# Experimental Investigation of Concrete Packages for Radioactive Waste Management: Permeability and Influence of Junctions

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# Experimental Investigation of Concrete Packages for Radioactive Waste Management: Permeability and Influence of Junctions

**Stéphane Poyet · Xavier Bourbon**

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**Abstract** We studied the feasibility of a concrete package for radioactive waste management in a joint program involving Andra (the French agency for radioactive waste management) and CEA (the French atomic energy commission). The package's long-term durability and radionuclides' containment were the major concerns. The presence of junctions between the prefabricated body and the poured-in-place lids was identified as a major weakness. The first objective of this study was to characterize the permeability of the selected concrete and of the package itself (that is to say accounting for the junctions influence). We used special specimens including a junction, and tested three different surface preparation methods. The second objective was to assess the influence of the manufacturing conditions (laboratory and industrial) on permeability.

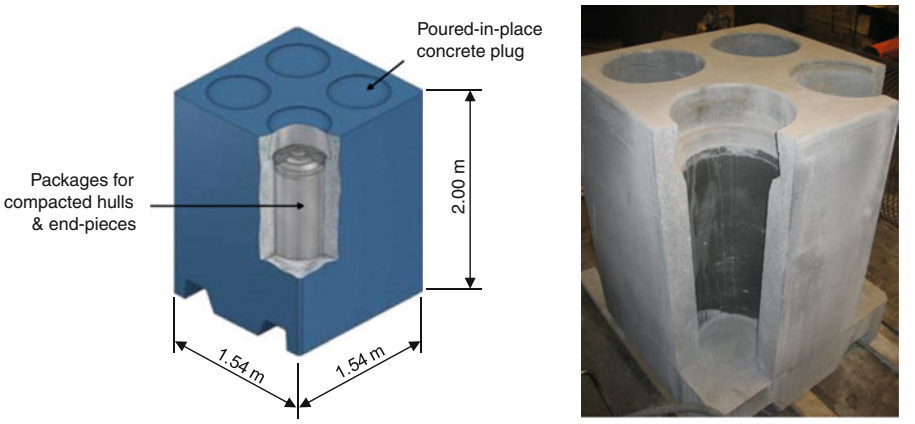
**Keywords** Concrete · Radioactive waste package · Permeability · Junctions · Surface preparation

## 1 Introduction

In the framework of radioactive waste management, cement-based materials would be used for the design of waste packages. The concrete transport properties and the resulting transfer capability of the packages are important issues pertaining to the evacuation of the gaseous hydrogen generated by water-radiolysis and radionuclides' retention over a long period of time.

S. Poyet (✉)
CEA, DEN, DPC, SECR, Laboratoire d'Etude du Comportement des Bétons et des Argiles,
91191 Gif sur Yvette Cedex, France
e-mail: stephane.poyet@cea.fr

X. Bourbon
ANDRA, Parc de la Croix Blanche, 1-7 rue Jean Monnet, 92298 Chatenay-Malabry Cedex, France




**(a)** Schematic description of the waste package **(b)** Photograph of a real package

**Fig. 1** View of the concrete waste package (Andra 2005)

A joint program involving Andra[1] and CEA[2] studied the feasibility of long-term durability and the retention capacity of a nuclear intermediate low-level waste package. It is based on a rectangular concrete package embedding four primary waste packages. It is constituted of a precast body closed by four poured and cured-in-place concrete plugs (Fig. 1) (De Coninck et al. 2005; Andra 2005). A unique concrete formulation is used for the plugs and the precast body. This design does not involve rebar reinforcement: rather, involves the use of short stainless steel fibers.

The confinement ability of this concrete package design relies on the concrete transport properties, which we characterized using gas permeability as a relevant durability indicator (Baroghel-Bouny 2006; Alexander et al. 2008). The presence of junctions between the precast body and the four newly poured plugs (and the corresponding bond) was identified as the major potential risk that could jeopardize the long-term confinement capability of the waste package.

The main objective of this study was to determine the permeability of the concrete used in the waste packages and of the concrete package itself (influence of the junctions) as well as to assess the influence of the manufacturing conditions (laboratory and industrial).

We designed an experimental program to quantify the influences of both the junctions' presence and preliminary surface treatment on permeability. We cast special cylindrical specimens including a vertical junction to simulate the bond between the prefabricated body and the four lids. We used permeability measurements to test three different industrial methods for the surface treatment: chemical deactivation and strong and medium abrasion. We also investigated the impacts of manufacturing conditions using samples cast and cured in laboratory as well as specimens cored from an existing package built, cured, and stored in industrial conditions.

