Concrete damage due to Alkali-Silica reaction: a new method to determine the properties of the expansive gel

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ABSTRACT: In this study the mechanism of Alkali-Silica Reaction (ASR) is investigated. A combined numerical and experimental research is presented. A meso mechanical model based on lattice theories is used as a starting point. Examples show that the model is able to simulate the damage mechanism in concrete due to ASR. One of the important input parameters in the model, but also one of the key players in the mechanism of ASR, is the amount of expansion of the gel and as a result the internal forces that are generated by this expansion. An experimental set-up is developed to measure the pressure generated during the reaction on a micro scale in order to assess the local pressure developed on each grain by its swelling.

1 INTRODUCTION

1.1 *The ASR phenomenon*

Damage due to alkali-silica reaction (ASR) is a phenomenon that has been observed in many structures all over the world. Numerous studies have been published on this subject (see for example Bödeker (2003)), but the mechanisms of ASR are not yet completely understood. ASR occurs between certain forms of silica present in the aggregates and the hydroxile ions (OH^-) in the pore water of a concrete. The hydroxile ions will attack the siloxene bonds and alkali silicate gel is formed. The formation of the gel itself is not deleterious. However, the gel absorbs water and its subsequent expansion is the start of the deterioration of the concrete structure. If the gel can creep into pores or existing cracks it is probably not doing any damage, but when all the free space is filled up, further expansion of the gel will create internal stresses in the cement matrix, which can lead to cracks propagating radially from the reactive aggregates. Externally, damage in concrete structures due to ASR is visual as random oriented crack patterns, similar to crack patterns known from drying shrinkage. The damage due to ASR reduces the mechanical properties of the concrete (Schlangen & van Breugel 2005) and with that the structural safety of a structure can be lost. Furthermore, cracks formed in concrete structures due to ASR increase the permeability and the ingress of for instance water and chlorides, which can lead to reinforcement corrosion.

1.2 *What has been done?*

Already a series of 12 international conferences have been organized in the past on the topic of alkali aggregate reaction in concrete. All this research has led to national and international standards, recommendations and procedures describing how to test reactivity of aggregates, how to determine the risk of getting ASR in a certain concrete and methods to determine whether or not it was ASR that caused damage in a structure.

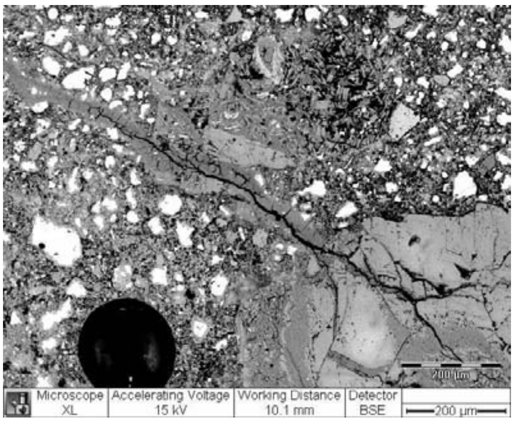


Figure 1. Penetration of ASR gel into crack

To test the possible swelling in a concrete due to ASR the concrete prism test (CPT) and the (ultra) accelerated mortar bar test (U)AMBT (see for instance Xu et al. 2000 and Grosbois & Fontaine 2000) are now widely accepted and standardized. The result of these tests is an expansion of the concrete in time. The CPT should run for a year, while the UAMBT gives results in about 1 or 2 weeks. If the measured values stay below a certain threshold, the risk for getting ASR in a structure with this concrete is low. Both tests, however, give no explanation for the mechanism that takes place. Furthermore these tests do not tell if the mechanism is possibly different if the deformations are to some extent restrained as is the case in a real structure.

