Probabilistic Modelling of Containment Building Leakage at the Structural Scale: Application to the PACE Mock-Up

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Abstract. This work follows studies conducted in the framework of the French research program MaCEnA (PIA), aiming to predict air leakage through a reinforced (and prestressed) concrete structure. As mentioned by the international Benchmark VeRCoRs, only very few teams were able to predict them and variations of at least one order of magnitude between participants were observed.

Reinforced concrete tightness estimation is of the utmost importance for confinement vessels but also to assess concrete structures durability. One of the reasons for these difficulties lies in the fact that air leakage prediction is the last step of complex, multiphysics and coupled simulations. On the one hand, to predict concrete permeability, saturation evolution of the porous network needs to be correctly addressed. On the other hand, cracks predictions (numbers, openings, and appearance time) is essential but not sufficient since roughnesses, tortuosities and connectivities of these latter also strongly influence the leakage rate.

After a first part showing the capacity of the used model to mimic the behavior of a structural representative volume, this contribution quantifies the effect of the use of autocorrelated random fields modelling the tensile strength on the concrete structural leakage prediction. The results highlight that the air leakage prediction can easily vary by one order of magnitude for the same random field parameters. Moreover, during mechanical loading, observation of the cracks evolutions (numbers, openings and positions) allows for quantifying the prevalence of material and structural heterogeneity and explains the sudden evolution of leakage rate.

Keywords: Reinforced concrete · Leakage · Stochastic finite elements · Autocorrelated random fields

1 Introduction

Despite the recent progress of the last decade and especially during the French research program MaCEnA (PIA), accurate prediction of air leakage through a reinforced (and

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prestressed) concrete structure remains a difficult question. Indeed, as mentioned by the international Benchmark VeRCoRs (phase 2) restitution report, only very few teams are able to predict them and variations of at least one order of magnitude between participants are observed [1]. Even when global leakage is quite well predicted, the repartition between localized leakage (through cracks for instance) and diffuse one (through the porous network of cementitious material) is poorly estimated. Reinforced concrete tightness estimation is of the utmost importance for confinement vessels but also to assess concrete structures durability.

One of the reasons for these difficulties lies in the fact that air leakage prediction is the last step of complex, multiphysics and coupled simulations. On the one hand, to predict concrete permeability (i.e. flow through the connected porous media), saturation evolution (in time and space) of the porous network needs to be correctly addressed as well as the description of the porous network. On the other hand, cracks predictions (numbers, openings, and appearance time) are essential but not sufficient since roughnesses, tortuosities and connectivities of these latters also strongly influence the leakage rate. Moreover, localized phenomena (cracking) and continuous ones (stresses, strains, saturation) are strongly coupled. Indeed, saturation evolution (generating shrinkage), creep strains, early age behavior, mechanical stresses could lead to localized cracks due to reinforced concrete heterogeneity (material or structural ones). The most frequent technique employed to account for the heterogeneous nature of concrete at the structural scale is random field generation applied to one (or more) concrete behavior parameter.

This contribution aims to quantify the effect of the use of autocorrelated random fields modelling the tensile strength on the concrete structural leakage prediction. On the contrary to structural tests that are very expensive and cannot be reproduced, numerical simulations can be performed for many realizations of the same random field. In this contribution, the results of more than 50 simulations (for 2 different random fields) of a RSV (representative structural volume) involving rebars and prestressed tendons and based on a real structural experiment [2] will be analyzed. For this calculation, regularized damage model is used and the leakage rate results from the mechanical fields (damage and strains) post-processing through the recently developed coupling law between damage and leakage that could consider leakage rate evolution during cracks closure [3]. The first part of this contribution presents a deterministic calculation which considers the ageing of the concrete structure whereas the second part aims at studying the effect of heterogeneity (structural ones i.e. prestressed cables tubes and material ones i.e. concrete heterogeneous nature).

2 Deterministic Leakage Prediction of a Structural Representative Volume

2.1 PACE Mock-Up Brief Description

The PACE mock-up is a facility to study the Representative Structural Volume (RSV) in the standard zone of a nuclear power plant (PACE: “PArtie Courante de l’Enceinte” in French) and was built in a collaboration between the EDF R&D department and the MPA Karlsruhe (Materials testing and Research institute of the Karlsruhe Institute of Technology (KIT)). With realistic dimensions (see Fig. 1), the specimen is loaded similarly to a closed ring under internal pressure.

