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# Literature review of modelling approaches for ASR in concrete: a new perspective

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**ABSTRACT**

The assessment of concrete structures affected by alkali–silica reaction (ASR) is a complex problem due to the multiscale nature of this long-term phenomenon. The reaction starts within the concrete constituents and developed at aggregate level by inducing swelling and deterioration of concrete material, which eventually affect the capacity of the structure. Due to this multiscale nature of the phenomenon, the problem is studied by various researchers in numerous manners. In this paper, a literature review of the main modelling approaches for ASR in concrete is presented within a new perspective. The models are categorised on the basis of their input and output parameters, instead of adopting the classical classification on the base of the scale (e.g. micro, meso and macro). The main aim of the review is to understand to which extent the available models are able to describe the deteriorating impact induced by ASR in concrete material and if the approaches can ultimately be extended to structural analyses.

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Alkali–silica reaction (ASR); concrete; modelling approaches; literature review

## 1. Introduction

The alkali–silica reaction (ASR), within the group of alkali–aggregate reactions, is a harmful long-term deteriorating process that evolves at different scales. The chemical process involves *silica* ions, available in the aggregates, and *alkali* ions, mainly present in pore solution together with *water* (*reaction products level*). The formed alkali–silica gel, when exposed to moisture, tends to swell. Its expansion, while confined in the pore structure of concrete, builds up an internal pressure with the consequent formation of cracks in the aggregates and in the cement paste (*aggregate level*). As a consequence, the concrete is expanding and its mechanical properties are degrading (*concrete level*). The reduction in material resistance compromises the performance of the structure in terms of both capacity and durability (*structural level*).

Due to the multiscale nature of the phenomenon, which starts at reaction products level and with possible consequences up to structural level, the problem has been studied by different expertise (e.g. geologists, material engineers, structural engineers) in different fields (e.g. material sciences, structural mechanics). Therefore, several modelling approaches were developed with different aims.

An overview of the modelling techniques (Section 2) is presented by categorising the available modelling approaches on the basis of their starting scale, which is defined as the level at which the input parameters are defined. The different methods were classified on the basis of their input

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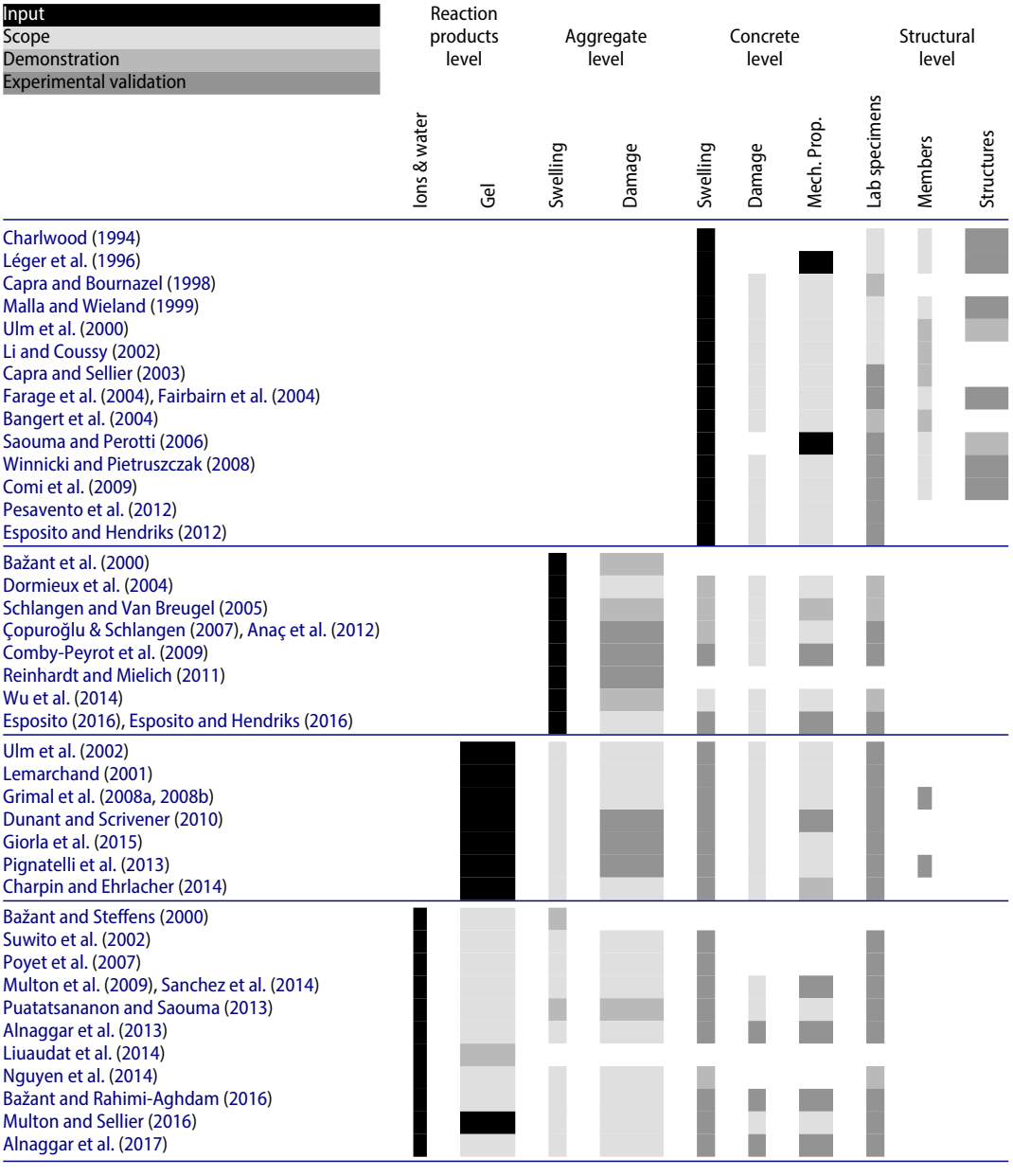
This paper is adapted from Esposito (2016).

**Table 1.** Overview of modelling approaches for ASR in concrete.




parameters as: models based on concrete expansion (Section 3), models based on internal pressure (Section 4), models based on the gel production (Section 5) and models based on the ions diffusion–reaction mechanisms (Section 6). The attention is focused on understanding to which extent the available models are able to capture the multiscale nature of ASR in concrete, are able to describe its deteriorating impact on concrete material and if the approaches can ultimately be extended to structural analyses.

## 2. Overview

In general, literature reviews classify models on the basis of the observed scale (Pan et al., 2012; Saouma & Xi, 2004). The models able to simulate the behaviour of structures are classified as structural or macroscopic. The approaches which investigate the phenomenon at reaction products or aggregate level are defined as microscopic or mesoscopic. It should be noticed that authors adopt different definitions of structural, macro, meso and micro scale; for clarity this terminology is not adopted in the presented classification.

To propose a consistent and comprehensive literature review, the available modelling approaches are subdivided on the basis of their starting scale, which is identified as the level at which the input parameters are defined. Table 1 reports an overview of the available models for ASR-affected concrete.