Ferraris et al. (1997) and Binal (2004) developed methods to tests the pressure that is generated in a prism of concrete in which ASR takes place. The deformation of the concrete is restrained and the forces generated measured. This is the structural effect. But on a local scale a similar restraining happens. The cement matrix in between the aggregate particles will give this restraining. If this cement matrix is stronger there will be more restraining. The composition of the concrete determines how the ASR mechanism will evolve. The silica in the aggregates react with the alkali ions in the pore water and a gel is formed. The gel takes up water and wants to swell. This gel is maybe inside the aggregates and could crack the aggregates, if the force generated by the swelling gel is enough to overcome the strength of the aggregate. The same holds for the strength of the interface and the strength of the cement matrix. ASR gel could enter cracks, swell and maybe propagate the cracks (see Figure 1). But in all cases it should be taken into account that the aggregates, interface and cement matrix can not freely expand but are restrained by its surroundings. If this restraining is too large the reaction might even stop the ASR process. An important parameter in the whole mechanism is the pressure that the gel can generate. This is also an important input parameter for models that could help in explaining the ASR mechanism .

Models to simulate ASR in concrete structures on various levels can be found in literature. Ulm et al. (2000), for instance, developed a model on the macro-level to simulate the expansion of concrete due to ASR. In this model a lot of attention is given to the coupling of diffusion taking place through the material, the chemical reaction taking place inside the material and the resulting deformations. Modelling of the reduction of mechanical properties due to ASR is performed by Schlangen & van Breugel (2005) with a 2D meso-level model in which aggregate are explicitly taken into account. Comby-Peyrot performed similar simulations, however, in this case a 3D model was developed, resulting in more detailed outcome. In the research by Andic-Cakir et al (2007) different types of pressure generated by the gel were discussed on a meso-level, resulting in different expansions of concrete. This paper is a continuation of that research.

1.3 *The aim of the present research*

The aim of the research presented in this paper is to model ASR mechanism and to develop a test method to measure the input parameters for the model, especially the local expansions and pressures generated by the gel.

2 MODELLING ASR DAMAGE

2.1 *The basics of the model*

The mechanism of ASR is modelled in this research with a meso-mechanical lattice type model (Delft Lattice model) in which the aggregate structure is taken into account using digitized images of the real material, see Figure 2. In the model, the materials are discretized as a lattice consisting of small beam elements that can transfer normal forces, shear forces and bending moments (Schlangen & Mier, 1992; Schlangen & Garboczi, 1997). The simulation of fracture is realized by performing a linear elastic analysis of the lattice under loading and removing an element from the mesh that exceeds a certain threshold. In the present simulations the normal stress in each element is compared to its strength. Details on the elastic equations as well as the fracture procedure of the model are explained by Schlangen & Garboczi (1997).

In this application of the lattice model attention is focused on the simulation of eigenstresses and crack growth that develop in the material as a result of ASR as discussed in Schlangen & van Breugel (2005).

2.2 *Experiments that are modelled*

Andic-Cakir et al (2007) performed tests in order to determine the effect of aggregate gradation on the concrete microbar expansions. Two different aggregate gradations were studied at constant cement content. Prismatic microbars of 40x40x160 mm were prepared with aggregate/cement ratio of 1 by weight and water/cement ratio of 0.33 by weight. Although in the original test method proposed by Grattan-Bellew et al. (2003) no fine particles (<4.75 mm) were used in the preparation of microbar specimens; in one of the mixtures tested in this study (M2), fine particles were also added to the mixture. Aggregate gradations and abbreviations of the relevant mixtures are given in Table 1. The concrete microbars were cured in 80^{o}C water for one day and in 80^{o}C 1M NaOH solution for the remaining test period. The average expansion values of 3 microbars were recorded up to 40 days.

Table 1. Aggregate gradation of the mixtures

Sieve aperture	Aggregate Content (by Weight)	
mm	M1	M2
<4.75	-	60
4.75-9.5	25	20
9.5-12.5	75	20
W/C	0.33	0.33

The main conclusions from the tests were that the expansion values of the two mixtures tested express a linear time-expansion relationship and that the mixture containing fine aggregate expanded more (about a factor 2.5) than the ordinary microbar sample. This may be due to the increased reaction sites by the addition of fine particles. Note, that the total volume of particles was the same in both mixtures.

