life of a structure is crucial information. Accelerated test methods exert high temperatures and high levels of alkali which is far from the real life examples, but as a result expansion potential can be estimated relatively fast. The representativeness of these tests is still suspicious but there are ongoing studies on performance testing for alkali silica reaction. Thomas and Fournier et.al [13] discusses some of these test methods, and pointed out the limited reliability/sensitivity of these test compared to field tests and observations. This study covers some accelerated testing proposed by RILEM (AAR-3 and AAR-4 concrete prism tests). These tests are modified tested based on ASTM C1293 [14].

The modeling part is structured along two approaches (within the limitations of the project focuses only on the application of ASR). Hymostruc software which was developed in Delft University of Technology will be used for generation of virtual microstructure. Basic task of this simulation is determination of pore structure and hydration products for a predefined material [15]. Today, this model is used in many research projects and is capable of three-dimensional modeling of materials. Also a numerical model, Delft lattice model [16] is used for crack formation analysis. Lattice models are capable of simulating fracture mechanism in cement based materials under different loading combinations. Schlangen [16] proved to successfully simulate the softening effect and crack formation on concrete matrix. Specific to ASR, model basically assumes 3 types of expansion points in the matrix; inside the aggregate, interfacial transition zone (ITZ) or mortar matrix [7] (for details see Figure 3). In this project these expansion properties will related to gel formation information obtained from the small scale testing† and are distributed throughout the concrete matrix. Computational results will be confirmed with the thin section analyses prepared from tests in TUD lab and from demolished real structures. By adjusting aggregate grading, shape and reactivity factors with changing expansion points, the aim is fully simulate an accelerated ASR test. One of the prospect outcomes of this project is to develop standard procedure that allows engineers to define certain material properties and computational resources to get

- Reliable expansion value predictions
- Provide information for structural analysis
- Check with durability performance requirements of overall structure.

Similar methods can be utilized to automate image analysis tools for implementing ASR affected structure's data. Using the model and fractured specimens it will be possible to extrapolate potential expansion values thus the remaining service life of a structure.

3 EMPIRICAL DATA COLLECTION

3.1 Experimental Observations

For the experimental part, two different testing approaches are used. Firstly, the RILEM recommended test methods for accelerated expansion testing, AAR 3 and AAR 4. The AAR 3 being run at 38° C and the AAR 4 run at 60° C, both having similarities with ASTM 1293 which is run at 38° C and all having in common the use (testing) of concrete prisms. A large part of the concrete prisms to be tested will be backward compatible performance tests, based on original mix design from excising structures that have experienced severe expansions due to ASR, where the original source location for the aggregate used are known and accessible. The aim being to properly correlate expansion tests to structures with a know reaction history, so the gap between accelerated test results and actual reactions in the field can be bridged.

Second part is a study of the micromechanical behavior of reactive aggregates, where they are tested and measured. A test set-up was designed and built, see Figure 4, consisting of a four chamber steel box wherein each chamber a specimen could be tested at the same time under ultra accelerated conditions, 80° C 1M NaOH. Additionally each pair of samples are subjected to different boundary conditions, one pair free to deform and the deformation is measured and the other pair restrained from deformation and the stress generated by the gel is measured. All instruments are fixed to frames extended over the chambers, resulting in expansions and stresses measured in a vertical direction (details can be seen on Figure 4). Two different specimen types are considered, both being of the same size 203 mm, the first an aggregate-paste "sandwich" where a fixed interface/reaction area is examined, and the second a single grain size mortar cube where in addition to the expansion and stress, the crack formations from either boundary condition can be compared.

3.2 Case studies

Several ASR affected structures are chosen for investigation and analysis. There are ongoing measurements and sampling studies on this structure. Additionally, polished and thin section analysis will be done in TUD. These analyses will guide us in understanding the impact on the reaction of structural elements.

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† Tests and simulations are in progress; comparative results will be available shortly after ongoing validation process.

Nautesund Bridge, Norway

Damages due to ASR, rarely cause a bridge to be demolished. Norwegian Ministry of Public Works Highways Department has been investigating this bridge located close to Oslo. In 2009, after 50 years of service life, this bridge was demolished for further field and laboratory investigations. It provided extra-ordinary data for our model in defining the micro to meso scale modeling approaches. The original aggregate quarry is found, and researchers are currently running tests on original concrete mix. Results from these experiments will be cross checked with core samples from this bridge.

A59 Motorway Bridges, the Netherlands

In the Netherlands, ASR has been recognized as one of the major concrete durability issues since 1995, after having found 20 structures on highway 59 affected by this phenomenon [17]. Renewed interest in minimizing distress resulting from ASR emphasizes the need to develop predictable modeling of concrete ASR behaviour under field conditions. Data collection for these bridges started in 2003, involving regular expansion values, relative humidity inside the concrete beams and temperature. This project plays an important role for investigating environmental influences on the ASR damages.