[1] Agence Nationale pour la gestion des Déchets Radioactifs, the French national agency for radioactive waste management (http://www.andra.fr/international/).

[2] Commissariat à l'Energie Atomique et aux Energies Alternatives, the French Atomic Energy Commission (http://www.cea.fr/english_portal/).

**Table 1** Concrete composition

| Compound | Nature/origin | Qty | Unit |
|---|---|---|---|
| CEM V/A 42.5 PM ES CP1 | Calcia (Airvault, France) | 454 | kg/m$^3$ |
| Water | – | 178 | l/m$^3$ |
| Calcareous sand [0–4] | Boulonnais quarry (France) | 984 | kg/m$^3$ |
| Calcareous aggregate [6–10] | Boulonnais quarry (France) | 672 | kg/m$^3$ |
| Silica fume Condensil S95 DM | SIKA | 45 | kg/m$^3$ |
| Steel fibres IFT ($L = 30$ mm Ø = 0.6 mm) | Fasertechnik | 85 | kg/m$^3$ |
| Superplasticizer Viscocrete 5400F | SIKA | 17.25 | kg/m$^3$ |


**Fig. 2** Schematic description and photos of the joined specimens

## 2 Methods

### 2.1 Materials

The concrete composition is given in Table 1. The main expected properties are good mechanical strength (the waste packages would be stacked on several levels), "good" durability, and low permeability (in relation to radionuclides' confinement). These specifications led to the choice of a European composite cement CEM V/A (ternary blend of clinker, fly ash, and slag according to the European standard EN 197-1) with silica fume. The resulting blend is composed of 50 % clinker, 20 % fly ash, 20 % slag, and 9 % silica fume.

The risk of alkali reaction is prevented by the use of calcareous aggregates. The use of superplasticizer allows an effective low water-to-cement (cement + silica fume), w/c, ratio equal to 0.37.

### 2.2 Specimens Preparation

The influence of junctions on permeability was investigated using joined specimens (that is to say including a vertical junction, Fig. 2) to simulate the bond between the precast body and the four poured-in-place lids.

It is well known in concrete repair science and technology that a good quality junction requires an appropriate surface preparation: that is to say a preliminary treatment of the surface to be covered with fresh concrete to ensure correct bonding between the two concrete

layers (Morgan 1996; Emmons and Vaysburd 1994, 1996; Vaysburd et al. 2001). Many different techniques can be used for surface preparation (Bissonnette et al. 2006). The main objective is to roughen the concrete surface to guarantee a good anchorage of the new layer (mechanical interlocking). Comparative studies have been published (Vaysburd et al. 2001; Bissonnette et al. 2006; Garbacz et al. 2005a,b, 2006; Courard et al. 2005; Julio et al. 2005). It appears that the bond strength does not always increase with surface roughness. In fact, high roughness requires aggressive methods (such as shotblasting or chipping) that can induce cracking just below the treated surface (plane of weakness). The latter is likely to impair the bond strength and the durability of the repair system (Morgan 1996; Vaysburd et al. 2001; Bissonnette et al. 2006; Garbacz et al. 2006; Courard et al. 2005).

In the case studied, cracking is to be strictly mitigated for safety reasons. We have then selected two soft methods (commonly used and mastered by concrete industrials): chemical deactivation (CD) and physical abrasion. We investigated three options:

1. strong abrasion (hereafter denoted SA);
2. medium abrasion (MA); and
3. CD.

Abrasion was obtained by blasting corundum particles on the surface to be roughened. MA aimed to partially uncover fibers and aggregates, whereas SA aimed to completely uncover them. It must be kept in mind that the difference between these two is clearly subjective and depends on the operator. CD was obtained using a commercial surface retarder (Pieri DRC 6/80) that delays the set and allows the cement paste surface to be removed by washing after unmolding.