2.3 *Simulations performed*

In the simulations a 2D regular triangular lattice consisting of 20000 beam elements is used. For the implementation part of the binary images of Figure 2 are used. The cross sections in the simulations represent an area of 30x30mm^2.

The beams that fall inside an aggregate, cement matrix, or just on the boundary of both (interfacial transition zone, ITZ) are assumed to have the properties given in Table 2.

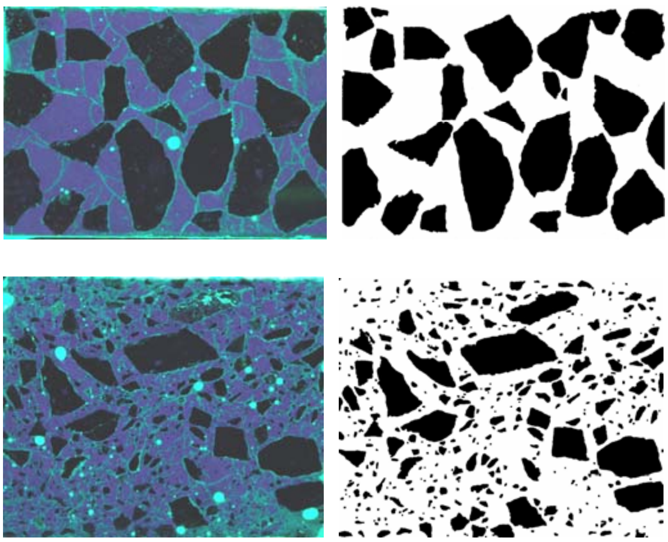


Figure 2. Digitized images of cross sections of M1 (upper row) and M2 (lower row) concrete and threshold binary images.

Table 2. Properties of beam elements in lattice.

Beam location	Strength	E-modulus
	[MPa]	[GPa]
Aggregate	10	70
Matrix	4	25
Interface / ITZ	1	10

From the experiments it is also clear that the gel enters the cracks and possibly also exerts pressure inside the cracks (Figure 1). To get some insight in the contribution of the different expansions (inside aggregates, at the ITZ and inside the cracks) three different loading modes are adopted in the simulations:

- only ITZ: All the elements at the boundary of aggregate and cement matrix, forming the ITZ are given an expansion (local strain). From a linear elastic analysis of the lattice the amount of strain is calculated to crack (stress is larger than strength) an element in the lattice. This element is removed from the lattice and the strain is applied again.
- ITZ+crack: The same procedure as the previous one. However, when a crack is formed, the element is not removed in the next step, but it is given the same expansion and properties as the elements in the ITZ.
- Aggregate particle: All the elements in the aggregate particles are given an expansion. A linear elastic analysis determines the element that is removed in the next step.

In the analysis the boundaries of the lattice are not restrained. The analysis in each step is linear elastic. In the present simulations no visco-elastic material behaviour is adopted for both the concrete and the gel.

2.4 *Results of the simulations*

The results of the simulations are presented as graphs with local versus total global strain (Figure 3) and cracks patterns in the material (Figure 4). In the graph presented in Figure 4 the local strain is the applied strain in the single elements. The total strain is the strain of the complete sample.

From this graph and from the crack patterns the following observations can be made:

- The initial strains for the loading modes ITZ and ITZ+crack are equal. However if the number of cracks increases, the internal pressure in the cracks in case of loading mode ITZ+crack results in a higher total strain. In case of the loading mode ITZ+crack the cracks localize much faster in a single crack. In case of only ITZ loading and especially in case of particle loading first distributed micro-cracks develop, which later coalesce in major cracks.

- The strain that is obtained for the two concretes M1 and M2 is almost equal in the case of the loading mode particle. Therefore the M1 concrete also has a slightly higher total strain.The volume (area in 2D) of particles is almost equal in both concretes. The M1 has somewhat more particle area in these simulations, because it is not possible to take into account the smaller fine aggregate particles of the M2 concrete for this scenario of expansion.