The reinforcement layout of the specimen mainly consists of rebars meshes near the intrados and extrados surfaces and four pre-stressing cables in the tangential direction. During the tests, the specimen is under a pressure of up to 6 bars (absolute term) that simulates the overpressure scenario in an accidental condition. The resulting pressure (Chaudronnier's equivalent pressure) is applied to the circumferential direction by mean of 128 GEWI's rebars connected to ears and tensioned by hydraulic jacks. As mentioned before, the specimen is post-tensioned by four tendons. The pre-stressing level was decreased over time in order to accelerate the pre-stressing losses and thus to simulate the aging of the structure. In addition, one pre-stressing cable in the original vertical direction is placed before concrete's pouring but without any pre-stressing force. Therefore, in order to simulate the pre-stressing of the containment in the original vertical direction, steel cushions, which were set under a pressure of up to 1 MPa, are placed on the original top and bottom surfaces of the specimen (please refer to [4–6] for more details about the mock-up).

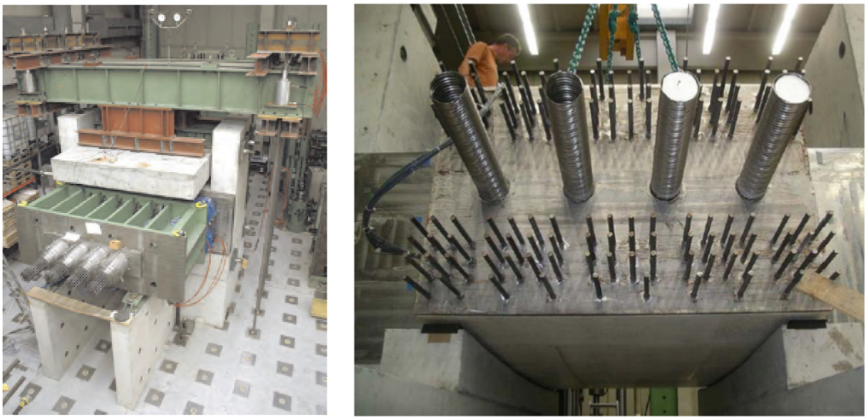

(a) (b)

Fig. 1. Pictures of PACE mock-up in Karlsruhe Institute of Technology: global view (a), side view before adding the loading device (b)

Regularly, pressure tests were performed to check of the leakage tightness of containment in France. These lasts were reproduced on the experimental mock-up and each pressure test is called RUN. As a result of some of these RUNs, especially RUNs 4, 5 and 6, cracking patterns appear on the extrados side (see Fig. 2). The black cracks, propagating horizontally, results from flexure loading, whereas the red ones, propagating vertically, are crossing cracks and are supposed to be the preferential paths for most of the leakage.

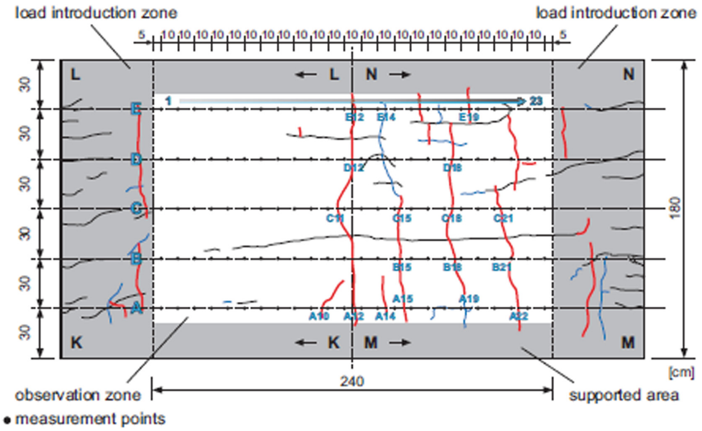


Fig. 2. Cracking extrados pattern after the RUN 4 [5]

2.2 Finite Element (FE) Model

The strategy described in Fig. 3 is based on a weakly coupled thermo-hygro-mechanical FE model. In this study, early age behavior is not considered and there is no experimental temperature evolution so the thermal part is not considered. The hydric model is based on phenomenological macroscopic model [7–9] with Neumann boundaries conditions type and the relationship between the relative humidity and the water content is the one defined by Thiery *et al.* [10].