Various models, especially in the early days, have focused on the description of the structural behaviour by imposing an *ASR expansion* at *concrete level*. They form the first category of modelling approaches in Table 1. The finite element method (FEM) was employed to couple the imposed expansion with a damage criterion for concrete. The imposed concrete expansion was first considered in the context of the thermal equivalence. Subsequently, thanks to systematic laboratory campaigns, kinetic laws were formulated considering the thermodynamic aspects, promoting a chemo-mechanical approach. The attention was mainly focused on the dependency of the concrete expansion from the environmental and boundary conditions. Attempts were made to correlate the swelling to the potential reactivity of the concrete mix design (e.g. alkali content). Having as an ultimate goal the assessment of affected structures, some researchers formulated the constitutive relationship for concrete considering microscopic phenomena in the context of mixture theory; the idea of ASR developing in a heterogeneous concrete material started to take root.

Thanks to microscopic laboratory observations, which revealed the connection between the *internal pressure* generated by the gel expansion and the consequent concrete behaviour, various models were developed *at aggregate level*. They are listed as the second category of modelling approaches in Table 1. The concrete was considered as a heterogeneous multiphase material composed by aggregates and cement paste and in some cases also by pore space. Three techniques could be distinguished in this category. First, mathematical models were employed to describe the correlation between the expansive gel, the internal pressure developed on the concrete constituents and consequent fracture process. Second, the micro-poro-mechanical theory, which provides an analytical solution method, was employed to define the nature of the mechanisms at aggregates level and to explain the evolution of the observed concrete free-expansion. Third, computational-based models, in which the concrete constituents are explicitly modelled by FEM, were proposed to investigate the correlation between the induced damage at aggregate level and the consequent concrete expansion.

To couple the physical chemistry of ASR with the mechanical behaviour of concrete, various modelling approaches were used to study the phenomenon at *reaction products level*. They are listed as the third category of modelling approaches in Table 1. The reaction kinetics was expressed as a function of the *change in mass or volume of the gel*, which is here named as gel production. This approach was first adopted to formulate or further develop models that investigate the phenomenon at aggregate levels. Two schools developed: one using analytical models based on the micro-poro-mechanical theory and one using computational-based models. In addition, some authors implemented this type of reaction kinetics in a chemo-mechanical approach to describe the behaviour of affected structural members.

Recently, the investigation at reaction products level have been further improved by the formulation of *diffusion–reaction* models at *reaction products level* to simulate the chemical process, the formation of the reaction products and their expansion. They are listed as the fourth category of modelling approaches in Table 1. First, mathematical models were developed to describe the flux of ions and water and their subsequent reaction, as well as the diffusion and expansion of the produced gel. Afterwards, the models were linked to existing damage models to describe the coupling between the reaction process and the mechanical behaviour of concrete. To date, these models have

only been scaled up to concrete level, by describing the expansion phenomenon. Both analytical micro-poro-mechanical techniques and computational modelling techniques at aggregate level have been used.

## 3. Models based on concrete expansion

A number of modelling approaches have been developed starting at concrete level and focussing on the analysis of massive structures such as concrete arch-dams. The effects of ASR were modelled by imposing an expansion strain in concrete. The evolution of the strain over time was derived from phenomenological laws or from reaction kinetics laws based on thermodynamic principles. Table 2 gives an overview and it may serve as a guideline for this section.

At the beginning, finite element analyses (FEA) of affected structures were performed considering the induced expansion similarly as a thermally induced strain. For this purpose, the thermal coefficient of concrete was defined as input parmeter. The numerical results were compared with the in-situ deformation measurements of affected structures, as showed by Malla and Wieland (1999).

Thanks to the large and systematic laboratory campaigns, phenomenological laws were formulated that link the induced concrete expansion to the environmental conditions (Larive, 1998; Swamy, 1992), the stress state of the material (Charlwood, 1994; Multon, 2004) and the reactivity of the material (Léger et al. 1996).

Charlwood (1994) has recognised the importance of compressive stress on the anisotropic expansion of affected concrete. He adopted a logarithmic law for the reduction of the concrete expansion on the basis of the compressive stress, which was defined on the basis of a minimum and maximum stress threshold. However, the ASR-induced concrete expansion was still treated as a thermal-induced strain. This model was subsequently adopted by Thompson et al. (1994) and Berra et al. (2010).

Léger et al. (1996) developed a phenomenological model in which the induced concrete expansion was (1) dependent on the stress state of the material (Charlwood, 1994), (2) linearly dependent on the temperature and the relative humidity above a certain threshold value and (3) a function of the total alkali content and aggregate type. The tensile strength and the elastic modulus of concrete were degrading on the basis of the imposed expansion. In comparison with previous models, this model has a large number of input parameters due to the fact that four phenomenological laws were adopted to account for various effects influencing the ASR-induced concrete expansion. The model was applied to study the behaviour of a spillway pier.

Capra and Bournazel (1998) merged a phenomenological approach with probabilistic cracking theory which aimed to account for the spatial distribution of the reaction sites within the structures. The damage was evaluated with linear fracture mechanics theory. The model was adopted to simulate the concrete expansion due to ASR in case of unconfined and confined conditions. No validation with experimental tests was carried out.

Subsequently, the thermo-chemo-mechanical models, which expressed the concrete free-expansion as a function of a thermodynamic kinetics law, were developed following the idea proposed by Ulm et al. (2000). The approach has been based on the large experimental campaign performed by Larive (1998), who tested several concrete mixtures stored under various environmental conditions. A phenomenological exponential law for the evolution of concrete expansion was derived based on three parameters: the latency time, the characteristic time and the asymptotic expansion value. The first two parameters are strictly linked to temperature effects, while the third is an indicator of the reactivity of the concrete. Ulm et al. (2000) explained this behaviour in the context of physical chemistry, considering the concrete as a porous material subjected to an internal pressure and to an external mechanical loading. They adopted a first-order reaction kinetics law, in which the two time parameters depend on the temperature and the activation energies within the Arrhenius concept. In order to account for the effect of temperature on ASR-induced concrete expansion, seven input parameters were required: latency and characteristic time, two energy activation parameters, reference temperature, thermal coefficient and thermal diffusivity. To estimate these parameters, the expansion