- In the case of ITZ loading (and also ITZ+crack loading) it can be seen that for a given local strain, the total strain that is obtained in the M2 concrete is about 3 times higher than in the M1 concrete. Explanation for this is that the surface area around the particles (the number of ITZ elements) in case of M2 concrete is a factor 3 higher than for the M1 concrete.

- The number of cracks in case of M2 concrete with smaller particles is larger than in case of M1 concrete.

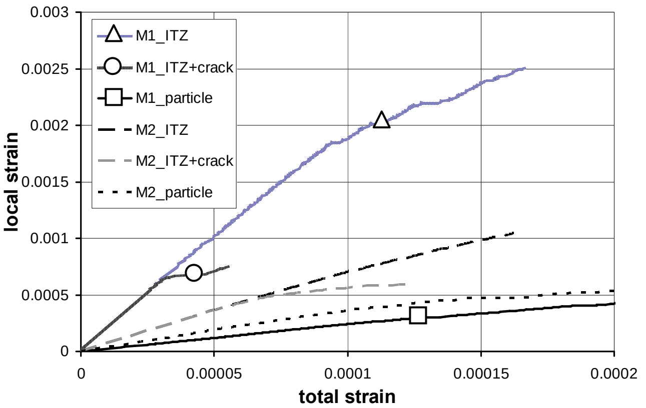


Figure 3. Local strain versus total global strain for M1 and M2 concrete with different loading modes.

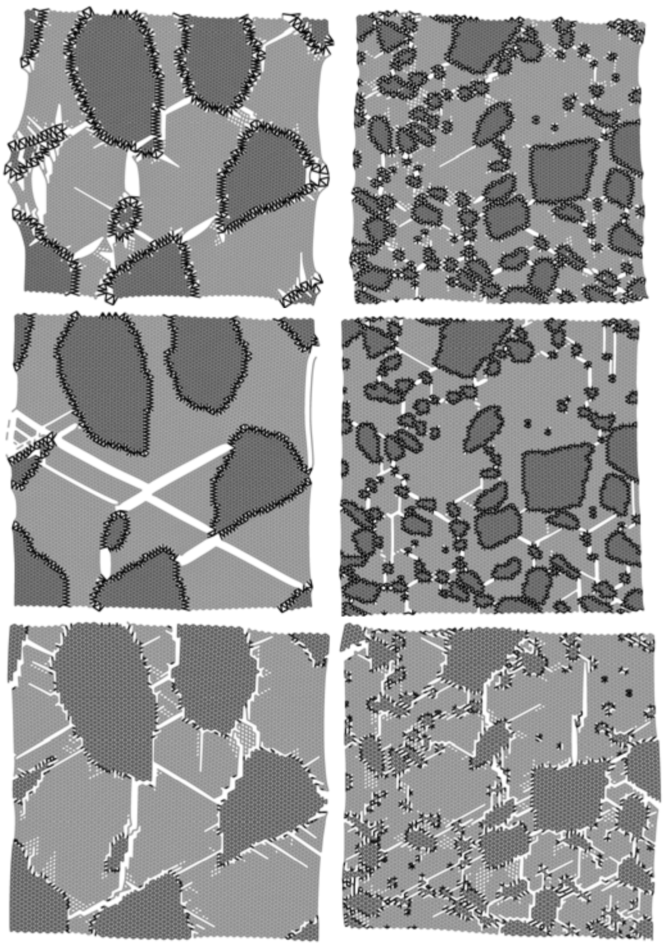


Figure 4. Simulated crack patterns in M1 (left) and M2 (right) concrete. From top to bottom the crack patterns for the different loading modes are shown: ITZ, ITZ+crack, particle.