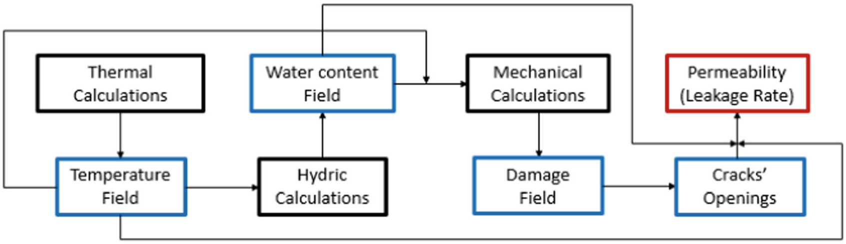


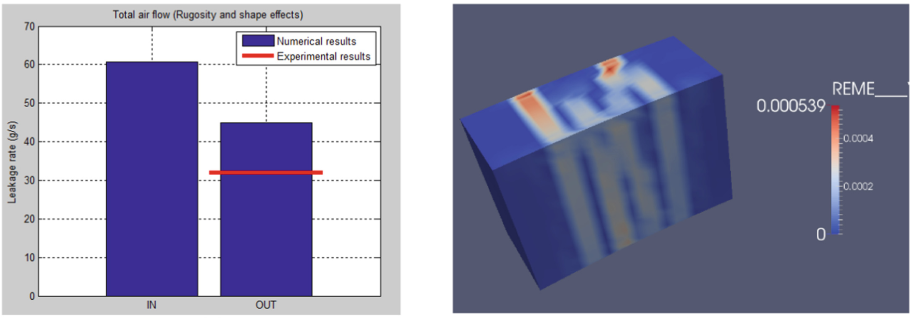
Fig. 3. Numerical THM weakly coupled (staggered) strategy to compute the global leakage

The mechanical model is based on strains partitioning and the total strain is the sum of thermal strains, desiccation strains, creep strains and elastic strains. This latter is used to compute the damage variable based on Mazars model. Please note that a part of the creep strains is also considered to calculate the Mazars equivalent strains. Finally, since the damaged model used is a local one regularized by fracture energy, the cracks (discontinuities) can be post-processed from the damage field using the approach of [11]. A reduction of the tensile strength of the concrete is also applied using a size effect law [12]. A more detailed description of the model used can be found in [13].

The global leakage rate can be seen as a post-processing of both hydric state of the porous media and the flow through the cracks. Indeed, in absence of cracks (or between two cracks) the flow is governed by the apparent permeability highly dependent of the saturation rate (the relation defined by [14] is used in this study). Through the cracks, the matching law defined by [3] based on an original idea of [15] is used to allow the possible decrease of the flow when the crack opening decreases.

2.3 Crack and Leakage Comparison

With this model and after the simulation of the mock-up life, including ageing through the drying and the decrease of prestressing, the comparison between predicted and experimental leakages for the run 6 is displayed on Fig. 4a. The predicted leakage slightly overestimates the experimental one. The comparison between numerical flow in and flow out also shows that even if the comparison is made on the experimental pressure plateau, the steady-state is not numerically completely reached.



(a) (b)

Fig. 4. Comparison between numerical results in terms of global leakage (a) and final damage pattern (REME = crack opening in meters).

Looking at the cracking pattern (Fig. 4b), the crack position is clearly different with respect to the experimental crack pattern but the number of damaged zones (that represent in a more diffuse manner the cracks) is comparable. It is nevertheless worth noting that simplifications were made on the geometry (empty vertical prestressing tube was not represented) and that the mesh is rather coarse (to decrease computation time). Moreover, a random field was applied to the damage strain threshold to avoid damage diffusion but the field variability is very small and is not representative of the heterogeneous material behavior.

3 Probabilistic Leakage Prediction of the RSV

3.1 Stochastic Finite Element (SFE) Model

To study the impact of the heterogeneous nature of the concrete and to consider the structural heterogeneity (namely the presence of an empty prestressing vertical and horizontal tubes), a Gaussian random field (RF) is arbitrarily chosen to model the tensile strength of the concrete. Gaussian autocorrelation function and two coefficients of variation are considered (Table 1). SFE simulations were performed on a thinner mesh but with a simplified loading path. Indeed, the numerical PACE mock up is only submitted to a tangential tension and permeability evolution during loading (quasi-instantaneous one) is computed. As for the deterministic simulation presented in the part 2, the reinforcements are modelled using bars elements that coincide with the concrete mesh. Only a half of the total specimen is meshed. A total of 56 realizations of both RFs were performed.

