Degradation of the mechanical properties in ASR-affected concrete: overview and modeling

R. Esposito, M.A.N. Hendriks
Delft University of Technology, The Netherlands

Abstract

The Alkali-Silica Reaction (ASR) can generate harmful effects in the concrete structures. In this paper the degradation of the mechanical properties of ASR-affected concrete is studied by comparing the experimental results available in literature. An overview of the macroscopic material modelling approaches related to this aspect is given. Eventually, a 1D crack model is proposed to model structures subjected to swelling. Fracture energy dissipation due to swelling or to external loading is treated in an integrated way.

1. Introduction

During their service life, concrete structures can be affected by chemical degradation processes. One of the most harmful processes is given by Alkali-Silica Reaction (ASR), which produces a hydrophilic and expansive gel. This reaction, which begins at microstructural level, may cause serious damage with consequent loss of structural capacity; the designer must be able to assess the safety at macrostructural level.

The loss in engineering properties is shown for the first time by Swamy in 1988 [1]. In the following years other experimental campaigns [2], [3], [4] are carried out, but, to data, not a clear behaviour can be defined.

In the last 20 years various structural models have been developed and implemented in finite element codes. In early proposals the gel expansion is taken in account with a thermal equivalent approach [5]. More advanced models have been developed by Ulm et al. [6], Farage et al. [7] and Saouma and Perrotti [8]. In each of them the influence of the ASR swelling on the mechanical properties is not thoroughly treated.

In this paper a 1D crack model, on the basis of a literature review, is presented in order to evaluate the degradation process in concrete structures subjected to applied load and/or ASR swelling. An application of the model is given. The model provides a good prediction of the stiffness degradation, but not for the strength development. A comparison with the approach proposed by Saouma and Perrotti [8] results suggests enhancements of the currently proposed model.

2. Overview of experiments regarding the mechanical properties of ASR-affected concrete

Despite many research on concrete structures, the determination of its mechanical properties is still a relevant topic. In ASR-affected concrete, where uncertainty plays a role on the development of its behaviour, the definition of the mechanical properties becomes a critical point. Several test campaigns have been carried out by different authors to define the variation of engineering properties in ASR-affected concretes.
The first tests have been performed by Swamy et al. in 1988 [1]. They concluded that the degradation of the engineering properties, viz. stiffness and strength properties, do not occur at the same rate. This trend is confirmed in all the further experiments. More recent information was provided by Ahmed et al. [3]. To date, this is the most complete test campaign available in literature. More test campaigns are published by Larive [2] and Giaccio et al. [4].

In Table 1 an overview of the mix designs used in the experiments is shown. The majority of the specimens were tested in water at a temperature equal to 38°C; only the specimens tested by Swamy et al. are stored at a temperature of 23°C and 96% of relative humidity. All the specimens are demolded after one day.

The experimental campaigns studied in particular the evolution of the Young’s modulus, the tensile strength and the compressive strength. Mostly it is concluded that the compressive strength is not a reliable parameter to detect the ASR swelling (see e.g. [1]). In fact in some cases an increase of compressive strength is observed. Regarding the Young’s modulus and the tensile strength degradation is observed. Known stress-strain relationships for damage of sound concrete in tension cannot describe the observed behaviour. A further analysis is needed to identify a relationship between the swelling and the loss in stiffness and strength. Therefore in this paper the attention is focused mainly on the evolution of the Young’s modulus and the tensile strength in ASR-affected concrete.
In Figure 1 the expansion vs. time curves are given. The Mix B tested by Ahmed is the most expansive one, with a maximum expansion equal to 2.7%. Instead, the specimens tested by Giaccio and Larive have the smallest maximum expansion: 0.33% for the Mix R2, 0.25% for the Mix R3, 0.14% for the Mix R4 and 0.196% for the Larive’s mix. The specimens prepared with the Mix A of Ahmed and the mix of Swamy show a similar expansive behaviour, the maximum expansion values are 0.73% and 0.63%, respectively.