3 MEASURING EXPANSION AND FORCE

3.1 *Description of device*

The swelling of the gel is the mechanism that creates the internal damage in the concrete and leads to the expansion of the concrete. As described above there is a need to know the force that is generated by the swelling of the gel, since that is the main missing input parameter for modelling the mechanism of mechanics involved in the ASR process. ASR is a slow process, which means an accelerated test is needed to obtain results in a short period of time. Similar conditions are used as in the accelerated mortar bar tests or micro-concrete tests (Grattan-Bellew et al 2003). The specimens tested have a cross section of 15x15 mm^2 and a length of 20 mm. To make the specimens first an aggregate particle is sawn to the size of 15x15x10 mm3. This specimen is placed in a mould and the remainder of the length of the final specimen is filled with cement paste (see figure 5). The specimens are cured in the mould for 1 day at 20°C and 99% RH, then they are placed in 80°C water for one day and tested in 80°C 1M NaOH solution after that. To test the specimens they are glued to a stainless steel frame as shown in Figure 5.

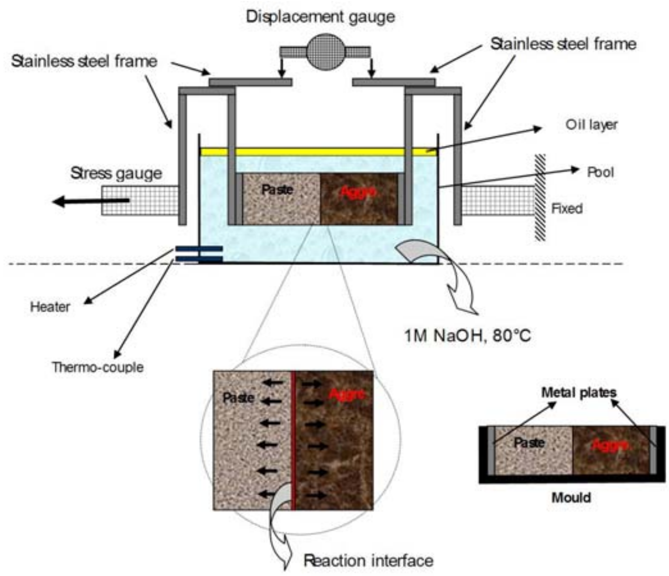
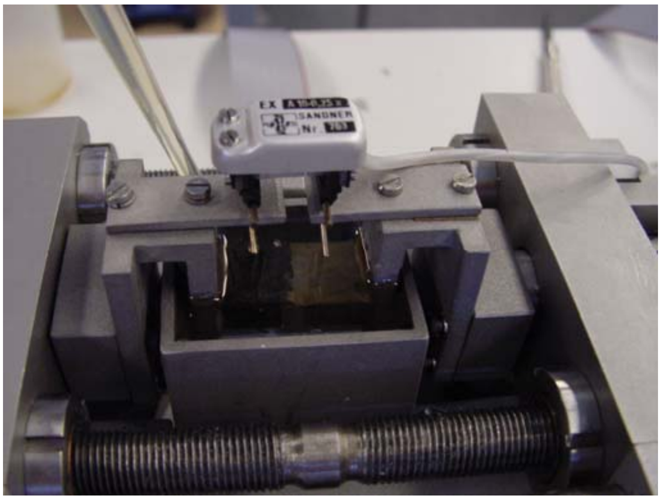


Figure 5. Principle design of new measuring device.

The steel frame is attached to a micro tensile-compression testing device (developed by Kammrath & Weiss). The shape of the testing frame is such that the specimen can hang inside a pool with the solution at 80°C and that the loading and measurement-parts are outside this pool, see Figures 5 and 6. The solution in the pool is covered with a layer of oil to prevent evaporation. The deformation of the specimen is measured with a displacement gauge mounted on to the steel frame as shown in Figures 5 and 6. The test can either be run in deformation (zero deformation) or in load control (zero load). In this way it is possible to test the free deformation that will take place due to the ASR formation, but also the stress that is generated if this deformation is restrained. Also different loading regimes are possible, for instance first a restraining of the deformations until a certain stress is reached and after that a free deformation to simulate the situation inside a concrete. Here first a stress has to be created to overcome the strength of the material and then the deformation due to the swelling of the gel can take place.