Table 1. Parameter of the random fields used.

Random field number	Tensile strength mean value [MPa]	Autocorrelation length [m]	Coefficient of variation [%]	Number of realizations
1	2.5	30	10	30
2	2.5	30	15	26

Figure 5 displays the obtained crack opening field for one realization just after the first crack. It should be highlighted here that the first crack always appears at the center of the RSV due to the presence of the empty prestressed tube which creates a strong heterogeneity (at least stronger than the one created by the random field).

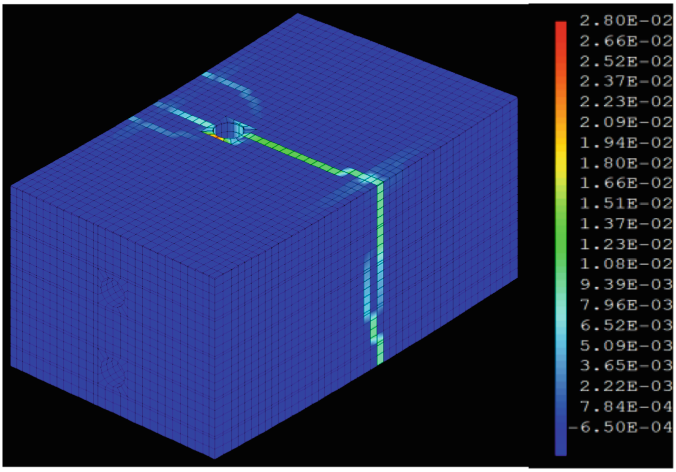


Fig. 5. Crack opening [mm] field just after the damage of the first finite elements

3.2 Crack and Leakage Results

Figure 6 gathers the results of permeability evolution for the 26 realizations with the 2nd random field (similar results are obtained with the first one). One can notice that the global trend is the same but that the final permeability (presented here as the ratio with respect to the initial one) can differ from at least one order of magnitude. The total flow cannot be directly compared to the experimental one because this probabilistic study only considers the evolution of flow through the cracks (permeability evolution of the porous media due to drying is not considered) but interesting feature can be deduced from this graph.

Firstly, some permeability sharp decrease during the loading progress. This decrease is attributed to secondary cracks that relax stress state of the rebars close to the location on previous cracks. Consequently, even if the total applied displacement is close to be the same between two successive time steps, the total crack opening is divided into two (or more) crack openings. As the flow through the crack is directly proportional to the cube of the crack opening (following Poiseuille law), the total flow decreases. In other words, in term of tightness, two cracks slightly open is preferable to one crack largely open.

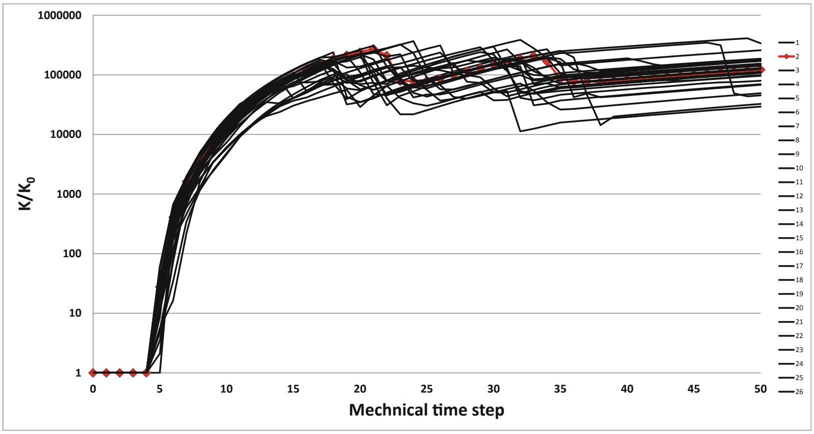


Fig. 6. Evolution of relative permeability (initial permeability $K_0 = 1.e{-}17$) versus the mechanical loading.