**Table 2.** Models based on concrete expansion.

| | | | No. input parameters | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Model type | Imposed strains dependent on | Mechanical | Temp. | RH | Stress state | Reactivity | Validation (V)/Demonstration (D) |
| Charlwood (1994); Thompson et al. (1994) | Phenomenological | Stress state | 2 | 1 | – | 2 | – | Powerhouse (V) |
| Léger et al. (1996) | Phenomenological with reduction of stiffness and tensile strength | Stress state, temperature, moisture, reactivity | 6 | 2 | 2 | 2 | 1 | 2D FEA spillway pier (V) |
| Capra and Bournazel (1998) | Phenomenological with probabilistic fracture mechanics | Stress state, temperature, moisture, reactivity | 1 | 2 | 1 | 2 | 3 | Lab specimens (D) |
| Malla and Wieland (1999) | Phenomenological with linear elastic fracture mechanics | – | 2 | 1 | – | – | – | 3D FEA arch-gravity dam (V) |
| Ulm et al. (2000) | Thermo-chemo-plastic with kinetics law | Temperature | 5 | 7 | – | – | 1 | 2D FEA dam and bridge box girder (D) |
| Li and Coussy (2002, 2004) | Thermo-chemo-plastic with kinetics law | Temperature, moisture | 5 | 4 | 1 | – | 1 | 2D FEA bridge pier (D), 3D FEA bridge pylon (D) |
| Capra and Sellier (2003) | Thermo-hygro-chemo-damage with kinetics law | Temperature, moisture, reactivity | 11 | 1 | 1 | – | – | 2D FEA of lab specimens (V) and of RC beam (D) |
| Farage et al. (2004), Fairbairn et al. (2004) | Thermo-chemo-cracking with kinetics law | Temperature | 8 | 2 | – | – | 1 | 3D FEA lab specimen (V) and 2D FEA dam (V) |
| Bangert et al. (2004) | Thermo-hygro-chemo-damage based on mixture theory | Temperature, moisture | 10 | 3 | 2 | – | – | 2D FEA lab specimens and beam (D) |
| Saouma and Perotti (2006) | Thermo-hygro-chemo with kinetics law and reduction of stiffness and tensile strength | Stress state, temperature, moisture | 8 | 5 | – | 1 | 1 | 2D FEA lab specimens (V) and dam (D) |
| Winnicki and Pietruszczak (2008), Winnicki et al. (2014) | Thermo-hygro-chemo-plastic for RC with kinetics law | Stress state, temperature, moisture | 11 | 3 | 1 | 1 | 1 | Lab specimens (V) and 2D FEA dam (V) |
| Comi et al. (2009) | Thermo-chemo-damage with kinetics law | Stress state, temperature | 18 | 5 | – | – | 1 | 2D FEA lab specimens and dam (V) |
| Pesavento et al. (2012) | Thermo-hygro-chemo-damage based on mixture theory | Temperature, moisture | 3 | 7 | 5 | – | 2 | 2D FEA lab specimens (V) |
| Esposito and Hendriks (2012) | Thermo-chemo-cracking rheological-based | Temperature | 6 | 5 | – | – | 3 | Lab specimens (V) |

curve at a certain reference temperature was required. The imposed expansion was not dependent on the moisture content and the stress state of the material. The induced damage was evaluated in the framework of a plasticity criterion. The model's abilities were demonstrated with 2D FEA of a gravity dam and a bridge box girder.

The thermo-chemo-mechanical approach proposed by Ulm et al. (2000), based on the thermodynamic reaction law, was further developed and applied in combination with existing damage models.

Li and Coussy (2002) extended the kinetics law by including the dependency of the imposed concrete strain on the moisture content. The damage criterion was formulated within the plasticity theory. The model aimed to be used for structural assessment. For this purpose, a strategy for the estimation of input parameters was suggested including: residual expansion tests on core extracted from the structure at different time, monitoring of crack formation on the structure, monitoring of thermal–hygrometric conditions of the structure. The case study of an ASR-affected pier in a reinforced concrete (RC) bridge was studied. The chemo-mechanical model was adopted to describe the behaviour of the concrete. The reinforcement bars were 'homogenised into the pier', without considering their influence on the stress state of the concrete and thus on the ASR phenomenon. In a following publication (Li & Coussy, 2004), the authors presented a 3D finite element analysis of a bridge pylon where the reinforcements were modelled as beam elements perfectly embedded into the affected concrete.

Capra and Sellier (2003) adopted a probabilistic approach, following up the work of Capra and Bournazel (1998), to describe the main damage mechanisms in affected structures. The reaction kinetics was linked to the consumption of alkali and it was dependent on temperature and relative humidity. Three damage variables were identified to describe the probability of cracking due to the ASR-induced concrete expansion, tensile and compressive stresses. The model was able to simulate the anisotropic expansion behaviour observed in constrained laboratory specimens; its abilities were further demonstrated for an affected RC beam subjected to a moisture gradient.

Farage et al. (2004) implemented the thermo-chemo-mechanical model proposed by Ulm et al. (2000) within a smeared fixed cracking model. They adopted an ideally plastic stress–strain relationship to describe the behaviour of affected concrete in tension. This ductile post-cracking relation is derived from a back analysis of only one set of experimental tests (Larive, 1998). The model was validated with 3D FEA of laboratory specimens, and further applied by Fairbairn et al. (2004) to a concrete dam.

Saouma and Perotti (2006) mainly focused on the expansion redistribution effect generated by the coupling between internal swelling and stress state of the material. The volumetric imposed strain, which is a function of temperature (Ulm et al., 2000) and moisture content (Capra & Bournazel, 1998), was distributed along the principal stress directions on the basis of the current stress state, the tensile and compressive strength of the material and the stress threshold below which no expansion was allowed. The induced material deterioration was imposed as a reduction of the stiffness and tensile strength in time following an exponential curve; no degradation of compressive strength is assumed. The model was validated by simulating the confined expansion tests performed by Multon (2004); subsequently a gravity dam was studied by 2D FEA. This approach meets the needs of practical engineers and it is still widely used (Saouma, 2013).

Winnicki and Pietruszczak (2008) described the chemo-mechanical interaction within the framework of a thermo-hygro-chemo-plastic model for reinforced concrete. The deterioration induced by ASR was integrated in a continuum model, previously developed for RC structures, assuming that the formation of expansive phases resulted in degradation of mechanical properties of the material. The imposed concrete strain depended on the compressive stresses following Charlwood (1994), on the temperature following Ulm et al. (2000) and on the relative humidity in agreement with Capra and Bournazel (1998). They have pointed out the importance of an appropriate modelling techniques to describe the coupling between internal swelling and external mechanical loading as well as the mechanical degradation induced in the material. The model was validated at material level against free-expansion and confined expansion tests on laboratory prisms and cylinders. It was further applied to study the crack formation in a gravity dam (Winnicki et al., 2014).

Comi et al. (2009) studied the damaging effects in affected concrete in the context of their fracture energy based-bidissipative damage model. The model is able to describe the anisotropic swelling behaviour observed in confined expansion tests as a consequence of the interaction between concrete expansion and cracking. The cracking process was evaluated by employing two isotropic damage variables for tension and compressive stresses. The model was validated in terms of expansion evolution for confined concrete specimens. It was further employed to investigate the behaviour of a concrete gravity dam.

Esposito and Hendriks (2012) developed a thermo-chemo-cracking model based on the approach proposed by Saouma and Perotti (2006). The rheological model aimed to explain the link between the expansion and the degradation of mechanical properties in affected concrete, which is not accounted for in the aforementioned modelling techniques. The reaction kinetics law proposed by Ulm et al. (2000) was adopted. The damage mechanism was described by two parallel inelastic springs, one of them working in series with the imposed expansion. The model aimed to reproduce the stiffness and tensile strength degradation in both unaffected and affected concretes. The validation, against laboratory specimens stored under free-expansion conditions, showed the limitation of the model. It was concluded that further investigations on the deteriorating impact of ASR on concrete material can only be modelled by observing the phenomenon at aggregate level rather than at concrete level.

To link the reaction kinetics to the physics of the phenomenon, Bangert et al. (2004) and Pesavento et al. (2012) adopted mixture theory, considering the concrete as a multiphase reactive porous media composed by a solid skeleton and capillarity porosity. The swelling of reaction products was evaluated as an imposed strain on the concrete skeleton, which depended on the temperature and the degree of saturation of water. The imposed strains were linked to the difference in density between the reactive and unreactive skeleton. They accounted for the coupling between the ASR phenomenon and the pressure exerted by the water in the capillarity porosity and in the skeleton; thus, the thermo-hygro-chemical coupling was formulated. The material model was formulated in the mathematical framework and further implemented in FEM.

