MODELLING ASR EXPANSIONS BASED ON MEASUREMENTS OF LOCAL PROPERTIES OF EXPANDING 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. These pressure measurements are used to fit the model parameters. The simulation of concrete expansions with these parameters are realistic. Some improvements in modelling the speed of reaction are still needed.

Keywords: alkali-silica reaction, micro-mechanics, basalt, mechanics, lattice model

1 INTRODUCTION

Research in the past has resulted in insight on how to prevent ASR in structures. Mainly these measures focus on at least one of the three following aspects: (1) using aggregates without reactive silica; (2) using cementitious material that leads to a low alkali content in the pore water; (3) sealing the structure against water ingress. It is good, however, to understand the real mechanism behind ASR and the way it results in damage of concrete structures. The three measures described above are not always feasible, just because no other raw material to make concrete are available at a certain location or sealing the structure is not practical.

Modelling of ASR and ASR damage have attracted significant attention among the concrete science community [1-4]. However, the community is still far away from using a single model for a complete simulation of the gel formation and generated damage mechanism. Alkali silica reaction modelling requires consideration of numerous parameters according to the state of art theories. Dissolution related characteristics of reactive silica, thermo dynamical aspects of gel formation, microstructure of concrete, random localization of the reactive sites, knowledge of the reaction mechanisms are just some of the examples among them [5].

It is generally possible to consider modelling of concrete in two main groups; (1) modelling of gel formation and its expansion; (2) modelling of ASR related damage. In this paper, authors take an attempt to combine both: simulating the correct crack formation and the connected concrete expansion. It is aimed to simulate ASR damage in a cementitious material bearing dissolved reactive aggregate. The model that is used is a lattice type model [6]. It is applied for ASR in concrete as described in [7,8]. It models concrete on a meso-scale in which particles embedded in a cement matrix are taken into account. With the model the concrete expansion can be simulated. One of the inputs in the model is the local expansion of the gel. For that the mechanical properties of the gel should be known. In this paper a test procedure, test results and a method to fit the model-parameters are described.

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2 MEASURING ASR-GEL PROPERTIES

2.1 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 concrete microbar tests [9]. 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 mm^3. This specimen is placed in a mould and the remainder of the length of the final specimen is filled with cement paste (see Figure 1). 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 for the following test period. To test the specimens they are glued to a stainless steel frame as shown in Figure 1

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 Figure 1. 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. 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.

2.2 The first results

The first tests are performed on olivine basalt aggregates, the same material as in the tests on concrete microbars described in [8] and simulated in paragraph 3.3. From the chemical composition of the basalt, described in detail in [9], it was found that the basalt consist of 44% of SiO_2, which makes the material highly reactive. In Figure 2 two typical results are shown. The first result is of a test in load-control, where actually the load is kept to zero and the free deformation is measured in time. In the graph (Figure 2a) 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 70 μm.

The second test (Figure 2b) is performed under deformation control. To be able to control this test properly, first a compression load (of 120 N) was applied to the specimen. Then the system was switched to deformation control (zero deformation). It can be seen in the graph that at first the load decreases due to relaxation. Subsequently the reaction starts, the gel is formed and tries to expand. Because the deformation is restrained, the compression load increases again.

3 MODELLING ASR DAMAGE

3.1 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 4. 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 [6] 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 in [6]. The model used in this paper is a 2D version. The real mechanism of ASR is of course 3D. Although the model can also be used as a 3D model, it is believed that the ASR damage process can be described with sufficient accuracy also in 2D as far as crack patterns and expansions are concerned. This saves computer memory and time enormously. Only when the situation of the material is different in three directions of the material, i.e. when there

are moisture gradients present in a certain direction or when reinforcement bars give a restraining of deformations in a certain direction, then the real 3D situation has to be modelled.

As input in the model the properties for the aggregate and the cement matrix in the concrete are chosen according to the values in Table 2, based on values described in [6]. The properties for the interface, the swelling gel, are fitted from the tests described in paragraph 2.2. The procedure that is followed to determine these parameters is given below.