We prepared the joined specimens using a three-stage process (Fig. 3). It was designed to be as close as possible to the protocol used for the fabrication of the real concrete packages:

1. The first specimen half (phase I concrete) was cast within a standard metallic mold (internal diameter = 113 mm and height = 226 mm, according to the European standard EN 12390-1). A metallic part (a half cylinder to be removed for the casting of phase II concrete) was placed in the mold before casting. We unmolded the specimens 1 day after casting. A vibration table was used during this phase in the same way as the waste packages.
2. We kept the specimens in ambient air for 27 days before abrasion (blasting of corundum particles). In the case of CD, the junction surface was coated with the surface retarder before casting. Immediately after unmolding, it was brushed and abundantly rinsed with water.
3. 28 Days after casting of phase I concrete, we put the specimens (for 2 days) under water to saturate the open porosity in the vicinity of the junction zone. This was done to prevent early desaturation of phase II concrete because of phase I suction. Note that the treatment efficiency was not verified experimentally or confirmed anyhow. After the water in excess was removed, they were put in the metallic molds, and the second part of the specimens was cast (phase II concrete). We did not use vibration during this phase to mimic the waste packages closure. The samples were then kept in their molds for 28 days with a thin layer of water on the upper surface.

Simultaneously, we prepared plain specimens ($113 \times 226$ mm, without junction) the same day as the Phase I joined specimens (using the same concrete batch). We unmolded the samples one day after casting, and then we kept them for 27 days in sealed bags before we cored small samples (40-mm diameter) from them (Fig. 4a). We effected sawing of both top and bottom ends and discarded them (about 15 mm). We cut each resulting cylinder into three

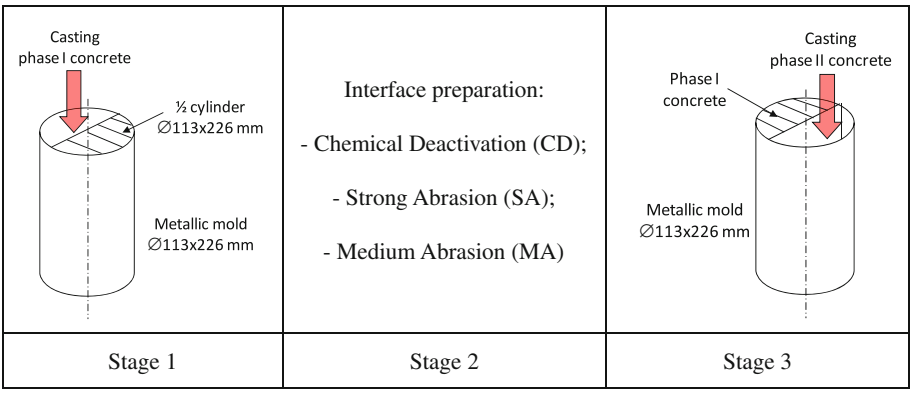
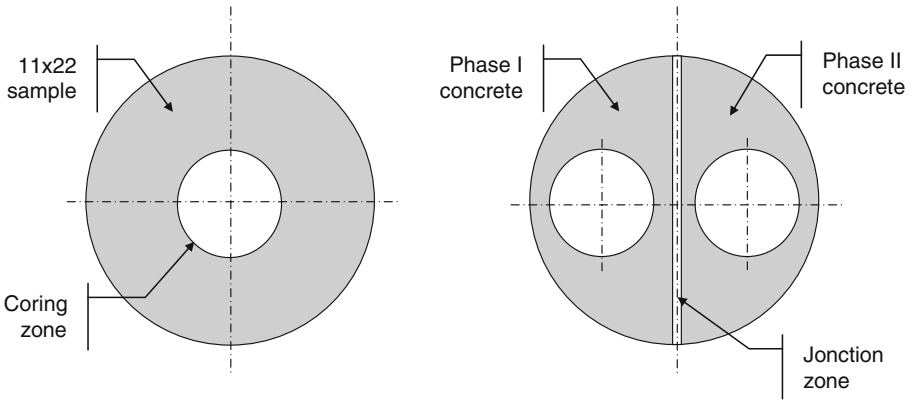



**Fig. 3** Three-stage process for the fabrication of the joined specimens




**(a)** Coring from the plain specimens **(b)** Coring from the joined specimens

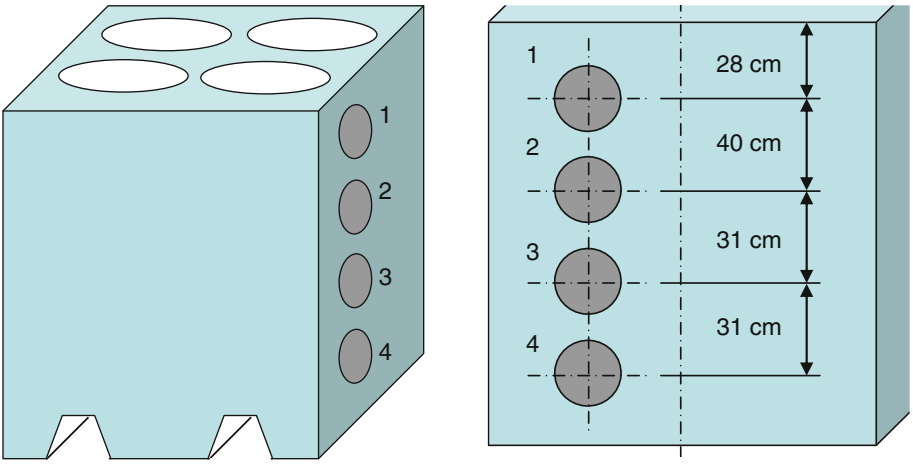
**Fig. 4** Schematic description of the coring operations for permeability measurement