4 CONCLUSIONS

This paper outlines a multi-scale performance assessment tool for ASR affected structures. General principles and methods to be used in this project are listed and discussed as a part of the durable concrete design and service life simulation model. The developed tool can be used in any construction project where ASR-proof design is of concern. Model covers classification and simulation aspects from micro to macro level issues on ASR in a unique integrated database. This information can be used in an efficient material management system for durability issues. Within the context of this study, several pitfalls and challenges are also foreseen. First pitfall is on the limited capabilities of simulations and testing on coupling effects with other degradation processes. Secondly, integrated knowledge sharing requires clear and reliable verification processes. Contractors, clients, research institutes and consultancy companies are aimed as the main audience of the project outcome. It can be foreseen that the tool will contribute to the projects in a large spectrum from cost estimation to the technical feasibility. This comprehensive integrated tool will enable simulations on alternative material combinations, national and international codes as well as a variety of environmental profiles. Model results will be confirmed with case study analysis, real structures from Netherlands, Norway, and accelerated test results that will be executed in TU Delft labs. This work will provide a framework of thought which may also be implemented for other degradation processes in cement based materials. Various models can be interlinked towards the goal of integrated knowledge and prediction methods for durable concrete design.

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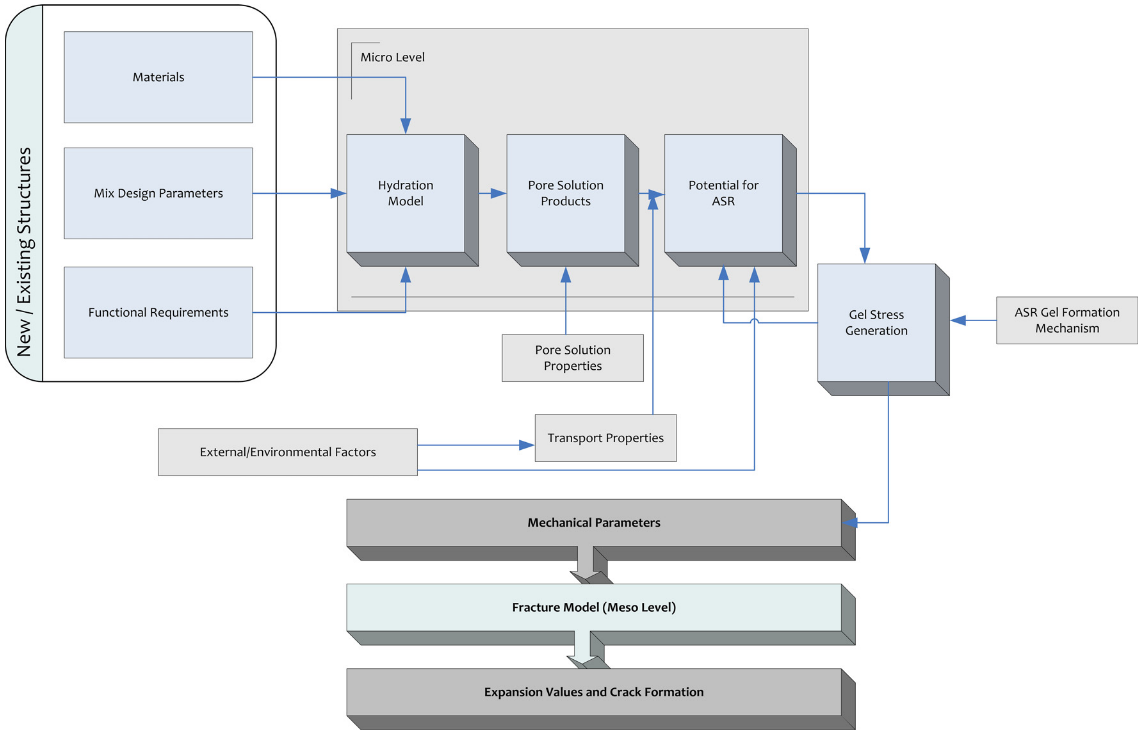