Bangert et al. (2004) employed a regularised continuum isotropic damage model based on damage variables, which did not account for the cracking induced by the expansive alkali–silica gel at aggregate level. As a result, affected concrete specimens stored under free-expansion conditions do not present any damage; the cracking can occur only in confined affected specimens. The model's abilities were demonstrated by means of 2D FEA of laboratory specimens and of a beam.

Pesavento et al. (2012) adopted a non-local isotropic damage model based on two damage variables related to the external mechanical loading and internal chemical loading. The damage variable associated with the chemical reaction was derived by fitting the experimental results in terms of expansion vs. Young's modulus curve. The model was validated by 2D FEA of laboratory specimens; only part of the specimens is meshed, taking advantage of symmetry, due to the heavy computational effort which is needed to solve the complex equation system. The validation procedure analysed specimens subjected to various hygro-thermal conditions and stored under free-expansion conditions. The comparison was made in terms of induced expansion and mass variation of concrete.

The models based on concrete expansion have as primary goal the assessment of ASR-affected structures and their starting point is the (most visible) effect of ASR on concrete material: the concrete expansion. The first pioneers treated ASR-induced concrete expansions as a thermal equivalent strain. However, it was soon recognised that this expansion depends on environmental conditions and stress state of the material and it causes damage of concrete material. In order to account for all these effects, phenomenological laws were adopted to describe the evolution of concrete expansion, as function of temperature, moisture, stress state. Subsequently, they were further implemented in available damage models for concrete. As a consequence, these models present a large number of the input parameters, which are not always available for the great variety of concrete mixtures, environmental conditions and confinement state.

**Table 3.** Models based on internal pressure.

| | | | No. input parameters | | | |
|---|---|---|---|---|---|---|
| | Model type | Imposed | Microstucture | Mechanical | Reactivity | Validation (V)/Demonstration (D) |
| Bažant et al. (2000) | Linear fracture mechanics theory | Pressure in particle rim | 3 | 3 | 2 | Idealised one-particle cubic cell (D) |
| Dormieux et al. (2004) | Chemo-poro-micro-elastic | Pressure in porosity | 2 | 2 | 1 | Lab specimens (D) |
| Schlangen and Van Breugel (2005) | Lattice model with quasi-brittle aggregate, ITZ and matrix phase | Strain in aggregate and/or ITZ | 4 | 6 | – | 2D FEA lab specimens (D) |
| Çopuroğlu and Schlangen (2007), Schlangen and Copuroğlu (2010), Anaç et al. (2012) | Lattice model with quasi-brittle aggregate, ITZ and matrix phase | Strain in aggregate and/or ITZ | 4 | 6 | – | 2D and 3D FEA lab specimens (V) |
| Comby-Peyrot et al. (2009) | Particle model with linear elastic aggregate phase and elastic damage matrix phase | Strain at aggregates rim | 4 | 11 | – | 3D FEA lab specimens (V) |
| Reinhardt and Mielich (2011) | Linear elastic fracture mechanics | Pressure in aggregates | 2 | 1 | 1 | Rock specimens (V) |
| Wu et al. (2014) | $FE^2$ multiscale model | Strain in porosity at lower level | 4 | 6 | 8 | 3D FEA lab specimens (D) |
| Esposito (2016), Esposito and Hendriks (2016) | Micro-poro-fracture | Pressure | 4 | 6 | – | Lab specimens (V) |

## 4. Models based on internal pressure

Thanks to the technological advancement in microscopic investigation, at the beginning of this century several approaches have investigated the ASR mechanisms at aggregate level, to explain the induced effects at concrete level. The concrete was represented as a heterogeneous material composed primary by aggregates and matrix phases. In the latter, the cement paste and small particles (e.g. sand) were included, while in the former only gravel particles were considered. Some authors have also considered the presence of an interfacial transition zone (ITZ), which surrounds the aggregates to the matrix. The expansion of concrete was obtained as a direct result of the gel swelling. For these models, it is of primary importance to define the microstructure of concrete (e.g. volume fraction and shape of aggregate phase) and the mechanical properties of each phase; consequently the number of input parameters can be larger than the ones presented in the previous section. Table 3 gives an overview of the proposed models, which start from an assumed internal pressure.

Three typologies of approaches can be recognised: (1) mathematical models that describe damage mechanisms at aggregate level, (2) micro-poro-mechanical methods that analytically correlate the local and global quantities at aggregate and concrete level and (3) numerical methods that compute, through FEM techniques, the damage at aggregate level within the different phases of concrete. All the approaches adopted the concept of representative elementary volume (REV) that has been defined as an infinitesimal portion of the three-dimensional material system under consideration.

The first typology of approaches includes mathematical models, which adopted linear fracture mechanics theory to study the cracking phenomenon in reactive particles.

Bažant et al. (2000) considered concrete specimens made of waste glass particles. These particles, differently from natural aggregates, consist of pure silica with a ordered crystalline structures; as a consequence the ASR develops fast and the reaction products are uniformly distributed around the particle rim. The analysed REV consisted of idealised periodic cubic cell made of a single spherical particle embedded in the cement paste matrix. The pressure induced by the expansive reaction products was considered as an internal loading. The influence of both external and internal loading on the cracking was accounted in the context of effective stress concept. The relationship between tensile strength and expansion of concrete is established by means of the stress intensity factor; neither a correlation with the compressive strength nor with the Young's modulus is made. The approach is mainly employed to identify the *pessimum size* of aggregates, which leads to the maximum concrete expansion.

With a similar focus, Reinhardt and Mielich (2011) investigated the correlation between expansive pressure and cracking for natural rocks. In this case, the internal pressure was applied within the aggregates. Comparison with experimental results on reactive rocks showed that the critical stress intensity factor appears to govern the cracking of the aggregates and to be sensitive to the alkaline environment.

The second typology of approaches adopts the micro-poro-mechanics theory, which blends the concepts of poro-mechanics, micro-mechanics and analytical homogenisation approaches.

Dormieux et al. (2004) were one of the first research group to treats ASR-affected concrete in the framework of micro-poro-mechanics theory. The concrete was considered as a porous material composed by a pore space, filled by expansive gel products, embedded in a solid matrix, representing the concrete skeleton. The state equations and the mechanical characteristics at the global scale (concrete level) were analytically evaluated on the basis of the quantities at local scale (aggregate level). The ASR phenomenon was simulated by means of cracks growing in the vicinity of the aggregates, which were not explicitly considered. A reaction kinetics was proposed to link the gel mass production and the damage process, but this has not been adopted during the validation process. The approach can be defined as smeared, since the overall behaviour of the material depends only on the elastic properties of the solid matrix (two mechanical input parameters) and on the shape and volume fraction of the pore space (two parameters to describe the microstructure). They showed that the concrete free-expansion results from the crack propagation at aggregate level after saturation of the pore space

is reached. The initial delay in concrete expansion is directly related to the filling of initial porosity. This concept has been further developed by Lemarchand et al. (2005), as shown in next section.