3.2 Fitting the ITZ parameters

In the model it is assumed that the gel is mainly formed in the ITZ between aggregate and cement matrix. It is not important for the model if this is exactly on the boundary between the two or that the expanding gel forms cracks inside the matrix or in the aggregates. The beam elements located in the ITZ just describe the expanding mechanism in this zone. To determine the properties of these elements the tests described in paragraph 2.2 are modelled with the mesh shown in Figure 3. In the mesh three different elements are used, i.e. matrix, ITZ and aggregate. The modelling of the first test, the free expansion is simple. The elements in the ITZ are given a strain in time such that the total deformation of the specimen corresponds with the measured deformation. Since the specimen is not restrained, the stiffness of the elements are not of influence. The second test, restrained deformation, is used to determine the stiffness of the ITZ beam elements. In this simulation the strain of the first test is applied to the elements and the stiffness in time is chosen such that the reaction load in the simulations corresponds with the measured load in the test. The stiffness of the beam elements has to decrease in time to have the correct fitting. This stiffness is then a combined stiffness and relaxation of the complete zone around the real interface between aggregate and cement matrix. Thus it includes the gel, but also the maybe partly cracked cement matrix and aggregate.

In Figure 2 the resulting curves of the fitting are compared with the experimental curves. In Figure 2b also the simulated load is plotted versus time in case that there is only relaxation (in the elements) of the initial pre-stressing load on the specimen. This means only a decrease in stiffness in time and no expansion of the elements.

3.3 Simulation of concrete microbar test

Andic-Cakir et al [8] 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. CEM I 42.5 is used as cement. Although in the original test method proposed by Grattan-Bellew et al. [10] 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 specimens are always saturated during the tests, which means that no expansions due to volume changes are expected. The average expansion values of 3 microbars were recorded up to 40 days. 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. Main explanation for this is the increased reaction sites by the addition of fine particles, by which the total surface area of the aggregate particles is increased. Note, that the total volume of particles was the same in both mixtures. The crack patterns observed in both concretes are shown in Figure 4. Figure 6a gives the strain measured in both materials.

In the simulations a 2D regular triangular lattice consisting of 20000 beam elements is used, see Figure 5. For the implementation part of the digitized images of Figure 4 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. The simulated crack patterns for both materials are given in Figure 5 and the simulated strains are shown in Figure 6b. The simulated strains shown in Figure 6b compare very well to the strains measured in the tests as shown in Figure 6a. In the simulations the material with the smaller aggregates (M2) also has a 2.5 times larger expansion. Note however that the time axis is different between the experimentally obtained and simulated curves. In the next section this will be discussed in more detail.

4 DISCUSSION AND CONCLUSIONS

In this paper a model is presented to simulate expansion of concrete due to ASR. The model is a meso-mechanical model that takes the heterogeneous microstructure f concrete into account. The input for the model is the expansion of ASR-gel formed in at the boundary zone between aggregates and cement matrix. The expansion of the gel is measured in a new test device. In this machine the expansion of gel formed in a single interface is measured. This is different from deformation measurements on mortar or concrete specimens that usually are performed to determine the expansion due to ASR of the material, see for instance [8, 10].

The stiffness including the visco-elastic behaviour of the gel is determined from measurements in the same device from tests with restrained deformation. Not only the visco-elastic behaviour of the gel is determined in this way, but actually the visco-elastic behaviour of the zone in which the gel is formed and (micro-)cracks occur. In literature also tests are reported in which the pressure is determined that develops in mortar and concrete specimens in which ASR takes place [11, 12]. However in these tests the complete material with many interfaces is tested. In these tests there is therefore an external restraining from the test-setup, but also an internal restraining from the material (cement paste) itself. This makes the interpretation of the results very complicated. In the test setup used in the research presented in this paper, only one interface, one location where gel is formed and therefore also only one location where pressure builds up is present in the specimen. Which means it is a direct measurement of the properties.

