Air permeability of concrete damaged by Alkali-Silica Reaction (ASR)

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RESUME Les professionnels chargés des tests de durabilité du béton sont confrontés à un défi majeur : prédire et évaluer les propriétés de transfert du béton affecté par les Réactions de Gonflement Interne (RGI), telles que la Réaction Alcali-Silice (RAS). Dans ce contexte, l'objectif de cette étude est de mesurer l'évolution de la perméabilité à l'air du béton en fonction du développement de la RAS, pour différents niveaux d'expansion et de saturation. Les premiers résultats obtenus montrent que le développement de la RAS et des fissures induites conduit à une augmentation de la perméabilité à l'air des bétons, en particulier dans les bétons saturés. Les données de cette étude permettent d'évaluer l'évolution des propriétés de transfert en fonction de l'expansion générée, de la fissuration induite et du degré de saturation du béton.

Mots-clefs Durabilité, Perméabilité, Expansion, RAS.

I. INTRODUCTION

Internal Swelling Reactions (ISR) are endogenous and deleterious chemical reactions that cause pressure in concrete, leading to the creation of cracks in the material and in the affected structures. In the literature, most studies characterized the evolution of mechanical properties with expansion, but few are interested in transfer properties. It has been shown that even if these reactions lead to a reduction in the mechanical properties of the concrete, they do not necessarily lead to a decrease of their mechanical safety (Morenon et al., 2019). However, the induced cracking naturally impacts the durability of the material. The transport properties of concrete play a key role in predicting the durability of concrete structures (Basheer et al., 2001) ; (Abbas et al., 1999) ; Ollivier et al., 2012). In the case of structures with a containment function, the quantification of changes in permeability caused by the development of the ISR is necessary. Gas permeability also allows, as a characteristic indicator, the evaluation of the sustainability potential of the structures affected, regardless of their function.

On site, the degree of saturation of the core of massive structures and the concrete cover subjected to rain is often high (upper than 80%) (Stark., 1992). With climatic variation, saturation of structural concrete varies between 30 and 80%. For a saturation rate exceeding 60%, air transfer is minor in ordinary concrete due to the continuity of the liquid phase (Abbas et al., 1999). Besides, the Kelvin Laplace equation shows that a crack with an opening larger than one micrometer will be drained even at a very high saturation rate (99.99%). Knowing that the air permeability of concrete is largely influenced by its degree of saturation (Abbas et al., 1999) ; (Monlouis-Bonnaire et al., 2004) ; (Carcassès et al., 2001), it is relevant to carry out measurements on different saturation rates of cementitious materials damaged by ASR.

The aim of this study is to experimentally characterize the interaction between the physico-chemical state and the transport properties of damaged cementitious materials. The measurements are carried out on concretes affected by Alkali-Silica Reaction (ASR) in order to represent different types of expansion and different cracking pattern. Permeability measurements should be taken at several well-defined times to judge the effect of cracking connectivity and also their state of filling by reaction products.

II. MATERIALS AND METHODS

A. *Concrete mix design and pre-conditioning*

In the present study, one type of concrete was studied: T11 which is used to obtain concrete developing ASR. The water-to-cement ratio (w/c) was of 0.56. The cement adopted for the realization of the concrete mix is CEM II A-LL 42.5 R CE PM-CP2 NF from the Airvault cement plant.

For Alkali-Silica Reaction, concretes were made using different type of aggregates:

- A non-reactive (NR) 0/4 mm calcareous limestone sand from France, Boulonnais quarry (2650 kg/m^3; water absorption 0.5%)
- Potentially reactive (PR) (4/14 and 14/20 mm) aggregate formed of silica and limestone from the North of France (density 2660 kg/m^3; water absorption 0.5%; reactive silica content 7%)

The concrete was made without any admixture. The mixing water was doped with NaOH in order to obtain an equivalent alkali content of 5 kg/m^3.

TABLE 1 presents the concrete mix used for concrete affected by ASR.

TABLE 1. T11 concrete mix (kg/m^3)

Ciment CEM II	Calcareous aggregate	Silica and limestone aggregate		Water	Na_2O_{eq}
	0/4 mm	4/14 mm	14/20 mm		
350	772	316	784	195	5

In this study, the choice was made to adopt the ASR degradation strategy proposed by IFSTTAR (Méthode d'essai n°44., 1997).

For conditioning and preserving concrete that undergoes alkali-aggregate reaction, an endogenous curing method was used for the first 28 days. At the end of the curing period, all specimens were immersed in water at 38°C. This temperature was chosen because it is standardized, as immersing the specimens in water at 20°C could slow down swelling reactions for several years. A pump was used to homogenize the solution in terms of temperature and ionic species present in the water.

B. Experimental techniques

For this work, swelling monitoring was carried out on cylindrical specimens (Ø11xh22 cm), and permeability measurements were performed on cylindrical specimens (Ø15xh5 cm).