equivalent pieces (60-mm height), which we used to measure the concrete permeability. We used six samples (40 × 60 mm) taken from two different plain specimens.

In the same way, we cored samples (40-mm diameter) from the two halves of the joined specimens (Fig. 4b). As described before for the plain specimens, the top and bottom parts were sawn and thrown away. We cut each cylinder into three new samples (60-mm height) and used them to estimate the impact of the three-phase casting on permeability. We tested a total of 15 cored samples (40 × 60 mm):

- six samples from phase I concrete (from two different joined specimens), and
- nine samples from phase II concrete (from three different joined specimens).

We also performed permeability experiments to evaluate the increase in concrete permeability when it is poured in industrial conditions. We drilled samples from an existing concrete container that was fabricated in industrial conditions and kept 28 days under a tarpaulin to prevent excessive drying. Then onward, it was kept at ambient air without any protection in a closed shed. We expected these conditions to be representative of the fabrication and conservation in industrial conditions. We cored the samples 10 months after casting, along a vertical straight line on one side of the package (Fig. 5). We prepared each core (40 × 200 mm)




**(a)** General view of the waste package **(b)** View of the cored side of the waste package

**Fig. 5** Position of the samples cored from the real waste package (not drawn to scale)

as described above resulting in three new samples (40 × 60 mm). We tested a total of 11 samples.

### 2.3 Permeability Measurement

We measured permeability using a Hassler sleeve (Hassler 1944). This is a constant head device that is very close to the well-known Cembureau permeameter (Kollek 1989). The Hassler sleeve allows applying gas injection pressures up to 5 MPa. Percolation throughout the sample is ensured using an impervious casing (neoprene) and a confinement pressure up to 6 MPa. The gas flow rates are measured using a bubble flow-meter at the outlet. Two versions of this apparatus are available: the first requires large samples (113-mm diameter, up to 226-mm height) whereas the other accepts small samples (40-mm diameter, up to 10-cm height). A description of these devices can be found in Farage et al. (2003). The devices have already been used in others studies (Farage et al. 2003; Gallé and Daïan 2000; Gallé and Sercombe 2001). All the measurements were carried out using pure nitrogen. We evaluated the effective concrete permeability $k_e$ ($m^2$) using the following equation (Kollek 1989; Basheer 2001):

$$k_e(P_i) = \frac{2\mu L P_o Q}{S\left(P_i^2 - P_o^2\right)}, \tag{1}$$

where $P_i$ and $P_o$ are the absolute inlet and atmospheric pressures (MPa), respectively; $L$ and $S$ are the height (m) and the cross section ($m^2$) of the specimen, respectively; $\mu$ is the dynamic viscosity of nitrogen (Pa s); and $Q$ is the gas flow rate (at the outlet and in steady state) ($m^3/s$).

Owing to gas compressibility, the measured effective permeability $k_e$ depends on gas pressure. We used the approach proposed by Klinkenberg (1941) (Basheer 2001) to assess the intrinsic permeability $k$ (does not depend on the experimental conditions). This approach assumes that a linear relationship exists between the measured effective permeability $k_e$ and the inverse of the experiment mean pressure $\overline{P} = \frac{1}{2}(P_o + P_i)$:

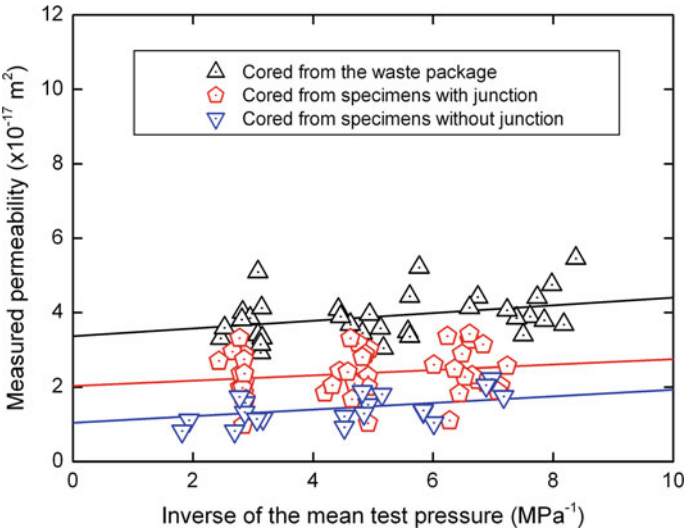



**Fig. 6** Results of the permeability experiments performed on cored samples. The *solid lines* stand for the Klinkenberg linear interpolation

$$k_e = k\left(1 + \frac{b}{\overline{P}}\right), \tag{2}$$

where $k$ is the intrinsic permeability ($m^2$) and $b$ is a positive coefficient (Pa), which describes the effective permeability variations induced by gas compressibility. The measurement of at least three values of the effective permeability $k_e$ allows evaluating the intrinsic permeability $k$ as well as the Klinkenberg coefficient $b$ using linear regression and the least-squares method.

Following the recommendation of Kollek (1989), we completely dried the samples at 105 °C (until constant weight) before permeability measurements. It is known that heating at 105 °C can be harmful for cementitious materials pore structure resulting in permeability increase. Yet according to the French experience, drying at 105 °C appears as the best compromise between the time needed for drying and the consequent pore structure alteration (Ollivier 1997; Villain et al. 2001; Carcassès et al. 2002). After drying, we left the samples one day in an air-conditioned room at 20 °C in a closed desiccator above silica gel (to prevent water intake). All the tests were conducted in an air-conditioned room at 20 ± 2 °C.

## 3 Results

### 3.1 Concrete Permeability

The results of the permeability measurements are presented on Fig. 6: the measured permeability values $k_e$ are plotted versus the inverse of the mean test pressure $\overline{P}$. In such a plot, the y-intercepts of the Klinkenberg lines are the intrinsic permeability values $k$, whereas the slopes are equal to $k \times b$.

For the samples cored from plain specimens, we obtained a mean value of the intrinsic permeability equal to $1.0 \times 10^{-17}$ $m^2$ (Table 2). For the samples cored from joined specimens,

**Table 2** Permeability measurements using cored samples

| Samples cored from | Number of tests | Intrinsic permeability $k$ ($m^2$) | | Klinkenberg coeff. $b$ (MPa) | |
|---|---|---|---|---|---|
| | | Mean | COV (%) | Mean | COV (%) |
| Plain specimens | 6 | $1.0 \times 10^{-17}$ | 27 | 0.085 | 34 |
| Joined specimens | 15 | $2.0 \times 10^{-17}$ | 30 | 0.035 | 41 |
| Package | 11 | $3.4 \times 10^{-17}$ | 19 | 0.032 | 27 |

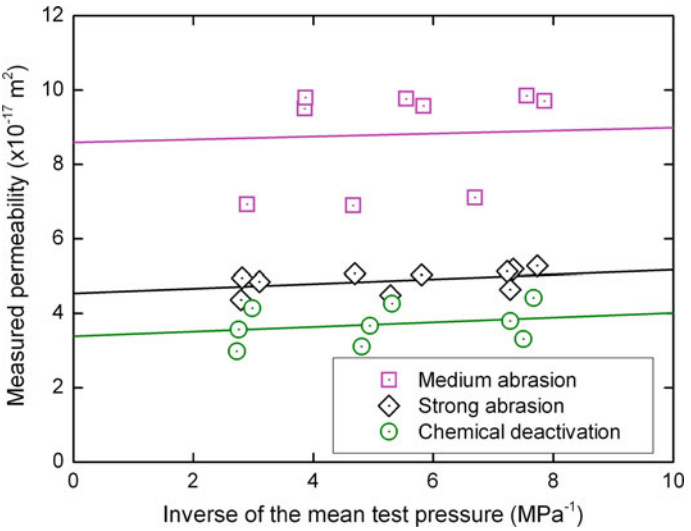



**Fig. 7** Influence of the surface preparation (CD, MA, and SA) on permeability. The *solid lines* stand for the Klinkenberg linear interpolation

the mean intrinsic permeability obtained was $2.0 \times 10^{-17}$ $m^2$. It is twice the value obtained using plain specimens without junction. It is worth mentioning that we obtained the same mean value for phases I and II concretes despite the difference of curing duration (56 days for phase I and 28 days for phase II concrete).