After fitting the properties of the ITZ-elements from the experiments the model is used to simulate expansions in real concrete samples. Expansions in two materials (M1 with only large aggregates and M2 with large and small aggregates) are simulated and compared with the experimentally observed expansions. The concrete with the smaller aggregates has more expansion, both in experiments and simulations, due to higher surface are of aggregates and thus higher ITZ and locations where gel is formed. Also the amount of strain that is simulated compares very well to the experimentally observed strains in both concretes. The main difference however is the time axis. In the simulations the strain builds up much faster compared to the experiments, see figure 7. The explanation for this can be found in the way the input parameters for the model are determined. It is assumed that the reaction degree in both the tests of free expansion and restrained deformation is equal. However it is known from literature, see for instance [13], that the reaction is much slower when the material is restrained. This means that there is a mismatch in time between the tests shown in Figure 2 and that the visco-elastic properties of the gel can not be directly determined from Figure 2b by assuming the expansion from Figure 2a. The expansion corresponding with the pressure building up measured in the test shown in Figure 2b should be smaller. Currently tests are being performed in which the amount of pre-stressing on the sample is being varied. In this way the visco-elastic properties can be determined correctly.

It is the opinion of the authors that the procedure described in this paper can also be used to determine and predict the expansions in different concretes, with different aggregates. Further measurements to support this are ongoing. It can also be analysed which matrix strength or strain capacity is needed to be able to lower the strain or delay the expansion in the material so much that it does not lead to deterioration of the structure. In [13] it is shown that this approach can be successful by adding micro-fibres to the matrix to enhance the strain capacity and with that decrease the rate of the alkali silica reaction.

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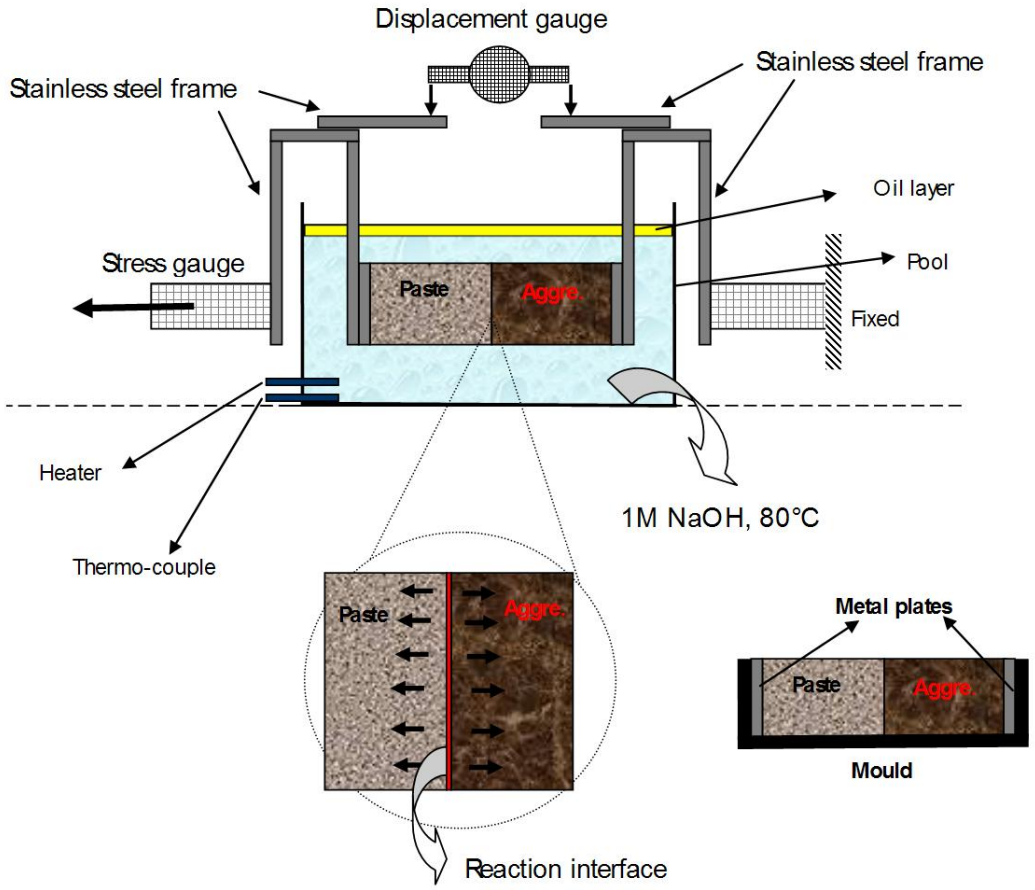
TABLE 1: Aggregate gradation of the mixtures.