Inspired by the previous experiences in the field of micro-poro-mechanics theory, Esposito and Hendriks (2016) proposed a micro-poro-fracture-mechanical model to understand the deteriorating impact of ASR on concrete. The concrete was modelled as a heterogeneous material. Its microstructure was composed by cracks embedded in a solid matrix, formed by aggregates and cement paste. The macroscopic quantities of the overall material were analytically determined adopting the concept of a representative elementary volume. The approach resulted in a three-dimensional smeared model, which aims to characterise the macroscopic deterioration of concrete subjected to any combination of external and internal loads. After validation of the model for the case of unaffected concrete, the relation between expansion and degradation of mechanical properties was studied for the case of concrete under free-expansion. Although the authors are able to reproduce the relationship between stiffness and strengths degradation, an overestimation of the stiffness degradation is reported. The latter result is inputed to the absence of permanent deformation in the model formulation. This result highlights the importance of accounting for the coupling between ASR and creep phenomena (Alnaggar et al., 2017; Bažant & Rahimi-Aghdam, 2016; Giorla et al., 2015).

The third typology of approaches regards the numerical computation of the phenomenon at aggregate level. The structure of concrete at the local scale was modelled by FEM techniques; this approach allows to compare the damage mechanisms at aggregate level with the one observed on laboratory specimens under microscope (e.g. polished section analysis). The computational effort, which can be quite elevated, depends from the REV dimension and mesh size adopted.

Schlangen and Van Breugel (2005) adopted the lattice model, already developed in their research group (Schlangen & Van Mier, 1992). The concrete was considered as a three-phase material composed of aggregates, cement paste and ITZ phases. A peculiar characteristic of this technique was that the aggregates were modelled by using their real shape and not as spheres. Each phase was meshed by beam elements able to transfer normal forces, shear forces and bending moments. A brittle fracture mechanism was adopted: when an element reached its tensile strength, it was removed from the system. The swelling of the alkali–silica gel was treated as an imposed expansion randomly distributed within the aggregate boundaries. The relation between the location of swelling points and the resulting concrete expansion was investigated in comparison with experimental findings (Çopuroğlu & Schlangen, 2007; Schlangen & Copuroğlu, 2010). The model is able to simulate the ASR-induced damage mechanisms at aggregate level and to approximate the concrete expansion. They evaluated the degradation in terms of tensile strength, but no comparison is made with experiments. The lattice model has been further applied by Anaç et al. (2012). Microscopic observations from polished section analyses were adopted both as input to describe the lattice mesh and in comparison with numerical results. The damage, numerically estimated, was compared with damage rating index (DRI), which evaluates the presence of cracks and gel formations correlated to the ASR phenomenon.

Comby-Peyrot et al. (2009) employed a full three-dimensional FE model, in which the aggregates were represented by particles. Only gravels, embedded in a mortar matrix formed by the small size aggregates and the cement paste, were considered. The particles behaved linearly elastic, while a non-local Maziar model was adopted for the mortar phase. Mechanical tests on mortar bars, like Brazilian splitting test and bending test, were used to identify the input parameters. The ASR phenomenon was simulated by swelling of the aggregate rim. The imposed strain is evaluated as an increment of the particles volume, which is input by fitting the expansion evolution of unconstrained concrete specimens. The model is able to reproduce the crack pattern of damaged affected concrete and its Young's modulus degradation.

Wu et al. (2014) proposed a multiscale material model ranging from reaction products to concrete level. The concrete was modelled by aggregates, represented by spherical inclusions, embedded in the cement paste, which was formed by a pore space and the product derived from the cement hydration. The expansive alkali–silica gel was considered, rather than a phase, as an imposed strain in the pore space of the matrix, at one scale lower than the aggregates. The imposed strain depended

on the moisture content and on the temperature, following the same kinetics law proposed by Ulm et al. (2000). The behaviour of concrete was determined by a numerical two-scale homogenisation approach, which solves the boundary values problem for the REV employing the FEM at both scales. The aggregates were considered as elastic phase, while the cement paste followed a viscoplastic behaviour. The isotropic damage criterion was formulated only at aggregate scale, but the effects of reaction products, within the cement paste phase, was accounted via the deterioration of its mechanical properties. The model's abilities were demonstrated for two specimens subjected to different environmental conditions; only the damage pattern at aggregate level is shown.

The models based on internal pressure were developed to understand the effects of ASR phenomenon on the material behaviour of concrete. All the models are based on the assumption that an internal pressure is developed at aggregate level due to the formation of ASR reaction products (commonly named also as alkali–silica gel) and that the degradation of concrete material can be explained by the cracking process occurring at the microstructure (aggregate level). The application of these models requires therefore information concerning the concrete microstructure and thus the mix design of concrete. The evaluation of the damage process is mainly based on the fracture mechanics theory and does not require formulation of phenomenological laws, as was the case for the models based on concrete expansion (Section 3). However, a further step should be made to employ these models for the assessment of full-scale structures (e.g. bridges, dams). Additionally, it should be noted that the models do not explain why the ASR reaction products are formed, but only its interaction with the damage of concrete is addressed.

## 5. Models based on gel production

To couple the physical chemistry of ASR with the mechanical behaviour of concrete, various modelling approaches have studied the phenomenon at reaction products level. The reaction kinetics was expressed as a function of the change in mass or volume of the expansive alkali–silica gel, which was subsequently translated into an imposed strain or pressure at aggregate level. Depending on the complexity of the adopted methods, different output levels were reached. In the majority of the cases, the ASR effects were described at concrete level and they were used to assess the behaviour of structural elements. Table 4 gives an overview of models based on the gel production.

In the framework of micro-poro-mechanical theory, Ulm et al. (2002) and Lemarchand et al. (2005) have investigated the connection between the swelling of reaction products at aggregate level and the consequent concrete expansion. They both considered a variation in gel mass that provokes an internal pressure, exerted within the porosity space, on the concrete skeleton.

Ulm et al. (2002) have demonstrated that 'the swelling pressure activates the same fractional-dilatation mechanisms' at aggregate level, which are present during concrete cracking by external applied loading. The initial delay between the activation of ASR and the concrete expansion, was obtained from the reaction products filling the existing pore space. The stress-induced anisotropy expansion, observed in confined concrete, was considered as a result of the chemo-poro-plastic dilatation, in which the compressive stresses pressurise the solid matrix and delay the occurrence of irreversible deformations.

Lemarchand et al. (2005) applied chemo-poro-elastic theory to identify the nature of the free-expansion behaviour of concrete between the topochemical or the through-solution nature mechanism. In the topochemical mechanism the reaction products uniformly fill the porosity, following the reaction kinetics related to the dissolution of silica, while in the through-solution mechanism the ASR phenomenon is described by the cracking process around the aggregates. They have concluded that both mechanisms were able to describe the exponential free-expansion curve; however the characteristic time, within which the expansion is developed, results a function of the reaction kinetics.