In Figure 2 the degradation of Young’s modulus and splitting tensile strength vs. the expansion is given. The tensile strength is tested only by Ahmed and Swamy. The Young’s modulus is tested on cylindrical specimens with different sizes: 150x300mm for Ahmed, 100x200mm for Giaccio and 130x240mm for Larive. The splitting tensile strength is tested on cylindrical specimens with diameter 100mm and height equal to 100mm for Ahmed and 200mm for Swamy.

Figure 2(a) shows that the ASR swelling cannot provoke the total degradation of the Young’s modulus. Moreover, a different degradation trend is observed on the basis of the reactivity of the mix: the higher the maximum expansion, the lower the residual stiffness after expansion.

The tensile strength vs. expansion curves (Figure 2(b)) are less revealing than the ones for the modulus of elasticity. In this case it is not possible to identify a clear trend between the tensile strength and the maximum expansion value. Note that the tensile strength is not totally deteriorated when the ASR can be considered as stopped.

In Figure 3 the normalized values of Young’s modulus and tensile strength, obtained from Ahmed’s experimental tests, are presented as a function of the ratio between the ASR expansion strain and the strain which represents the beginning of the concrete cracking phenomenon in case of mechanical loading ($\epsilon_{cr}=f_{cr}/E_{0}$): 

$$\chi = \frac{E_{ASR}}{\epsilon_{cr}}$$

The resulting normalized values $E^*$ and $f_{t}^*$ are defined as the ratio between the current damaged value of the Young’s modulus ($E$) and tensile strength ($f_t$) and their initial values evaluated at 28-days ($E_0$ and $f_t$). It is possible to observe that the degradation of both stiffness and strength occurs at substantially higher strain levels with respect to a sound concrete subjected to a mechanical load ($\chi > 1$). When the reaction can be considered stopped, the residual stiffness is less than the residual strength. This highlights that the two properties degrade at a different rate.

Figure 3: Degradation of mechanical properties vs. the ratio $\epsilon_{ASR}/\epsilon_{cr}$: Normalized values of (a) Young’s modulus and (b) indirect tensile strength.
3. Degradation of mechanical properties in ASR-affected concrete: overview of modelling

The ASR was first identified by Stenton in 1940 [9]. Research was aimed at identifying the factors which provoke and influence the reaction. The process can be divided in two phases: the gel formation and the gel expansion due to water absorption (Dent Glasser and Kataoka [10]). In the second phase the concrete matrix starts to damage and visible cracks can occur. This last phase is more relevant from the macro point of view.

In this section an overview of the structural models is given highlighting the degradation of the mechanical properties.

In early proposals the gel expansion is taken in account with a thermal equivalent approach [5]. In this model the concrete is modelled linear elastic and no degradation law is adopted.

Later, researchers tried to couple the chemical and mechanical aspects of the problem and they started to consider the concrete as a porous material in which the ASR swelling is an internal source. In order to define the evolution of the swelling in time on the basis of the environmental condition several kinetic laws have been developed, but the most adopted one is the one proposed by Larive [2]. This group of models is called chemo-mechanical models. The first one is proposed by Ulm et al. [6].

Ulm’s model defines the concrete as an elastic material with an internal swelling and it delimits the concrete capacity adopting a plasticity’s criterion. The reduction of strength and stiffness is not treated.

This model is enhanced by Farage et al. [7], allowing cracking in the concrete matrix. A ductile post-cracking behaviour is considered on the basis of experimental observations (Figure 4(a)). The strength of the concrete is assumed to remain constant under the expansion. The proposed law is different from the known post-peak law adopted for sound concrete in tension; therefore this model is suitable only for ASR-affected concrete not subjected to critical mechanical loading.

The approach proposed by Saouma and Perotti [8], best known for the modelling of the volumetric redistribution of the swelling in function of the stress state, takes in account the stiffness and strength’s degradation with the following formulation (Figure 4(b)):

\[
E' = 1 - (1 - \beta_E) \xi
\]

\[
f' = 1 - (1 - \beta_f) \xi
\]

where \( \xi \) is the reaction extent coefficient evaluated with the Larive’s kinetic law, \( \beta_E \) and \( \beta_f \) are the corresponding residual fractional values when the expansion is equal to its maximum value. In this model it is possible to define as input two different residual values for the stiffness and the strength.