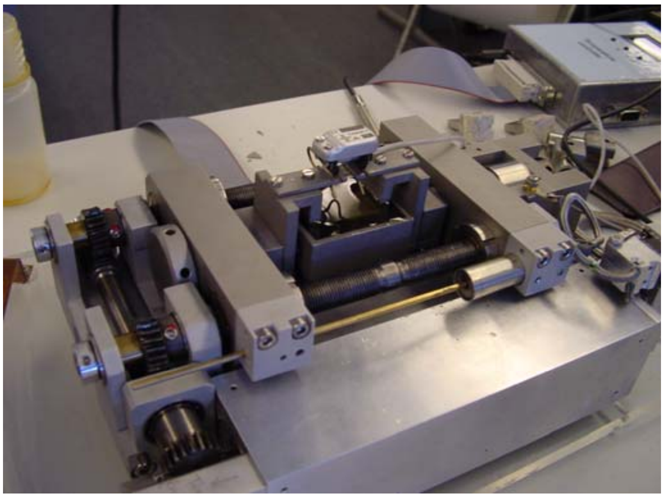


Figure 6. New measuring device in tensile testing machine.

3.2 *First results*

The first tests are performed on basalt aggregates, the same material as in the tests described in paragraph 2.2. As is often the case with the development of a new device a lot of small difficulties have to be tackled before any results are obtained. Until now only a few tests have been performed. In Figure 7 one of the results is shown that were obtained in load control. In the graph the free deformation of the specimen during the test is given. The measurement in the graph starts, a few hours after the specimen has been submerged into the pool containing the solution, from the moment the temperature in the specimen was 80°C and the temperature in the frame and the machine reached a stable value. What can be seen is that the specimen elongates during the first 5 days to a total value of about 60 μm. Then the temperature sensor in the pool started to malfunction and due to that the temperature in the pool decreased to room temperature which can be seen in the graph as a (thermal) shrinkage of the specimen. After 7 days the sensor was replaced, the pool heated again to 80°C and the deformation seems to pick up the same curve.

The tests with restrained deformation are not performed yet, but are still in preparation.

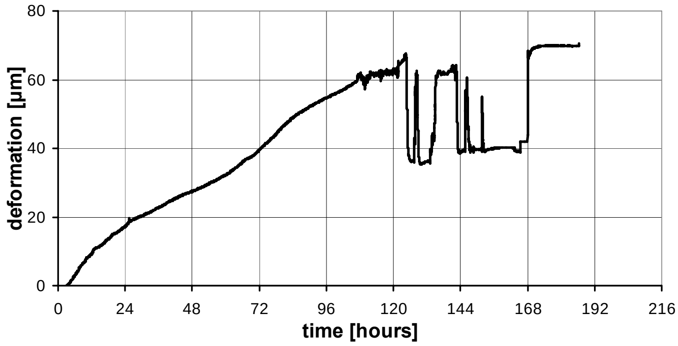
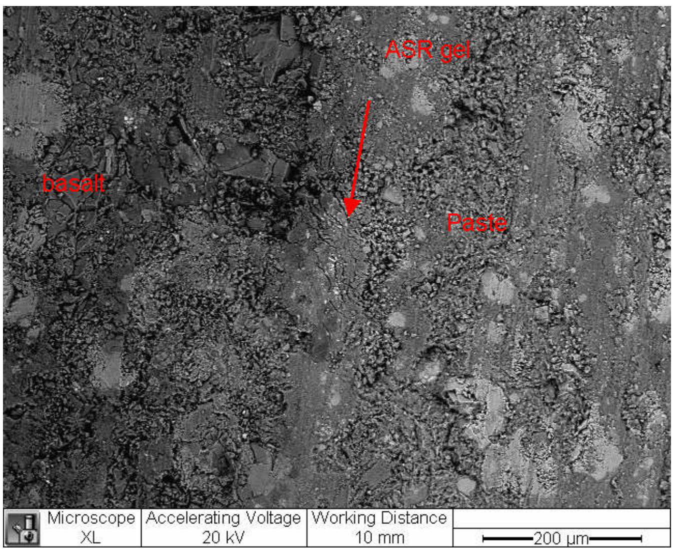


Figure 7. Measurement of expansion in ASR-test.