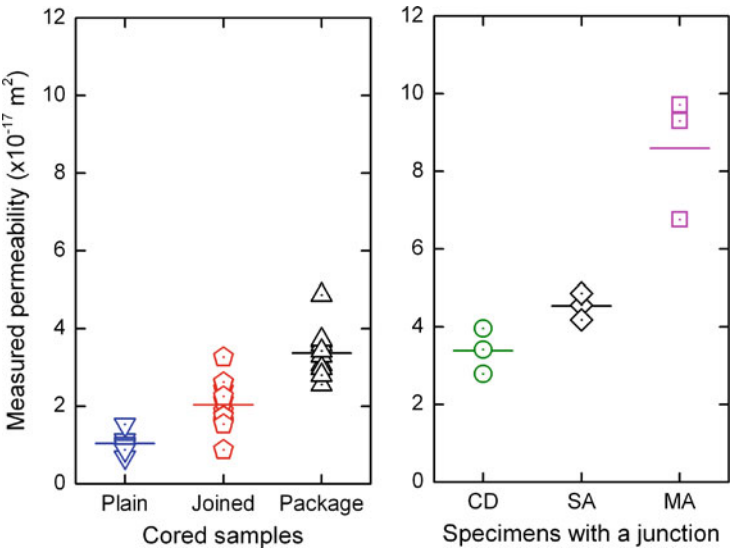
For the samples cored from the package, we obtained a mean value equal to $3.4 \times 10^{-17}$ $m^2$ (Table 2). This value is higher than the two values obtained using the lab-cast specimens despite the longer hydration time (the container was left untouched 10 months before the coring operations). It is also worth mentioning that the permeability values remain stable along the coring line. Neither higher nor smaller values were found in the upper or lower parts of the container. These results are in good agreement with the study of Camps (2008) who studied the same formulation and package.

### 3.2 Influence of Junctions

Before the permeability measurement, we surfaced and ground the joined specimens to remove the irregularities induced by the three-phase casting (that is to say the two extreme faces and all along the junction, cf. Fig. 2).

**Table 3** Permeability measurements using joined specimens

| Specimens | Number of tests | Intrinsic permeability $k$ ($m^2$) | | Klinkenberg coeff. $b$ (MPa) | |
|---|---|---|---|---|---|
| | | Mean | COV (%) | Mean | COV (%) |
| MA | 3 | $8.6 \times 10^{-17}$ | 19 | 0.005 | 61 |
| SA | 3 | $4.4 \times 10^{-17}$ | 7 | 0.014 | 41 |
| CD | 3 | $3.4 \times 10^{-17}$ | 17 | 0.018 | 32 |




**(a)** Permeability of the cored samples (A = samples cored from plain specimens; B = samples cored from joined specimens; C = samples cored from the real package)

**(b)** Permeability of the joined specimens (CD = Chemical Deactivation; SA = Strong Abrasion; MA = Medium Abrasion)

**Fig. 8** Compilation of the permeability measurements using cored samples (**a**) and joined specimens (**b**). Each *symbol* represents a tested sample, whereas the *horizontal lines* stand for the mean value of each sample set

Permeability depends on the surface preparation type (Fig. 7; Table 3). The higher value ($8.6 \times 10^{-17}$ $m^2$) was obtained using MA, whereas CD and SA led to smaller similar values: ($3.4 \times 10^{-17}$ and $4.4 \times 10^{-17}$ $m^2$ for CD and SA, respectively). CD gave the lower permeability values. A higher experimental variability was found for the MA: the values ranged from $6.7 \times 10^{-17}$ to $9.7 \times 10^{-17}$ $m^2$.

## 4 Discussion

### 4.1 Concrete Permeability

We did not find the concrete permeability to be a constant value over the three characterizations (Fig. 8a). As explained above, the first characterization was undertaken on specimens