- Expansion monitoring

The evolution of ASR was characterized by the concrete expansion. The monitoring of these expansions was based on longitudinal deformation measurements of the specimens using an extensometer. For this purpose, 6 stainless steel studs were glued in pairs to obtain 3 expansion measurement according to the height of the specimen. The pairs of studs were spaced 10 cm apart (deformation measurement basis) at equal distances from the mid-height of the specimen. The three measurement lines were separated by 120° on the lateral surface of the specimen.

- Permeability measurement

The air permeability measurements of the cylindrical samples were performed using a Cembureau type constant permeameter according to the standard (XP P18-463, 2011). In order to obtain a satisfactory accuracy of the intrinsic permeability, the Cembureau test includes four measurements of apparent permeability on four injection pressures applied for each measurement ranging from the following values: 1, 2, 3 and 4 bars (0.1, 0.2, 0.3 and 0.4 MPa) for three different samples.

The apparent permeability is obtained according to the following equation (Kollek., 1989):

$$k_A = \frac{Q_S}{S}\frac{2\mu L P_S}{(P_e^2 - P_S^2)} \tag{1}$$

With: k_A the apparent permeability (m^2), Qs the volume flow (m^3/s), μ the dynamic viscosity of the air (Pa.s), L the thickness of the sample, Ps the absolute pressure at the outlet (Pa), S the section of the sample (m^2) and Pe the absolute pressure at the inlet (Pa).

The degree of saturation of the concrete has a strong influence on the air permeability (Monlouis-Bonnaire et al., 2004) thus, six states of saturation were selected (80, 60, 40, 20, 3 et 0%) to perform the permeability measurements. In our study, the choice of the drying temperature was very delicate to minimize it's effects on the microstructure of initial and damaged concrete. Thus, for the drying methodology, it was proposed to apply drying by steps of increasing temperature as presented in TABLE 2.

TABLE 2. Conditioning protocol followed in this study

Saturation rate (%)	Drying temperature (°C)
From 100 to 30	40
From 30 to 20	50
From 20 to 3	80
From 3 to 0	105

This approach reduced the moisture gradients which can induce shrinkage gradients. Such gradients can be the cause of microcracking of the specimens during preconditioning. At the end of each drying and just before the permeability measurement, a homogenization of the concrete saturation is applied (at least same duration than drying) (Carcassès et al., 2001). This step helps to unify the saturation within the sample trying to obtain homogeneous permeability in concrete.

III. EXPERIMENTAL RESULTS

A. ASR expansion

FIGURE 1 shows the deformation of the two concretes after immersion in water at 38°C.

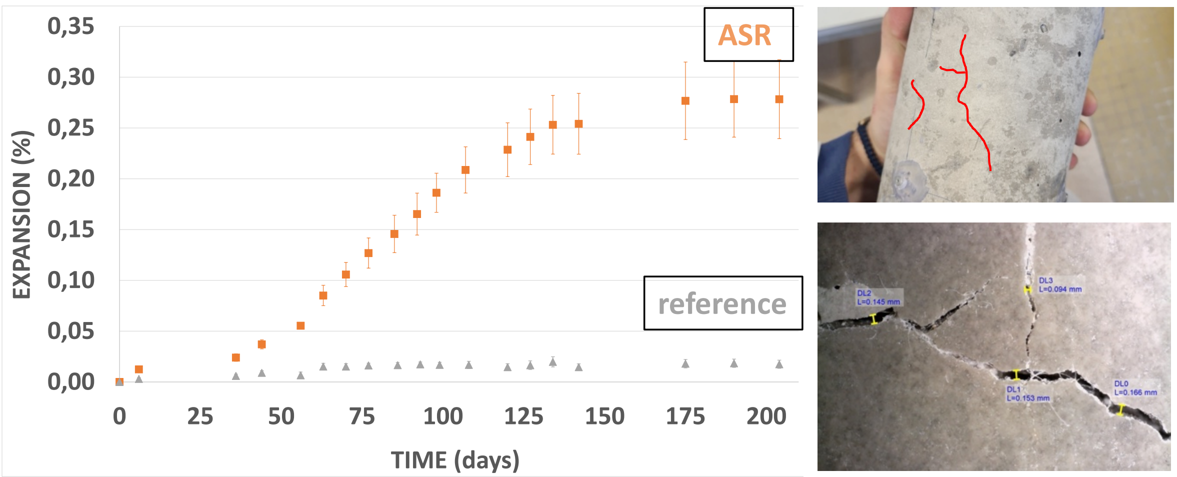

FIGURE 1. **Deformations of concrete as a function of time**

The reference concrete showed only slight water-induced swelling (water intake between the endogenous curing state and water immersion).