![Figure 4](image)

Figure 4: Literature information: (a) Ductile post-cracking behaviour proposed by Farage [7]; (b) Degradation law for stiffness and strength proposed by Saouma and Perotti [8].
The macroscopic material models presented above are focused on the swelling process. Less attention is given on degradation of the mechanical properties in ASR-affected concrete as a result of the swelling, perhaps due to the lack of information available in literature.

For an understanding of the structural behaviour of ASR affected concrete structures, it is important to link material damage as a result of ASR with damage as a result of other (mechanical) loading. Consequently models should address stiffness degradation, strength degradation and associated fracture energy dissipation as results of combined ASR loading and mechanical loading. The loading can be in any temporal order. With this in the background, the next section proposes a 1D crack model for ASR degradation in concrete.

4. 1D crack model for ASR-affected concrete

4.1. Experimental observations

Nowadays, the Alkali Silica Reaction has an harmful effect in many bridges, dams and hydropower structures. It can generate a large degradation in stiffness, up to 90%, and strength (Figure 3). In order to model ASR-affected concrete structures, in this section a 1D crack model is presented. Observing the experimental results presented in Section 2, in particular in Figure 3, the behaviour of the stiffness as a function of the strain due to swelling can be described as proposed in Figure 5 [11]. Three zone are identified. The degradation zone is bounded by two point called I and II, which correspond to the strains $\varepsilon_{I}^{\text{ASR}}$ and $\varepsilon_{II}^{\text{ASR}}$. The normalized stiffness $E^*$ is considered constant in zones 1 and 3 and equal to 1 and $E_{II}^*$, respectively. To date, the definition of these three zones and consequently of the parameters $\varepsilon_{I}^{\text{ASR}}, \varepsilon_{II}^{\text{ASR}}$ and $E_{II}^*$ is difficult due to the lack of information available in literature. The behaviour in the damage zone 2 is subjected to discussion. In the following section a hypothesis is given.

![Figure 5: Considerations regarding the stiffness degradation in ASR-affected concrete in free expansion conditions [11].](image)

4.2. Definition of the model

The model is conceived to work for two main situations: sound concrete subjected to mechanical loading and ASR-affected concrete in free expansion condition. In particular, it is focused on the stiffness degradation and the concrete behaviour in tension. The concrete is considered as a porous material and the ASR gel is seen as an internal expansive source. The gel is formed in the pores thanks to the water left by hydration process. When the pores are completely filled, the gel’s expansion is constrained and micro cracks can occur. The presence of these micro damage is confirmed by a degradation in stiffness and strength (Figure 2).
In order to simulate both the behaviour of sound concrete subjected to mechanical load and ASR-affected concrete in free expansion condition, the 1D model in Figure 6 is proposed, as a consequence of the following main observations:

- the model should represent the sound concrete behaviour on the basis of the known stress-strain relationships;
- ASR swelling leads to internal stresses eventually leading to a residual stiffness and strength;
- only a fraction of the ASR swelling results in the degradation of stiffness and strength.

The model (Figure 6(a)) consists of two parallel inelastic springs (first and second branch), both possibly subjected to damage. The ASR swelling is modelled using two stress-free expansion cells. One expansion cell (third branch) is placed in series to the two springs. This cell will result in expansion without causing internal stresses. The other expansion cell causes internal compression and internal tension stresses in the respective parallel chains.

The mechanical effects due to the swelling is considered with a smeared approach and the total strain, \( \varepsilon \), is defined as the sum of the strain due to mechanical load and the strain due to swelling.

The kinetic law proposed by Larive [2] is adopted to define the evolution of the volumetric strain due to swelling as a function of time and temperature:

\[
\varepsilon_{\text{vol}}^{\text{ASR}} = \varepsilon_{\infty} \left( \frac{1 - \exp \left( -\frac{t}{t_c} \right)}{1 + \exp \left( \frac{t - t_l}{t_c} \right)} \right)
\]

(4)

where \( \varepsilon_{\infty} \) is the maximum volumetric expansion and \( t_c \) are \( t_l \) are the characteristic and the latency time, respectively, defined as a function of the absolute temperature \( T \), as proposed by Ulm et al. [6]:

\[
t_c = t_{c0} \exp \left[ U_c / (1/T - 1/T_0) \right]
\]

(5)

\[
t_l = t_{l0} \exp \left[ U_l / (1/T - 1/T_0) \right]
\]

(6)

with \( t_{c0} \) and \( t_{l0} \) the values of the characteristic and the latency time at the reference temperature \( T_0 \) and \( U_c \) (5400±500 K) and \( U_l \) (9400±500 K) their activation energy.