**Table 4** Permeability to gas of various cementitious materials, see also (Tsivilis et al. 1999, 2003; Khan and Lynsdale 2002)

| References | Type | Cement content ($kg/m^3$) | W/C ratio | Porosity (%) | Compressive strength (MPa) | Drying temperature (°C) | Gas | Permeability ($m^2$) |
|---|---|---|---|---|---|---|---|---|
| Sugiyama et al. (1996) | Concrete | 460 | 0.40 | – | 42 | 60 | Nitrogen | $2.0 \times 10^{-17}$ |
| Sugiyama et al. (1996) | Concrete | 305 | 0.60 | – | 27 | 60 | Nitrogen | $9.0 \times 10^{-17}$ |
| Meziani and Skoczylas (1999) | Mortar | 639 | 0.40 | – | – | 60 | Argon, ethanol | $4.0 \times 10^{-17}$ |
| Villain et al. (2001) | Concrete | 353 | 0.58 | 14.3 | 33 | 105 | Air | $118.0 \times 10^{-17}$ |
| Villain et al. (2001) | Concrete | 353 | 0.49 | 12.0 | 49 | 105 | Air | $9.9 \times 10^{-17}$ |
| Villain et al. (2001) | Concrete | 421 | 0.27 | 7.0 | 115 | 105 | Air | $1.6 \times 10^{-17}$ |
| Jacobs (1998) | Concrete | 420 | 0.45 | 10.1 | 57 | 80 | Hydrogen | $3.0 \times 10^{-17}$ |
| Jacobs (1998) | Concrete | 300 | 0.60 | 12.7 | 33 | 80 | Hydrogen | $10.0 \times 10^{-17}$ |
| Jacobs (1998) | Concrete | 240 | 0.80 | 15.7 | 28 | 80 | Hydrogen | $20.0 \times 10^{-17}$ |
| Abbas et al. (2000) | Concrete | 377 | 0.32 | 8.4 | 100 | 105 | Oxygen | $1.0 \times 10^{-17}$ |
| Abbas et al. (2000) | Concrete | 409 | 0.33 | 10.0 | 109 | 105 | Oxygen | $10.0 \times 10^{-17}$ |
| Gallé and Sercombe (2001) | Concrete | 350 | 0.43 | 10.4 | 63 | 60 | Nitrogen | $2.4 \times 10^{-17}$ |
| Gallé and Sercombe (2001) | Concrete | 350 | 0.43 | 10.4 | 63 | 105 | Nitrogen | $6.6 \times 10^{-17}$ |
| Lion et al. (2005) | Mortar | 450 | 0.50 | 14.0 | – | 60 | Argon | $0.9 \times 10^{-17}$ |
| Yssorche et al. (1995) | Concrete | – | 0.35 | – | 85 | 50 | Air | $1.1 \times 10^{-17}$ |
| Yssorche et al. (1995) | Concrete | – | 0.60 | – | 35 | 50 | Air | $11.9 \times 10^{-17}$ |
| Yssorche et al. (1995) | Concrete | – | 0.75 | – | 20 | 50 | Air | $61.4 \times 10^{-17}$ |
| Loosveldt et al. (2002) | Mortar | 639 | 0.40 | – | – | 6 | Argon | $1.9 \times 10^{-17}$ |

**Fig. 9** Photographs of three different samples cored from the real waste package. Note the presence of entrapped air bubbles (samples diameter = 40 mm)

cored from plain samples (113 × 226 mm). The second was performed using samples cored from joined specimens (113 × 226 mm), and the last characterization was achieved using samples cored from a real waste package (cast and kept in industrial conditions).

We found the concrete permeability to be equal to $1.0 \times 10^{-17}$ m$^2$. This value is low when compared with those of the literature results (see Table 4 or Khan and Lynsdale 2002; Tsivilis et al. 1999, 2003 for more results). It is representative of a high-performance concrete.

We found higher values using the samples cored from the package and joined specimens. One may infer that the difference between the curing regimes of each sample set as below is the major cause of this permeability increase:

- The plain specimens were kept 28 days in sealed bags before the tests.
- The joined samples have experienced varying curing regimes. The phase II samples were left 28 days in their mold with a thin water layer on their top. After unmolding, the phase I samples were kept 27 days in ambient air and then for 28 more days in their mold with a thin layer of water.
- The real concrete package was kept 28 days after casting under a tarpaulin and then 9 more months in a closed shed (at ambient air) before the samples were drilled.

Yet, it must noted that we found no permeability difference between the phases I and II concretes of the joined specimens despite the difference between the curing methods. This has led us to think that cure is not the major cause of this increase. We infer that, for the joined specimens, the presence of a half cylinder placed in the mold before casting has made the concrete placement a little more difficult than for the plain specimens. We believe that this has led to the observed permeability increase (by a factor 2 from plain to joined specimens).