After the test explained above, the specimen was examined in the ESEM. In Figure 8 images are given which are taken from the interface between the basalt particle (on the left side of the image) and the cement paste (on the right side of the image). The band with a width around 70 μm in the middle of the image is ASR-gel. With the ESEM it is also observed that the basalt particle in a band near the interface was very porous and that all the glass phase present in this part of the rock was dissolved. The microstructure of the remainder of the aggregate particle seemed not to be changed.



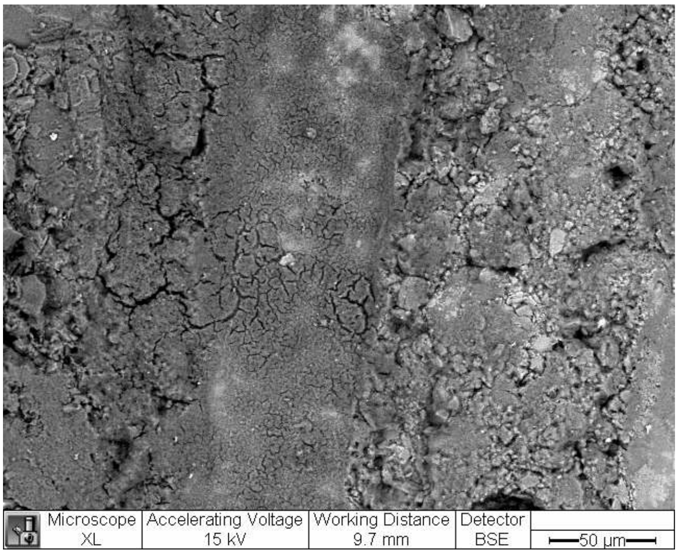


Figure 8. ESEM/BSE microphotographs of ASR gel at interface between aggregate particle (left) and cement paste (right).

4 DISCUSSION AND CONCLUSIONS

In this paper a test method and set-up is presented to measure expansions and forces that are generated by the gel that is formed in concrete due to ASR. The background for starting this research is that such values have to be known in order to explain the mechanical action inside concrete when it is attacked by ASR. Restraining on a structural level, but also inside the material itself will have an effect on the ASR mechanism, which can be investigated by numerical modelling.

The Delft lattice model is used to simulate crack patterns and deformation in concrete due to ASR expansions. Although assumptions are made for local properties of the material and the expansive gel, the results that are obtained look promising.

Different loading modes are applied in the simulations. Expansion of ITZ, expansion of ITZ+cracks (gel in cracks) and expansion of particles are used as variables for the two concretes M1 and M2 consisting of large and small particles respectively. It was found that when the expansion of the particles is used as loading mode, almost no difference in total expansion is found between the two concretes M1 and M2. But it was not possible to taken in account all the small reactive aggregates in the simulation of the M2 concrete. In case of ITZ loading the M2 concrete has a 3 times higher total expansion compared to the M1 concrete. Explanation is that the volume (area) of particles is equal for the two materials, but the surface area is about 3 times higher for the M2 concrete with smaller particles. The higher total deformation and the higher number of cracks in the M2 concrete as founds in the simulations is also found in the experiments on these materials as described in Andic-Cakir et al (2007).