Charpin (2013) and Charpin and Ehrlacher (2014) have studied the induced anisotropic expansive behaviour in confined concrete specimens by employing a chemo-micro-poro-fracture model. The concrete was composed of aggregate, ITZ and cement paste phases, which behaved elastically. The

**Table 4.** Models based on gel production.

| | | | No. input parameters | | | | |
|---|---|---|---|---|---|---|---|
| | Model type | Variation of gel | Microstucture | Mechanical | Creep | Reactivity | Validation (V)/Demonstration (D) |
| Ulm et al. (2002) | Chemo-micro-poro-plastic | Mass | 1 | 4 | – | 1 | Lab specimens (V) |
| Lemarchand (2001), Lemarchand et al. (2003, 2005) | Chemo-micro-poro-elastic | Mass | 6 | 3 | – | 1 | Lab specimens (V) |
| Grimal et al. (2008a, 2008b) | Thermo-hygo-chemo-damage rheological-based | Mass | 1 | 8 | 4 | 4 | lab specimens (V) and 3D FEA RC beams (V) |
| Dunant and Scrivener (2010) | XFEM with quasi-brittle aggregate and cement paste phases, elastic gel pockets | Surface | 2 | 8 | – | 1 | 2D FEA lab specimens (V) |
| Giorla (2013), Giorla et al. (2015) | XFEM with quasi-brittle viscoelastic cement paste phase, quasi-brittle aggregates and elastic gel pockets | Surface | 2 | 9 | 4 | 2 | 2D FEA lab specimens (V) |
| Pignatelli et al. (2013) | Chemo-micro-poro-damage | Mass | 1 | 16 | – | 7 | Lab specimens (V) and 2D FEA beams (V) |
| Charpin (2013), Charpin and Ehrlacher (2014) | Chemo-micro-poro-fracture | Volume | 6 | 7 | – | 1 | Lab specimens (V) |

expansive alkali–silica gel was formed at the aggregate rim and it flowed within the ITZ porosity. The overall concrete properties were analytically evaluated. The internal pressure, exerted by the gel in the cement paste, was evaluated as a function of the change in gel volume. The damage at aggregate level was represented by three orthogonal penny-shaped cracks, saturated by the gel, formed around the spherical aggregates. The damage criterion, based on energy approach, accounted for two mechanisms: the decohesion between the aggregate and ITZ phase and the cracking of the cement paste. The model was validated for confined laboratory specimens in terms of concrete expansion. Good agreement with experimental results is obtained for concrete specimens under compressive loading up to 10 MPa. For higher compressive stresses, the decohesive mechanism was not activated, thus the model underestimats the expansion values. The author reports an overestimation of the stiffness degradation, but no comparison is made with experimental findings.

Some authors have analysed the ASR-induced damage at aggregate level adopting computational methods in combination with microscopic observations.

Dunant and Scrivener (2010) employed the extended finite element method (XFEM) to model the evolution of concrete structure at aggregate level induced by the formation of the reaction products. In a two-dimensional system, circular inclusions represented the aggregates embedded in the cement paste matrix. The reaction products were accounted, within the aggregates, with randomly distributed gel pocket phases. The gel stiffness was calibrated by fitting the free-expansion curve of concrete at early stage. The swelling process was simulated by grow of the gel pockets until a preset percentage of the aggregate has reacted. To consider the heterogeneity of the material, the mechanical properties of the phases were distributed according to a Weibull law. A non-local continuum damage model was adopted where each phase had an elastic-brittle behaviour. The comparison of experimental and numerical results, obtained by 2D analyses, besides describing the damage at aggregate level, was able to reproduce the behaviour of concrete in terms of expansion and stiffness degradation. The latter was justified by the author as a consequence of the cracking in the aggregates and not in the cement paste. The authors report that 'the cement paste is mostly in compression, due to the dense aggregate packing, with stress level below the elastic limit'. This finding was in agreement with their experimental observation; however it should be pointed out that different damage mechanisms at aggregate level are reported in literature (Sanchez et al., 2015).

The model proposed by Dunant and Scrivener (2010) was further developed by Giorla et al. (2015), by considering the coupling between ASR and creep phenomena. This can explain the different damage process which results limited in the cement paste with respect to the aggregate phase. Being the ASR a long-term process, the internal pressure can induce permanent deformation within the cement paste that behaves as a viscoelastic material. The model was able to simulate the behaviour of affected concrete under multiaxial stress state. However, the comparison with experimental findings is performed only in terms of concrete expansion.

In the framework of thermo-chemo-mechanical model for structural analyses, some researchers have formulated a constitutive model for affected concrete to be used in FEA.

Grimal et al. (2008a, 2008b) extended the model proposed by Capra and Sellier (2003) including a reaction kinetics law, which is depended on the variation of gel mass on the basis of saturation degree of the concrete porosity; the combined effects of creep, shrinkage and ASR was considered. The material degradation was described by a probabilistic-based orthotropic damage model, which accounted for the damage by ASR-induced expansion, tension and compressive stresses (Capra & Sellier, 2003). The model was calibrated and validated, in terms of concrete expansion, by adopting a set of tests on unaffected and affected concrete under various confinement degrees. Subsequently, it was applied to the simulation of reinforced concrete beams partially immersed in water. The authors performed a 3D analysis in which the thermo-chemo-mechanical model was adopted to represent the behaviour of the concrete, while the bars and stirrups were considered as embedded reinforcements. The modelling approach is based on a large number of input parameters, which calibration requires a large number of experimental results on the same concrete mix design.

Pignatelli et al. (2013) further developed the model proposed by Comi et al. (2009), making the connection between reaction products and aggregate level. The concrete was modelled as a two-phase material, composed by wet gel and concrete skeleton. The swelling pressure resulted from the change in mass of the wet gel phase, which is depended on temperature and saturation degree through the reaction extent (reaction kinetics law). The damage of concrete induced by ASR was evaluated with a simplified micro-mechanical model, in which the unaffected skeleton and the gel phase work in series between themselves and in parallel with the damaged skeleton. The damage induced by tension and compressive stress was evaluated separately, with two isotropic damage variables (Comi et al., 2009). The model was able to predict the expansion behaviour of concrete laboratory specimens under free and confined expansion conditions. It was further applied to the simulation of concrete beams subjected to wetting conditions.

Similarly to the models based on internal pressure (Section 4), the models based on gel production explain the impact of ASR phenomenon on concrete material. By imposing the variation in mass or volume of the gel, the coupling between concrete expansion and damage is explained at aggregate level. In some cases, the coupling between ASR and creep is also analysed. In the majority of the cases, validation of the models is performed against laboratory tests. In few cases, structural analyses of ASR-affected members are performed. The strain induced on concrete by ASR are correlated to the variation of gel mass/volume, but they are subsequently imposed at concrete level and coupling with phenomenon such as cracking, creep, shrinkage is considered in a phenomenological framework.

## 6. Models based on ions diffusion–reaction

Recently, researchers have studied the chemical process at reaction products level in terms of ions diffusion–reaction mechanisms. In some cases, these mathematical approaches have been implemented in computational models for the description of the mechanical consequences of ASR in concrete. Table 5 gives an overview.

The chemical process has been first described in a mathematical framework, which allowed scaling up to aggregate level.

Bažant and Steffens (2000) adopted a mathematical model to describe the reaction kinetics in affected concrete specimens made of waste glass particles. This work was developed in combination, but separated, with Bažant et al. (2000), who have investigated the induced fracture mechanisms at aggregate level. Due to the employment of pure silica particles with an ordered crystalline structure, the reaction products formed a rim around the grains. The grow of the rim around the particle was associated with the diffusion of the water within the reaction products and the dissolution of the silica, while the swelling of the reactive rim was correlated to the water imbibation from the capillarity porosity. The model was applied to study the influence of particle size on the swelling pressure generated by the reaction products.