FIGURE 1: Data flowchart- steps in modeling effort

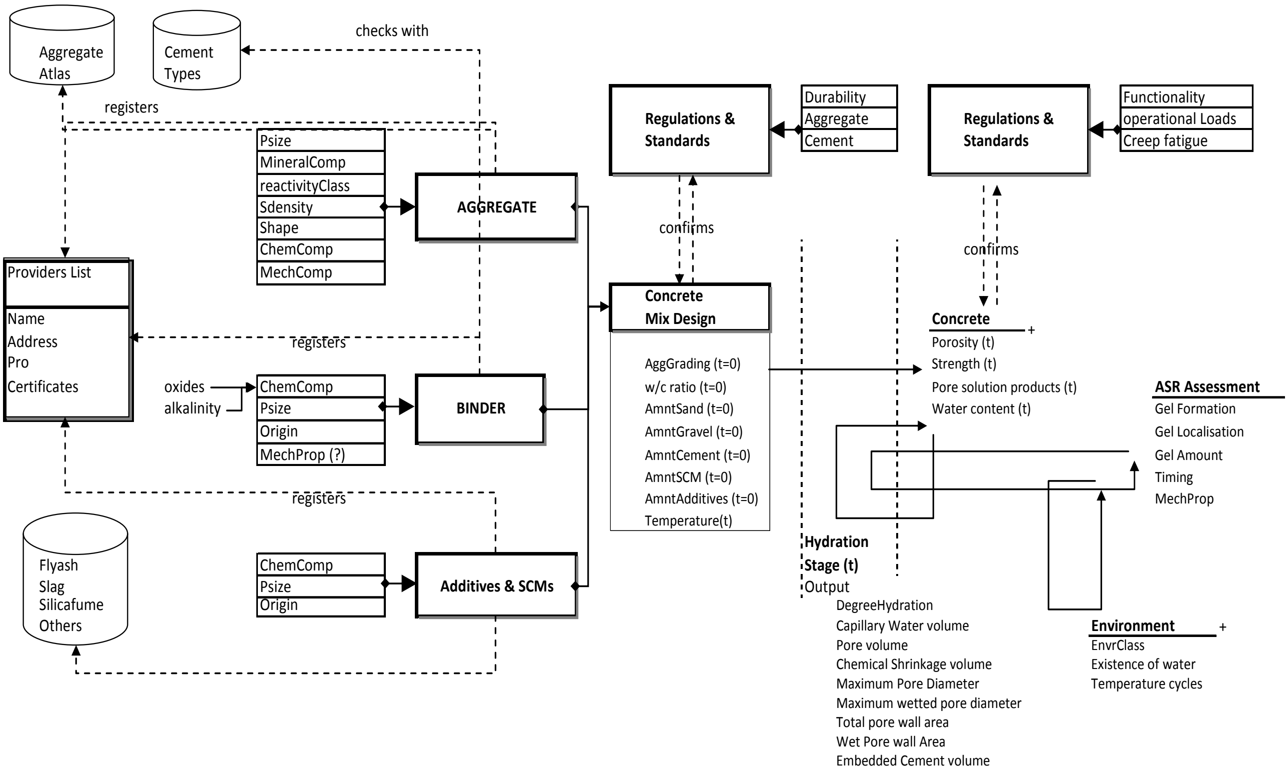


FIGURE 2: Data sharing and related parameters in material management system

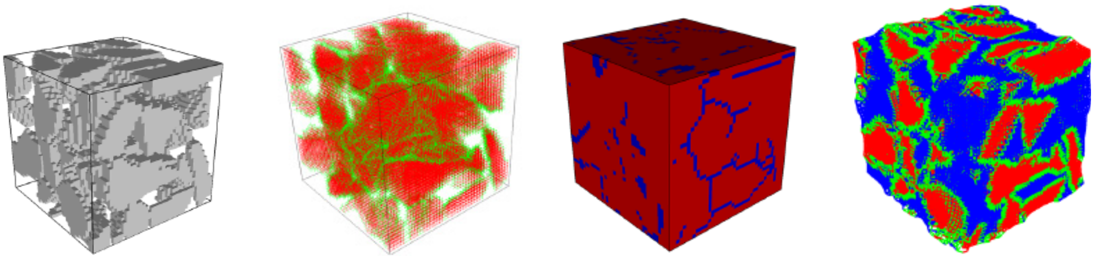
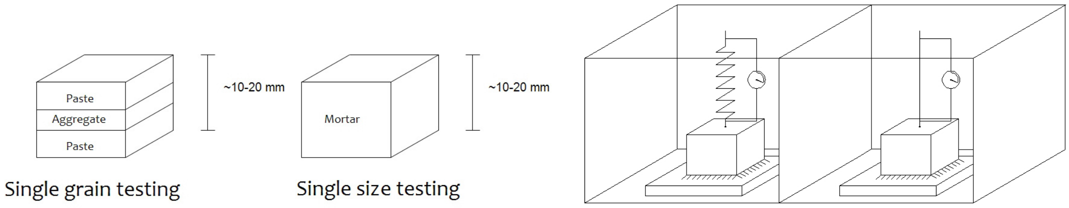


FIGURE 3: 3D Lattice model meshes for ASR expansion (Schlangen, 2010)



Single grain testing

Single size testing

FIGURE 4: Small scale testing set up by TUD