The linear expansion due to the swelling can be defined in agreement with the approach proposed by Sauoma and Perotti [8]. In order to take in account the (lateral) stress influence, the volumetric strain is redistributed along the principal stress directions through weight coefficients:

\[
\varepsilon_{\text{ASR}} = w_i \varepsilon_{\text{ASR}}^m \quad i = 1, 2, 3
\]

(7)

In this paper the attention is focused on the 1D modelling, that is only the situation along one principal direction is considered and the problem is formulated in terms of a linear expansion \( \varepsilon_{\text{ASR}} \).
The overall stiffness of the model is defined as:

\[ E = (1-d_1)K_1 + (1-d_2)K_2 \]  \hspace{1cm} (8)

where \( d_1 \) and \( d_2 \) are damage coefficients, which vary between 0 (not damaged system) and 1 (fully damaged system), defined on the basis of the maximum strains during the load history. Both in the first and second branch a linear tension softening law is assumed to describe the post-peak behaviour (Figure 6(b)-(c)) and the same law is adopted for the damage coefficients (Figure 6(d)-(e)):

\[ d_1 = d(\max\varepsilon_n) \hspace{1cm} \] \hspace{1cm} (9)

\[ d_2 = d(\max\varepsilon_d) \hspace{1cm} \] \hspace{1cm} (10)

Both the damage coefficients, based on the tension softening law, can be expressed as:

\[ d(\max\varepsilon_j) = \begin{cases} 
0 & \varepsilon_j \leq \varepsilon_{cr} \\
1 - \frac{\varepsilon_{cr}}{\varepsilon_n} \left( \frac{\varepsilon_n}{\varepsilon_j} - 1 \right) & \varepsilon_{cr} < \varepsilon_j < \varepsilon_n \\
1 & \varepsilon_j \geq \varepsilon_n 
\end{cases} \] \hspace{1cm} (11)

where \( \varepsilon_j \) is the strain related to the analysed branch.

The expansive cells placed in the first and third branch distribute the imposed strain generated by the ASR swelling in \( \varepsilon_{imv} \) and \( \varepsilon_\alpha \) :

\[ \varepsilon_{imv} = \alpha \varepsilon_{ASR} \] \hspace{1cm} (12)

\[ \varepsilon_\alpha = (1-\alpha + \gamma) \varepsilon_{ASR} \] \hspace{1cm} (13)

where \( \alpha \) is a distribution constant and \( \gamma \) is introduced to compensate that not all imposed strain leads to an overall strain \( \varepsilon \). Variable \( \gamma \) is a function of the degraded stiffness, which expression will be given later.

The strain \( \varepsilon_{imv} \) is now expressed as:

\[ \varepsilon_{imv} = \varepsilon - (1+\gamma) \varepsilon_{ASR} \] \hspace{1cm} (14)

and the strain \( \varepsilon_\alpha \) in the second branch is expressed as:
Based on equilibrium, the overall stress strain relationship is given by:

$$\sigma = E \left[ \varepsilon - \varepsilon_{\text{ASR}} \right] = E \left[ \varepsilon - \left(1 + \gamma - \alpha \right) \varepsilon_{\text{ASR}} \right]$$

Equation (15) combined with Eqs. (8) and (16) now defines a damage dependent macroscopic stress-strain relation with an explicit input of an ASR swelling strain $\varepsilon_{\text{ASR}}$. The damage evolution is defined by Eqs. (9)-(11). In the commonly used displacement based finite element method the strains $\varepsilon$ and $\varepsilon_{\text{ASR}}$ are supposed to be known within each Newton-Raphson iteration. A simple iterative process is needed to solve for the updated damage values ($d_1$, $d_2$) in the range $0 \leq d \leq 1$. Finally Eq. (16) defines the stress update.