Crack pattern analysis also brings important information. Indeed, the crack number and crack position strongly evolve from one realization to another. For most of the realizations, we can consider that we have obtained the steady state cracking regime (i.e. the spacing between two cracks is not sufficient to create a new crack and increasing the loading will only lead to an increase of cracks opening) and the crack number varies from 3 to 5 (for most of them 14 under 26 realizations, 4 cracks appears). The case n°2 (in red on the Fig. 6) is a special one. Indeed, the experimental crack pattern shows four cracks on the same side of the mock-up raising immediately the issue of the real symmetry of the boundary's mechanical conditions.

Figure 7 presents the damage pattern and the crack opening field obtained on the PACE extrados for this special case. The damage field is slightly diffuse (especially close to the rebars) but the crack opening field clearly shows four cracks on the same specimen side. Cracking along the rebars also started indicating that we have reached the cracking steady state regime. Although this special case is not a proof that the symmetry of experimental boundaries conditions was achieved, it shows that with a relatively small number of realizations, with a random field applied only on tensile strength and for a reasonable coefficient of variation, complete dissymmetry of the cracking pattern can be observed.

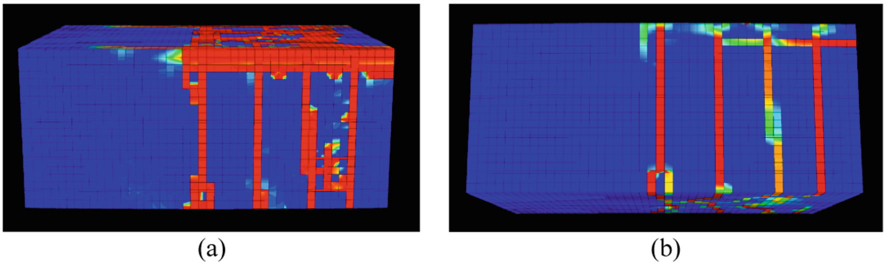

(a) (b)

Fig. 7. Damage field (a) and crack opening field (b) for the case number 2

Figure 8 displays histograms of the final relative permeability, highlighting relative and cumulated distributions and a Gausian probability density function (PDF) fitting relative frequencies. It is interesting to remind that the input RF was Gaussian. It probably explains this Gaussian trend, but with a larger dispersion (CoV ~53%).

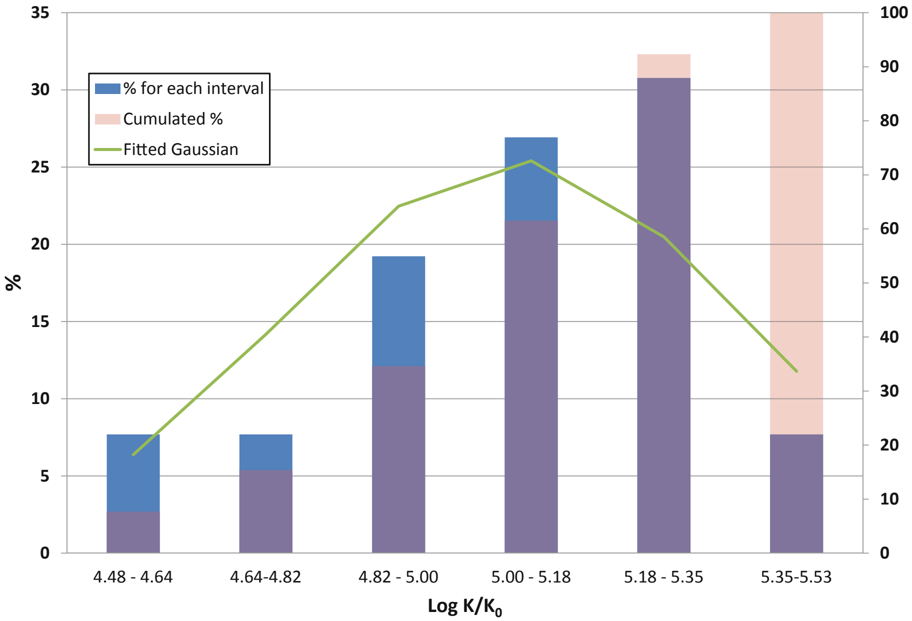


Fig. 8. Histogram of the relative final permeability

4 Conclusion

In this paper, simulations of the PACE mock-up are presented with two different approaches and objectives. During the first part, a HM simulation aiming at reproducing the complete life of the mock was conducted with boundaries conditions and loading as close as possible to the real one. The results show that considering the ageing effect (creep and drying of the porous media) allows to reproduce cracking and that numerical and experimental leakage are in the same order of magnitude.