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

TABLE 2: Properties of beam elements in lattice.

Beam location	Tensile Strength	E-modulus	Strain
	[MPa]	[GPa]	[-]
Aggregate	10	70	0
Matrix	6	25	0
Interface / ITZ	Not of interest	Fitted from tests	Fitted from test



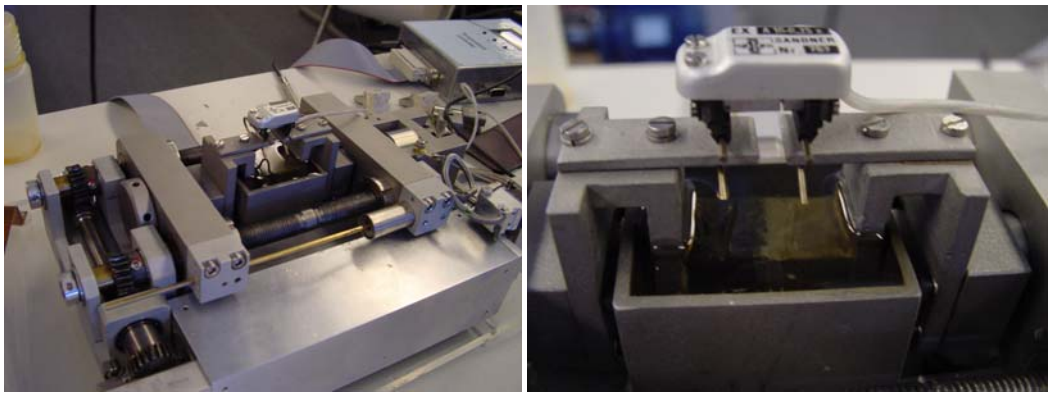


Figure 1: Principle design and photos of new device to measure mechanical properties of ASR-gel.