After 36 days of immersion in water at 38°C, the deformation rate of the concrete affected by ASR changed from the latent period (small expansion, comparable to water intake) to the acceleration phase (significative expansion). This acceleration phase lasted about 100 days before entering in the stabilization period. The maximum expansion reached was approximately 0.27%.

B. Permeability of concrete damaged by ASR

Air permeability was measured at six states of saturation (80, 60, 40, 20, 3 et 0%) for all samples. As an example, FIGURE 2 shows the apparent permeability of the concrete developing ASR as a function of the inverse of the mean pressure Pm for a degree of saturation of 40%. It is first important to note that the linearity of the apparent permeability with the inverse of pressure (Klinkenberg's law) was not modified by the apparition of the cracks due to ASR.

For the other degrees of saturation, similar results were obtained. The apparent pressure for an inlet pressure of 2 bars are given in the following part for the discussion of the results.

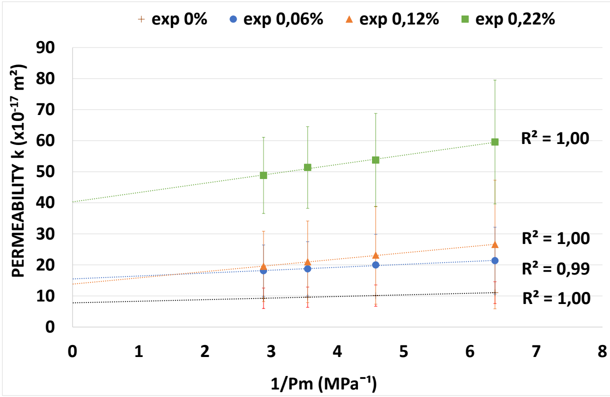

FIGURE 2. Permeability measured ASR-affected concrete for a saturation degree of 40%

For this saturation degree of 40%, the apparent permeability presents an important increase even for a small expansion. At 0.06% of expansion, the apparent permeability was twice the permeability of the concrete without damage (11.1×10^{-17} m^2 for an inlet pressure of 2 bars). The permeability continued to increase with expansion until reaching 5.4 times the permeability at initial state for an expansion of 0.22% (59.6×10^{-17} m^2). The intrinsic permeability for 0.06% of swelling is slightly higher than for 0.12%. It can be explained by the increase of the measurement dispersion with the level of expansion. This increase was due to the apparition of cracks with larger opening in some specimens. Similar behavior was noticed for the other saturation degrees but with different levels of modification of the permeability as discussed in the following part. The air permeability was strongly impacted by the level of ASR-expansion and by the induced cracking.

IV. SYNTHESIS AND DISCUSSION

FIGURE 3 shows the evolution of the permeability for an inlet pressure of 2 bars (k_{2bars}) of ASR-affected concrete as a function of the degree of saturation for the different levels of swelling.

As for usual concrete (Abbas et al., 1999), the air permeability increased nonlinearly with the decrease of the saturation level due to the opening of the pore network by the water departure. When reaching a low saturation rate (less than 3%), the strong increase of permeability testifies a stronger damage due to preconditioning.

In the case of concrete without damage, a very low permeability was detected for a degree of saturation equal to or higher than 60% as usual for such concretes (Abbas et al., 1999) which remain impermeable for high saturation levels. At the opposite, for damaged concrete, an expansion of only 0.06% was sufficient to reach an apparent permeability of about 12×10^{-17} m^2 at 80% of saturation, similar to the permeability of the concrete without damage at 40% of saturation. This only result points out the significant effect of ASR cracking on air permeability of concrete with high saturation degree.

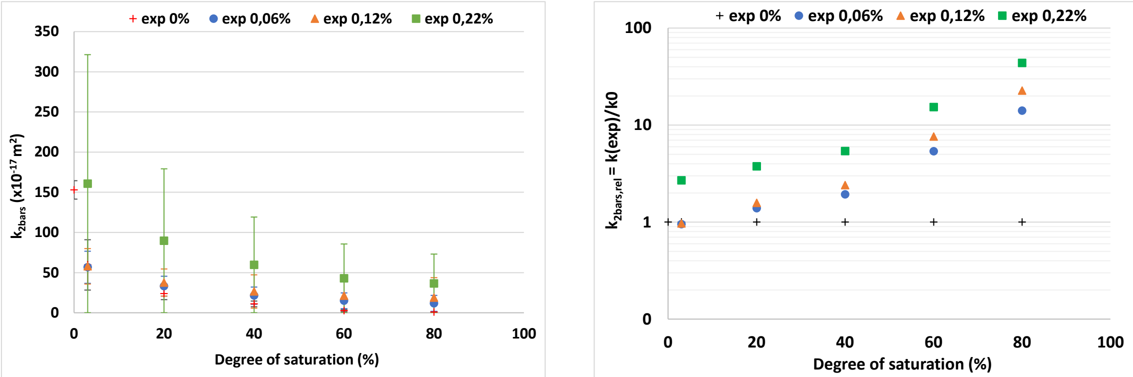

FIGURE 3. Evolution of the gas permeability and the relative permeability of a concrete affected by the ASR for different levels of expansion as a function of the degree of saturation