Suwito et al. (2002) investigated the pessimum aggregate size effect in ultra-accelerated mortar bar tests adopting an analytically solved micro-poro-mechanical model. The concrete was represented by a three-phase material composed by a spherical domain embedded in the homogenised matrix, which has the same mechanical characteristics of the concrete. The spherical domain was formed by the aggregate, centrally placed, surrounded by the cement paste phase. The reaction products were considered placed on the particle rim; they were assumed as a part of the aggregates and not as a separated phase. A linear elastic behaviour of the phases was considered and the effective properties of concrete were analytically determined. The reaction kinetics was represented by two diffusion processes: first the alkali ions flow within the aggregates and react with the silica ions, second the expansive alkali–silica gel, formed at the rim of the aggregates, flows into the cement paste porosity. The reaction products, which were defined as a viscous gel, generate expansion only when flowing in the cement paste porosity; no swelling power is assumed for the gel saturating the reaction rim. The model was validated by simulating the expansion of mortar bars with different aggregate size.

**Table 5.** Models based on ions diffusion–reaction mechanisms.

| | | | No. input parameters | | | | |
|---|---|---|---|---|---|---|---|
| | Model type | Diffusion–reaction mechanism | Microstucture | Mechanical | Creep/Shrinkage | Reactivity | Validation (V)/Demonstration (D) |
| Bažant and Steffens (2000) | Mathematical | Dissolution silica, water diffusion within gel rim, water imbibation from porosity | 1 | 1 | – | 4 | Idealised one-particle cubic cell (D) |
| Suwito et al. (2002) | Chemo-micro-poro-elastic | Diffusion alkali ions, diffusion of gel in cement paste | 3 | 5 | – | 5 | Lab specimens (V) |
| Poyet et al. (2007) | Chemo-micro-poro-elastic | Diffusion–reaction of sodium and calcium ions within gel rim | 3 | 2 | – | 6 | Idealised one-particle cubic cell (V) |
| Multon et al. (2009), Sanchez et al. (2014) | Chemo-micro-poro-damage | Diffusion–reaction of sodium and calcium ions within gel rim | 5 | 5 | – | 5 | Lab specimens (V) |
| Puatatsananon and Saouma (2013) | Computational multiscale | Diffusion alkali ions, diffusion of gel in cement paste | 3 | 12 | – | 3 | Lab specimens (V) |
| Alnaggar et al. (2013) | Lattice discrete particle | Dissolution silica, water diffusion within gel rim, water imbibation from porosity | 5 | 16 | 4 | 8 | 3D FEA lab specimens (V) |
| Liuaudat et al. (2014) | Mathematical model | Forward and backward diffusion–reaction of alkali and silica ions in the rim | 4 | 6 | – | 9 | 1D interface system between aggregate and cement paste (D) |
| Nguyen et al. (2014) | Chemo-elastic | Diffusion–reaction of sodium ions | 1 | 4 | – | 4 | 1D penetration of NaCl ions in concrete beam (D) |
| Bažant and Rahimi-Aghdam (2016), Rahimi-Aghdam, Bažant, and Caner (2016) | Diffusion-based and creep-based chemo-mechanical model | Dissolution silica, water diffusion in gel, water imbibation from porosity | 1 | 28 | – | 13 | 3D FEA lab specimens (V) |
| Multon and Sellier (2016) | Poromechanical | Diffusion and fixation of alkali ions in gel and diffusion of alkali ions due to leaching | 4 | 8 | 4 | 5 | 3D FEA lab specimens (V) |
| Alnaggar et al. (2017) | Lattice discrete particle | Dissolution silica, water diffusion in gel rim, water imbibation from porosity | 8 | 12 | 13 | 9 | 3D FEA lab specimens (V) |

Poyet et al. (2007) described the reaction kinetics for the case of spherical aggregates embedded in the cement paste, assuming that the reaction products are situated at the rim. The model accounted for the transport of sodium and calcium ions in the aggregates and for the equilibrium of their concentrations outside the particles. The stechiometric proportion between the alkali and silica ions involved in the reaction was assumed fixed. The diffusion process was considered dependent also on the precipitation of portlandite, which influences the expansion rate of concrete. They assumed that the chemical reaction generates two products with fix composition: the C-S-H gel, that is a harmless species and a natural constituent of the cement paste, and the expansive alkali–silica gel. The variation in molar volume of the reaction products is considered as the cause of the damage at aggregate level, which was assumed isotropic, and consequently of the concrete expansion. The approach was validated, in terms of concrete free-expansion, for laboratory specimens, which differentiate only in aggregate grading.

Liuaudat et al. (2014) proposed a diffusion–reaction model, in which the chemical reaction generates, at the aggregate rim, two types of reactive products with different density. The approach was adopted to study the mechanisms for a single interface system between aggregate and cement paste. The model is able to explain the relationship between swelling power and compositions of reaction products as well as the effect of portlandite on the silica dissolution. At the moment, it is not applied for the description of the behaviour of affected concrete.

Nguyen et al. (2014), similarly to Poyet et al. (2007), have correlated the induced concrete expansion to the diffusion of the alkali ions, which leading to dissolution of the silica, forms the expansive reactive products. The approach accounted for the tortuosity of undamaged porous material, which can influence the diffusion process. The concrete was considered as a linear elastic material. The approach is able to reproduce the kinetics law between concrete expansion and time, which is usually used as input constitutive relationship for the approaches discussed in Section 3.

Some of the aforementioned mathematical approaches have been further implemented in existing damage models.

Alnaggar et al. (2013) have adopted a lattice discrete particle model, which simulates the concrete at the scale of coarse aggregates. The coarse aggregate were represented by spherical particles, subjected to a rigid body kinetics. The ASR was modelled as an erosion of the aggregates with the subsequent formation of a reaction rim; the amount of formed gel mass was computed by following Bažant and Steffens (2000). The generated local swelling was governed by water imbibition and it was imposed as internal strain on the aggregates. The shrinkage and creep phenomena were also accounted as imposed strains on the particle, by applying the superposition effect. The behaviour of concrete specimens stored under free-expansion and under confinement was well reproduced, in terms of expansion and cracking in concrete. The degradation of mechanical properties, which was found within the bounds proposed by ISE (1992), is estimated, for the same concrete mixture adopted in the validation procedure, by modifying two input parameters correlated to the reaction kinetics. The approach adopts a heavy computational procedure and it is based on large number of input parameters, which are mainly adopted to characterise the microstructure and the fracture process at aggregate level. In fact, it is worth to note that the lattice particle model was at first developed to describe the fracture process in unaffected concrete; for the validation of the model five different experimental tests were adopted (Cusatis et al., 2011).

In a further version of their model, Alnaggar et al. (2017) evaluate both the ASR, creep and shrinkage phenomena as a results of thermal, hygrometric and chemical conditions at aggregate level. The calibration of the input parameters was performed considering two free-expansion curves at different moisture contents and basic creep tests. The application of this model to explain the expansion of laboratory specimens was possible thanks to the large amount of experimental data available. Nevertheless, the authors highlight the strong coupling between ASR and other phenomena inducing inelastic strains in concrete.