The second part of this contribution allow to present the results of a probabilistic study of the same mock-up but with a thinner mesh and simplified loading (only mechanical one) in order to both decrease the calculation time and increase the representativity of the crack by damage band. The results highlight that the experimental results which can be a priori seen as a particular case (non-symmetry of the crack position) can be sometimes be retrieved but above all, the simulations show a larger uncertainty spread from mechanical random field (CoV $= 15\%$) to leakage rate (variation of more than one order of magnitude on the prediction of the leakage rate).

References

1. Corbin, M.: Overview, synthesis and lessons learnt from the International Benchmark VeRCoRs (2018)
2. Niklasch, C., Herrmann, N.: Nonlinear fluid-structure interaction calculation of the leakage behaviour of cracked concrete walls. Nucl. Eng. Des. **239**, 1628–1640 (2009)
3. Bouhjiti, D.E.M., et al.: New continuous strain-based description of concrete's damage-permeability coupling. Int. J. Numer. Anal. Meth. Geomech. **42**(14), 1671–1697 (2018)
4. Herrmann, N., et al.: PACE-1450 – experimental investigation of the crack behavior of prestressed concrete containment walls considering the prestressing loss due to aging. In: 20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20), Espoo, Finland, SMirt 20-Division 1, Paper 1671, 9–14 August 2009
5. Herrmann, N., Muller, H.S., Niklasch, C., Michel-Ponnelle, S., Le Pape, Y., Bento, C.: PACE-1450 the crack and leakage behavior of a prestressed concrete wall considering the prestressing loss due to aging. In: SMiRT 22, San Francisco, California, USA, 18–23 August 2013
6. Herrmann, N., Muller, H.S., Niklasch, C., Michel-Ponnelle, S., Masson, B.: The PACE-1450 test campaign – leakage behaviour of a pre-stressed concrete containment wall segment. In: Key Engineering Materials (2016)
7. Bazant, Z.P., Najjar, L.J.: Non-linear water diffusion in non-saturated concrete. Mater. Struct. **5**(1), 3–20 (1972)
8. Mensi, R., Acker, P., Attolou, A.: Séchage du béton: analyse et modélisation. Mater. Struct. **21**, 3–12 (1988). https://doi.org/10.1007/BF02472523
9. Granger, L.: Comportement différé du béton dans les enceintes de centrales nucléaires. Thèse ENPC, France (1995)
10. Thiery, M., Baroghel-Bouny, V., Bourneton, N., Villain, G., Stefani, C.: Modelisation du séchage des bétons. Analyse des differents modes de transfert hydrique. Revue européenne de Génie civil. Modeling of concrete drying. Analyse of different hydric transfert modes **11**, 541–577 (2007)
11. Matallah, M., La Borderie, C., Maurel, O.: A practical method to estimate crack opening in concrete structures. Int. J. Numer. Anal. Meth. Geomech. **34**(15), 1615–1633 (2010)

12. Sellier, A., Millard, A.: Weakest link and localisation WL^2: a method to conciliate probabilistic and energetic scale effects in numerical models. Eur. J. Environ. Civ. Eng. **18**(10), 1177–1191 (2014)
13. Bouhjiti, D.E.M., Baroth, J., Briffaut, M., Dufour, F., Masson, B.: Statistical modeling of cracking in large concrete structures under thermo-hydro-mechanical loads: application to nuclear containment buildings, Part 1: random field effects (reference analysis). Nucl. Eng. Des. **333**, 196–223 (2018)
14. Verdier, J.: Contribution à la caractérisation de l'évolution du taux de fuite des enceintes de confinement du parc nucléaire. Thèse de doctorat, Université Paul Sabatier Toulouse (2001)
15. Pijaudier-Cabot, G., La Borderie, C.: Mechanical damage, chemical damage and permeability in quasi-brittle cementitious materials. Eur. J. Environ. Civ. Eng. **13**(7–8), 963–982 (2009)