The difference of permeability between the sample without expansion and the samples with level of expansions of 0.06% and 0.12% was quite constant for the saturation degree upper than 20%. The main differences occurred for the saturation degree of 80%. At this saturation, the cracks induced by ASR were already emptied of water and an important air flow can cross the concrete by these cracks. For lower saturation degree, the small evolution of permeability was due to the drying of the initial pore network of concrete. The impact of the cracks on the evolution of the permeability was negligible in this domain of saturation.

For expansion of 0.22%, the effect was still greater. For this expansion, the decrease of the saturation degree leads to a most important increase of permeability in the damaged concrete. In this case, the shrinkage induced by drying can increase the opening of the cracks induced by ASR and thus leads to the permeability evolution.

From the same results, FIGURE 4 presents the evolution of the air permeability of ASR concrete for different levels of expansions according to the degree of saturation.

The increase of the air permeability with the increasing level of expansion was almost linear for concrete at high saturation degree (upper than 60%). The evolution of the permeability with the expansion becomes nonlinear for drier concrete. For saturation degree lower than 40%, the evolution was still quite linear for expansion level lower than 0.12% but nonlinearity appears for the largest expansion studied in the present work (0.22%).

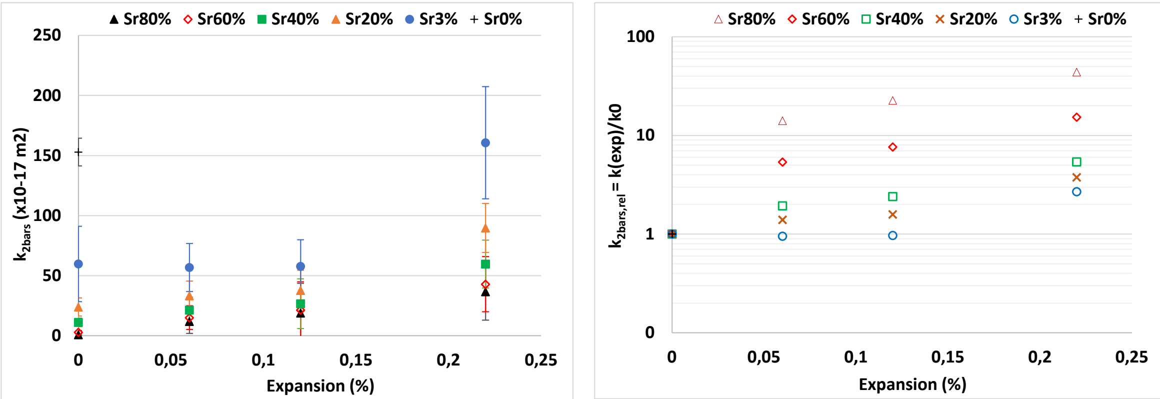

FIGURE 4. Evolution of the gas permeability and the relative permeability of a concrete affected by the ASR for different degree of saturation as a function of the expansion level

For permeability obtained on samples dried at 80°C (usual conditioning for air permeability measurement), the evolution of the permeability is null for expansion lower than 0.12% while cracks were always visible on the external surface. This result shows the importance of the saturation degree to characterize the cracks due to ASR by air permeability measurement. For too low saturation degree, the preconditioning strongly affects the concrete by thermal damage that results in bridging between wide open internal cracks. Then, the impact of the preconditioning takes too much importance compared to the effect of cracking induced by ASR, which can no more be quantified.

V. CONCLUSION

The safety requirements of reinforced concrete structures are not limited to the mechanical stability of these structures under various stresses. Indeed, the air-tightness of civil engineering structures is an essential and often requested additional requirement to ensure the maintenance of containment in case of a mechanical accident or chemical attack. This experimental program is a first tentative to quantify the effect of ASR on the air permeability of concrete in saturation conditions representative of real massive structures. The effect of cracking on air permeability has been well studied in the literature, but few of these studies evaluated the impact of the saturation degree on this effect. The permeability of concrete damaged by ASR evolves nonlinearly with the level of expansion and the saturation rate of the sample. Thus, the present work shows how the saturation degree can amplify the consequence of cracking on the increase of permeability. Concrete at 80% of saturation is usually impermeable as its pore network is closed by water. However, the same concrete can become permeable if it is damaged by ASR, even for small expansion since the induced cracks with an opening greater than 1 μm are emptied of water even for very high saturation. Next, the results presented in this paper will be analyzed in regard to the evolution of mechanical properties to obtain correlation useful to improve the modelling of damaged structures.

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