### 4.3. Calibration of the model

In order to relate the model’s parameters, $K_1$, $K_2$ and $\alpha$, to the material properties the model is calibrated considering two main situations: sound concrete subjected to mechanical load and ASR-affected concrete in free expansion condition.

In both the situations a straightforward relation can be established between the stiffness’ value in the first and second branch, $K_1$ and $K_2$, and the initial value of the Young’s modulus, $E_0$:

$$E_0 = K_1 + K_2$$

Equation (18) combined with Eqs. (19) and (20) this results in:

$$\alpha = \frac{E_1 + E_2}{E_1} \frac{\varepsilon_{cr}}{\varepsilon_{\text{ASR}}}$$

In the second case the ASR strain is equal to $\varepsilon_{\text{ASR}}^\ddagger$, and the following implication is imposed:

$$\varepsilon = \varepsilon_{\text{ASR}} = \varepsilon_{\text{ASR}}^\ddagger \rightarrow \varepsilon_{\text{u}}(\sigma = 0, d_1 = 1) = \varepsilon_{u,\text{ASR}}$$

Combined with Eqs. (21) and (15) this results in:
\[ \alpha = \frac{\varepsilon_u}{\varepsilon_{u_{ASR}}} \]  

(22)

Hence two equations for the distribution constant \( \alpha \) are found (Eqs. (20) and (22)), which leads to:

\[ \frac{K_1}{E_{II}} = \frac{\varepsilon_{II}^{u_{ASR}}}{\varepsilon_{u_{ASR}}} \frac{E_{II}}{E_u} = \varepsilon_{II}^\varepsilon \]  

(23)

Eq. (23) shows that the residual fractional stiffness, \( E_{II}^\varepsilon \), is a result of the proposed model and it is not a material parameter. The material parameters are the strains which delimit the degradation process of the mechanical properties due to mechanical load, \( \varepsilon_{cr} \) and \( \varepsilon_u \), and ASR swelling, \( \varepsilon_{I_{ASR}} \) and \( \varepsilon_{II_{ASR}} \). In conclusion, the three model’s parameters, \( K_1 \), \( K_2 \) and \( \alpha \), can be calibrated to material properties as:

\[
\begin{align*}
K_1 &= \frac{\varepsilon_{II}^{u_{ASR}}}{\varepsilon_{u_{ASR}}} \frac{\varepsilon_{II}}{\varepsilon_u} = E_{II}^\varepsilon \\
K_2 &= E_u - E_{II} = \left(1 - E_{II}^\varepsilon\right) E_u \\
\alpha &= \frac{\varepsilon_u}{\varepsilon_{II}^{u_{ASR}}} = \frac{1}{E_{II}^{\varepsilon}} \frac{E_u}{\varepsilon_{II}} 
\end{align*}
\]  

(24)

5. Application of the model

The model is adopted to simulate the stiffness and strength’s degradation of the Mix B analysed by Ahmed [3]. In Table 2 the material parameters of the model are given. The ultimate strain of the concrete is evaluated considering a crack distance of 30 mm [3]. The evaluation of the normalized residual stiffness value \( E_{II}^\varepsilon \) through Eq. (23) results in agreement with the experimental observations (Figure 5).

In Figure 7 the results obtained by the proposed model are compared with the experimental ones. In order to make a clear comparison, in the bottom part of the graphs the normalized values of stiffness (Figure 7(a)) and strength (Figure 7(b)) are given, whereas in the upper part the reaction extent coefficient is shown. The results are further compared with the Saouma and Perotti formulation (Eqs. (2)-(3)) [8]. In this approach the stiffness and strength’s residual values, \( \beta_E \) and \( \beta_f \) (which are equal to \( E_{II}^\varepsilon \) and \( f_{II}^\varepsilon \) in the adopted notation), are defined by experiments and used as inputted material parameters. In this case, they are assumed equal to 0.10 and 0.60, respectively.