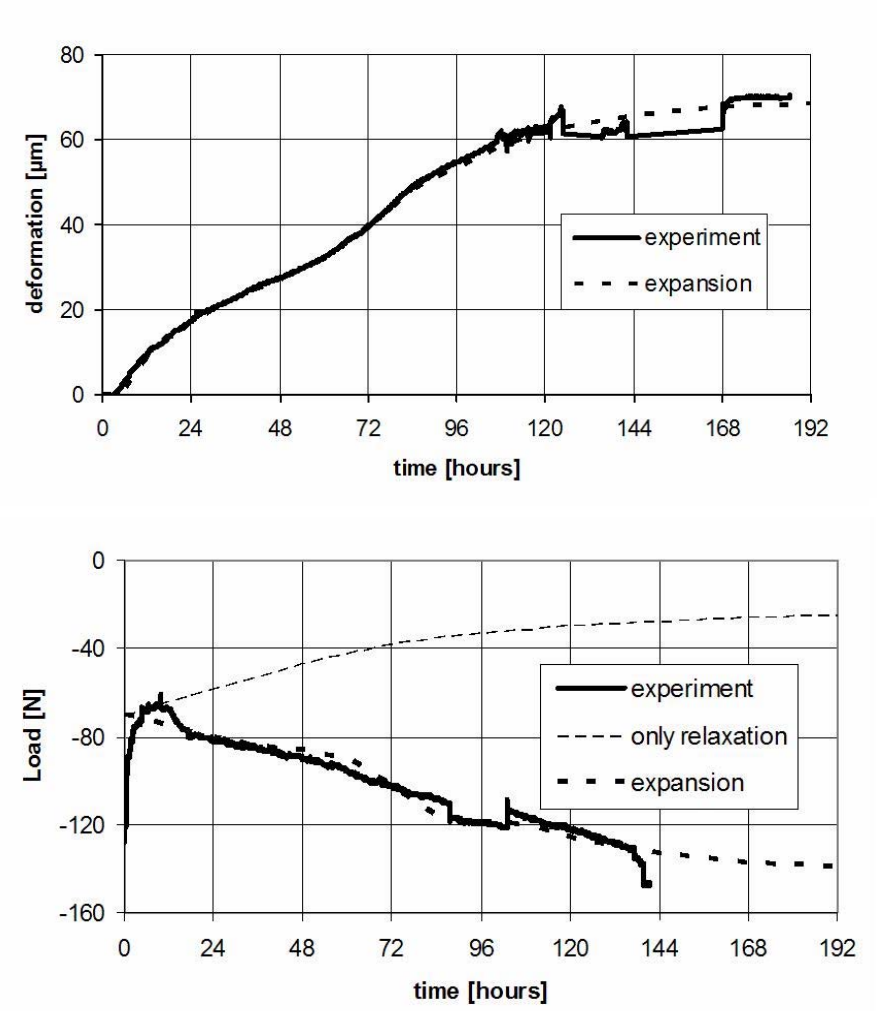


Figure 2: Measured mechanical properties of ASR-gel: Free deformation under zero load (a) and measured load under restrained deformation (b). In the graphs also the simulated results are shown after fitting the input parameters.

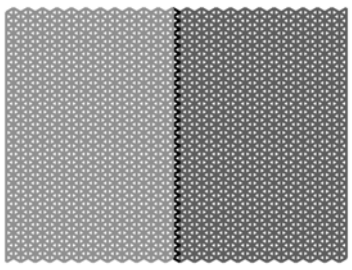


Figure 3: Modellization of specimen with lattice elements to fit gel properties.

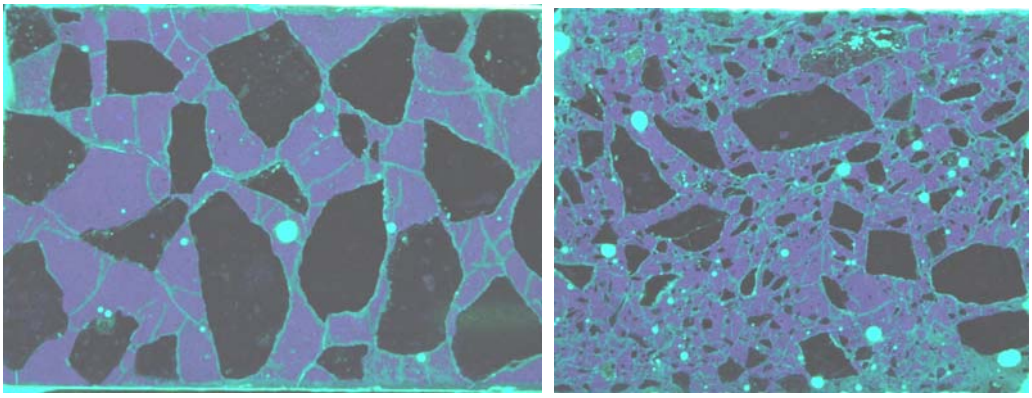


Figure 4: Digitized images of cross sections of M1 (a) and M2 (b) micro concrete bar specimens after accelerated test.

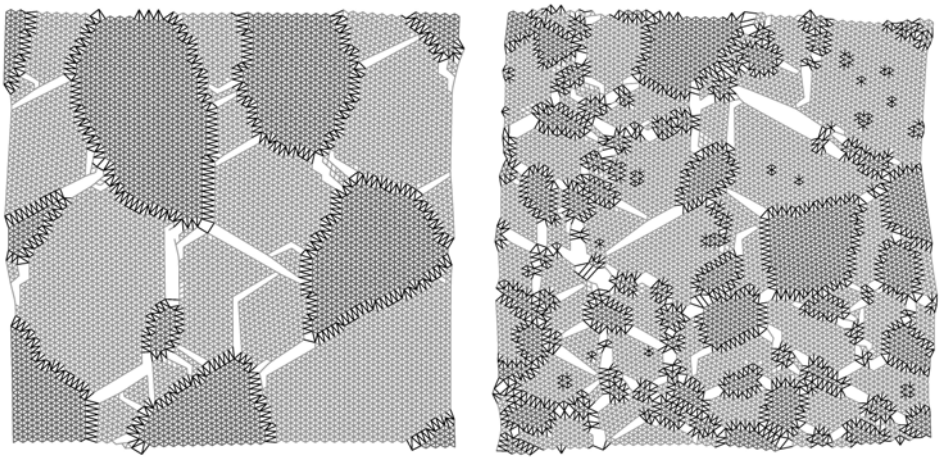


Figure 5: Simulated crack patterns in M1 (a) and M2 (b).