The first tests that are performed in the new test set-up show promising results. It seems to be possible to both measure expansions in a single aggregate-cement matrix connection and also the stresses that are generated when the deformation is restrained. With device it is also possible to study whether the reaction slows down in the case of restrained deformations. This could then answer the question if a better concrete (concrete with a stronger cement matrix or a more optimized packing) or a fibre concrete which does not allow for the opening of cracks can possibly slow down or stop the reaction.

In the device tests can be performed on different materials, both aggregate type and cement matrix (cement type). Specimens will be examined by ESEM after the tests. In this way it can be examined if it is only the interface or also the aggregate that expands. Furthermore, it can be measured how much of the aggregate will dissolve; is it only a rim at the surface, or will it be the complete aggregate? This depends on the type of mineral, but definitely contributes a lot to the damage mechanism due to ASR as discussed in Copuroglu et al (2007).

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REFERENCES

Andic-Cakir O, Copuroglu, O, Schlangen, E. & Garcia-Diaz, E. (2007) Combined experimental and modelling study on the expansions of concrete microbars due to ASR. Proc. Consec07, Tours, France.

Binal, A. (2004) A new experimental method and device for measuring alkali silica gel pressure in mortar. Proc. 12th Int. Conf. on Alkali-Aggregate Reaction in concrete, Beijing, pp. 266-272.

Bödeker, W. (2003) Alkali Reaction in Structural Concrete, a View from Practice. Deutscher Ausschuss für Stahlbeton, Vol 539, (in German).

Comby-Peyrot, I. (2006) Development and validation of a 3D computational tool to describe damage and fracture due to alkali silica reaction in concrete structures. PhD-thesis, Ecole des Mines de Paris, France.

Copuroglu, O., Andic-Cakir, O., Broekmans, M.A.T.M., Kuhnel, R. (2007) Mineralogy, geochemistry and expansion testing of an alkali reactive basaltoid from western Anatolia, Turkey. 11th Euroseminar on microscopy applied to building materials, 5-9 June 2007, Porto, Portugal.

Ferraris, C.F., Clifton, J.R., Garboczi, E.J. & Davis, F.L. (1997) 'Stress due to alkali-silica reactions in mortars'. Mechanisms of Chemical Degradation of Cement-Based Systems. Proceedings of the Materials Research Society's Symposium on Mechanisms of Chemical Degradation of Cement-Based Systems. November 27-30, 1995, Boston,

MA, E & FN Spon, London, England, Scrivener, K. L. & Young, J. F., Editors, p. 75-82.
Grosbois M. & Fontaine E. (2000) Evaluation of the potential alkali-reactivity of concrete aggregates: performance of testing methods and a producer's point of view. Proc, 11th Int. Conf. on Alkali-Aggregate Reaction, Quebec, 267-276.
Grattan-Bellew P.E., Cybanski G., Fournier B. & Mitchell L. (2003) Proposed universal accelerated test for alkali-aggregate reaction the concrete microbar test, Cement, Concrete, and Aggregates, Vol. 25, No.2, 29-34.
Schlangen, E. & van Mier, J.G.M. (1992) Experimental and numerical analysis of micromechanisms of fracture of cement-based composites, Cem. Conc. Composites, Vol. 14, 105-118.
Schlangen, E. & Garboczi, E.J. (1997) Fracture simulations of concrete using lattice models: computational aspects, Eng. Fracture Mech., Vol. 57(2/3), 319-332.
Schlangen, E. & van Breugel, K. (2005) Prediction of tensile strength reduction of concrete due to ASR, in Construction Materials (N. Banthia et.al. eds.), The University of British Columbia, Vancouver.
Ulm, F-J, Coussy, O., Kefei, L. & Larive, C. (2000) Thermo-chemo-mechanics of ASR expansion in concrete structures, J. Eng. Mech., Vol. 126, No. 3, pp. 233-242.
Xu, Z., Lan, X., Deng, M. & Tang, M. (2000) A new accelerated method for determining the potential alkali-carbonate reactivity, Proc. 11th Int. Conf. on Alkali-Aggregate Reaction, Quebec, 129-138.