Multon et al. (2009) have adopted a mathematical chemo-damage model, in which the reaction kinetics was described in agreement with Poyet et al. (2007). The concrete was modelled by a single-

aggregate REV composed by a particle surrounded by reactive products and embedded in the cement paste. The diffusion–reaction process was located at the rim and it generates variation in molar volume of the reaction products, which leads to an expansion of the aggregates. Considering the expansive alkali–silica gel as incompressible, its swelling was accounted as an isotropic imposed strain in the aggregates. The Young's modulus of the REV was reduced, considering an isotropic damage variable, due to the tensile stresses produced by the expansive aggregates in the surrounding cement paste. The model was based on a limited number of input parameters, among which only the ones related to the diffusion–reaction process need calibration. The validation was performed on mortar bar specimens, stored under free-expansion condition, with different aggregate size and alkali content. The comparison with experimental results was reported in terms of expansion. Sanchez et al. (2014) have adopted the model proposed by Multon et al. (2009) to simulate the evolution of mechanical properties vs. expansion in concrete specimens stored under free-expansion condition. The model overestimates the degradation in terms of Young's modulus and tensile strength. The evolution of compressive strength was reasonable represented by introducing an additional damage variable in compression, empirically correlated to the one in tension.

In a further development of the model, Multon and Sellier (2016) proposed a multiscale approach based on poromechanics in which the diffusion of alkali ions in aggregates and the fixation of alkali ions in the alkali–silica gel is considered. This formulation is based on the recent findings by Kim and Olek (2014) to describe the chemical sequence and the kinetic of ASR. The model was mainly developed to study the effect of alkali leaching in concrete, which is important to link the experimental results of accelerated tests to the development of ASR in existing structures. For this reason, the diffusion of alkali ions at concrete scale is also considered to take into account the alkali flow due to external boundary conditions. This model, in contrast to the other models presented in this section, does not consider an instantaneous reaction; consequently, the formation of the alkali–silica gel can be delayed due to the leaching of the alkali ions outside the concrete boundaries. In order to take into account the effect of damage and creep, the poromechanical model is implemented in the model proposed by Grimal et al. (2008a, 2008b). The model was validated in terms of concrete expansion against laboratory specimens.

Puatatsananon and Saouma (2013) have further developed, in a numerical framework up to structural level, the mathematical model proposed by Suwito et al. (2002) that ranged from reaction products to concrete level. The two diffusion problems of the alkali ions and of the gel, which were previously solved analytically (Suwito et al. 2002), were obtained with a finite difference analysis of a single-aggregate REV. A one-way coupling between the diffusion processes and the stress analysis was evaluated with FEA. The damage was considered only at aggregate level, by introducing interface elements between the particle and the cement paste in the single-aggregate REV. As a consequence, the predicted internal pressure was more realistic with respect to the one found by Suwito et al. (2002). The approach was validated, in terms of concrete free-expansion, for mortar specimens that differentiate only in aggregate grading.

Bažant and Rahimi-Aghdam (2016) and Rahimi-Aghdam et al. (2016) developed a diffusion-based and creep-based chemo-mechanical model by combining the microplane model M7 for concrete with the mathematical model proposed earlier for ASR kinetic (Bažant & Steffens, 2000). The ASR kinetics is governed by the diffusion of the alkali ions and the penetration of water within the alkali–silica gel; the ASR reaction is instead considered instantaneous. The model accounted also for the diffusion of alkali–silica gel into pores and cracks and for the formation of solidified alkali–silica gel when in contact with calcium. In order to account for the coupling between ASR and creep, which can release the stresses built up by the formation of the gel, linear viscoelastic ageing creep is considered in the undamaged part of the concrete. The model validation is performed against accelerated expansion tests by demonstrating the ability of the model to predict the effect of stress state, alkali content, temperature, moisture and drying on ASR expansion. For this model, observation similar to the one stated for Alnaggar et al. (2017) can be drawn. In order to understand the evolution of ASR and its interaction with other phenomena inducing inelastic stains, a complex model formulation is proposed which therefore require a large set of input parameters for its validation and application.

The models based on diffusion–reaction mechanisms aim to explain why and how the chemical reaction leads to the formation of reaction products. They highlight the need of observing the phenomenon at the level of aggregates and pores in the concrete. By postulating the diffusion of alkali ions via the pore solution and the subsequent chemical reaction, phenomena such as the pessimum size effect and the alkali leaching can be explained. It should be noted however that a solid link with the evaluation of the structural response of affected structures is still missing.

## 7. Concluding remarks

Due to the interactive multiscale nature of ASR in concrete structures, various modelling approaches have been developed. Their starting points were formulated at different scales. Considering the adopted techniques, different scopes could be reached, not always allowing an analysis at structural level.

To present an overview of the models for ASR-affected structures, a review of the available models was performed following a novel approach, in which the models were categorised on the basis of their starting scale. The starting scale is identified as the level at which the input parameters are defined. The scope of the models was specified for each approach. In each group, the models were divided, on the basis of the solution techniques, including mathematical, analytical and computational methods.

The literature review is not only an analysis of the various modelling approaches, but it also shows how the focus of the research moved from studying the impact of ASR-induced concrete expansion on the structural response to understanding the chemistry of ASR in concrete material. Considering the ASR-induced concrete expansion as the main driver of the phenomenon has lead to the use of phenomenological approaches, which are not available for the great variety of concrete mixtures, environmental conditions and confinement states. Moreover, the use of phenomenological approaches is risky as long as the interactive multiscale nature of ASR is not yet understood. The first attempts to consider the interaction between phenomena at aggregate and concrete level were the chemo-mechanical models. The definition of a kinetics law linking the concrete expansion to the chemical process is of practical use, but it still needs a more sophisticated formulation for use in structural analysis. On the contrary, if the emphasis is only on the chemical mechanisms, the focus is easily narrowed down to the reaction products level and far from the structural one. Considering complex models for the ions diffusion–reaction processes provides an understanding of the kinetics of ASR and its coupling with other mechanisms leading to inelastic deformations, such as creep and shrinkage. More effort is now required in order to upscale these models for structural analyses.

By analysing the various modelling approaches, it is possible to define some major characteristics for the technique to adopt. A selected technique, even if primarily developed for the aggregate–concrete level interaction, should facilitate down and upscaling to reaction products and structural level, respectively. Theoretical approaches are often employed to describe a particular mechanism, such as the flux of ions or the cracking in aggregates induced by the expansive alkali–silica gel. By their own, they are not able to describe the material and structural effects, but they can smoothly be implemented in other techniques. Computational approaches, which discretise the concrete constituents with FEM, perform detailed simulation of the damage at aggregate level, which can be compared with microscopic observations. Their computational effort is substantial and often is based on a relevant number of input parameters. They can be easily augmented with additional and refined modelling concepts, but their abilities to upscale to structures appear limited. Micro-poro-mechanical models provide an analytically solved approach which accounts for the microscopic aspects at the macroscopic scale. The approach results in a three-dimensional smeared model, which correlates the aggregates and concrete level. The microstructure of concrete is idealised and no direct comparison can be made with laboratory observation. It is a versatile techniques, which can cooperate with theoretical models, for the description of the ASR mechanisms, and with FEM, for the structural analysis.

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