| Table 2: Material properties of Mix B tested by Ahmed. |
|-----------------|-----------------|-----------------|-----------------|
| **Name**        | **Symbol**      | **Value**       | **Source**      |
| Young’s modulus | \( E_0 \)       | 21130 N/mm²     | Value at 28-day [3] |
| Tensile strength| \( f_{t0} \)    | 1.44 N/mm²      | Value at 28-day [3] |
| Compressive strength | \( f_{c0} \) | 41.0 N/mm²      | Value at 28-day [3] |
| Fracture energy  | \( G_f \)       | 0.147 N/mm      | \( G_f = 0.073 f_{c0}^{0.18} \) [12] |
| Cracking strain  | \( \varepsilon_{cr} \) | 6.81 10⁻⁴ | \( \varepsilon_{cr} = \frac{f_{t0}}{E_0} \) |
| Ultimate strain  | \( \varepsilon_u \) | 6.88 10⁻³ | \( \varepsilon_u = \varepsilon_{cr} + \frac{2G_f}{f_{c0}} \) |
| ASR strain at point I | \( \varepsilon_{I_{ASR}} \) | 1.20 10⁻ⁱ | Figure 5 |
| ASR strain at point II | \( \varepsilon_{II_{ASR}} \) | 1.32 10⁻² | Figure 5 |
| Residual fractional stiffness | \( E_{II}^\varepsilon \) | 0.11 | Eq. (23) and Figure 5 |
| **Model’s parameter** | | | |
| Stiffness in the first branch | \( K_1 \) | 2326 N/mm² | Eq. (24) |
| Stiffness in the second branch | \( K_2 \) | 18803 N/mm² | Eq. (24) |
| Distribution constant | \( \alpha \) | 0.52 | Eq. (24) |
The proposed model provides a good prediction of the stiffness degradation (Figure 7(a)); the initial delay in the degradation as well as the residual stiffness are well predicted. The degraded behaviour of the strength (Figure 7(b)) is not well modelled, especially its residual value. This is because the same assumption is adopted for the residual fractional value of stiffness and strength ($E = f$).

The Saouma and Perotti formulation allows the definition of two different residual fractional values for the two parameters, therefore the degradation of stiffness and strength is well predicted for expansion strains close to the maximum value. However this approach cannot predict the initial delay of the degradation and overestimates the structures’ degradation during the reaction development.

6. Conclusion

In this paper the attention is focused on the degradation of the mechanical properties due to ASR swelling. An overview of experimental tests and macro modelling is given. The experiments show a strong reduction in terms of stiffness and strength due to swelling. These properties degrade at different rates. Observing the experiments of Ahmed [3] regarding the Young’s modulus, the stiffness degradation process, due to ASR swelling, can be divided in three phases. At the beginning the stiffness is constant and its degradation starts at substantially higher strain levels compared to a sound concrete subjected to mechanical load. In the second phase the degradation occurs, but the ASR does not result in a complete deterioration. Therefore, it is possible to observe a third phase in which the stiffness remains constant even if the swelling process it still active. This third phase is especially evident for high-reactive mixes. These observations suggest introducing new material parameters to define the degradation of the mechanical properties due to ASR swelling. Due to the lack of information available in literature, these parameters cannot be defined yet.

Eventually, a 1D smeared crack model is presented. This model is suitable for both sound and ASR-affected concrete. It is formed by three branches, two placed in parallel and third one placed in series with the previous two. Stress-free expansion cells are introduced to model the imposed strain due to swelling. The equilibrium between the gel and the concrete skeleton in free expansion condition is provided from the two springs placed in parallel. Two damage cells are introduced to define the degradation due to mechanical load and swelling. The concrete is considered to be subjected to external and internal damage sources, therefore its mechanical properties are based on sound concrete and additional parameters are defined to characterize the ASR-affected concrete.

The model is used to simulate the degradation in stiffness and strength for mix B analysed by Ahmed [3]. The comparison provides a good results in terms of stiffness. The model cannot predict completely the behaviour in terms of strength degradation, because the same residual fractional value for stiffness and strength is adopted. The comparison with the approach proposed by Saouma and Perotti [8] suggests that two different values should be taken in account. This aspect is left for a future enhancement of the proposed model.

In conclusion, the 1D crack model can be adopted to model a brittle material like ASR-affected concrete. Future research focusing on additional experimental results, like the ones by Ahmed [3], and on micromechanical modelling, are suggested.
References