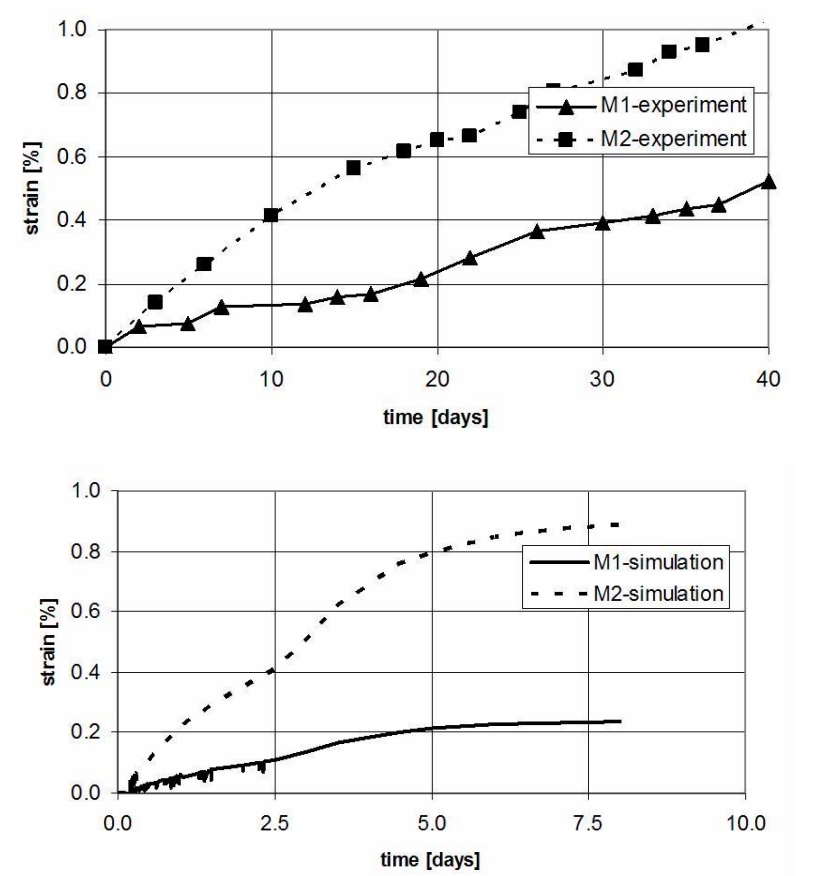


Figure 6: Strain versus time in M1 and M2 concrete: experiments (a) and simulations (b).

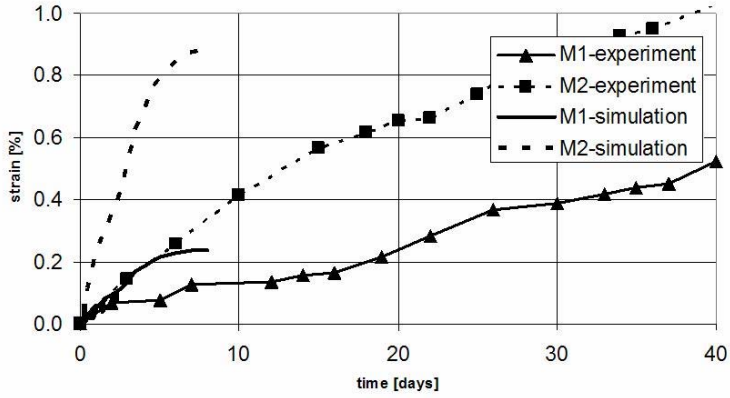


Figure 7: Strain versus time in M1 and M2 concrete; experiments and simulations combined.