We have frequently observed air voids and defects (Fig. 9) on the samples cored from the real package cast and kept in industrial conditions. In fact, the industrial manufacturing conditions (casting in a single phase, large height of the waste package, and the high viscosity of fresh material) did not allow evacuating all the entrapped air bubbles. The presence of air voids is known to increase permeability (Wong et al. 2011), but we believe that it must be taken as evidence of unsatisfactory concrete settlement resulting in permeability increase (by a factor 3.4 from plain specimens to the real package).

We believe that the observed permeability increase is representative of the difference between concretes made in laboratory (where small volumes are cast with great caution in controlled environmental conditions) and the concretes daily placed in industrial conditions in civil engineering structures (where high volumes are poured at the same time with time

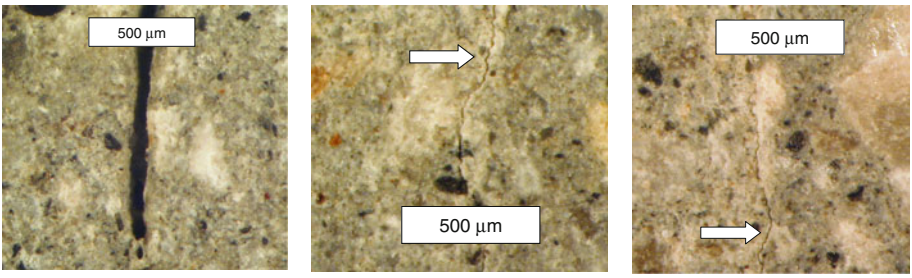



**Fig. 10** Photographs of a void (**a**) and cracks (**b, c**) observed all along the junction zone for MA specimens

constraints and outdoor casting whatever be the environmental conditions) (Vaysburd et al. 2004).

### 4.2 Influence of Junctions

Whatever be the surface preparation technique, we found that the joined specimen's permeability was greater than the plain specimen's permeability (Fig. 8b). As expected, the presence of a junction is a weakness with respect to transport and radionuclides' retention.

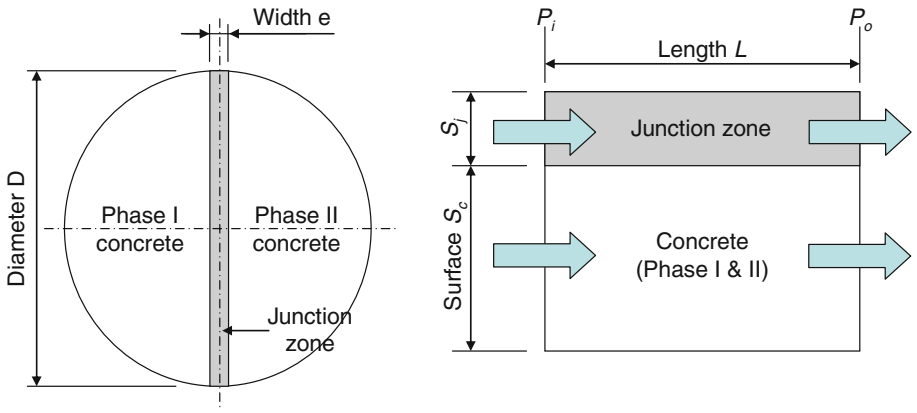
The use of surface retarder (CD) appeared to be the most effective method to mitigate the influence of junction on permeability. The less effective was MA. Based on the mean value obtained using the samples cored from joined specimens as the reference for the concrete permeability, we were able to quantify the impact of each surface treatment on permeability: the sample's resulting permeability is multiplied by 1.7, 2.2, and. 4.3 for surface retarder (CD), SA, and MA, respectively.

We examined the joined samples using a stereozoom microscope (Olympus SZH). In most cases (especially for CD and SA samples), the junction zone was not observable. Yet, for some samples (especially for MA samples), voids and microcracks could be found along the junction zone (Fig. 10). The presence of defects along junction zones has already been observed by various authors in the field of concrete repair (Garbacz et al. 2005a,b; Breitenbücher et al. 2005). The voids were assumed to be present because of the entrapped air bubbles (due to the absence of vibration), whereas cracks were assumed to be present because of phase II concrete-restrained shrinkage (Beushausen and Alexander 2006; Zhou et al. 2008).

We estimated the junction zone permeability using elementary homogenization. Owing to the configuration of the specimens (Fig. 11a) and the gas flow direction, we used a very simple scheme in parallel (Fig. 11b). It is based on the description of repaired concrete structures proposed by Emmons and Vaysburd (1994, 1996) and Vaysburd (2006), which states that the sound concrete and the repaired concrete are separated by a transition zone properties of which differ from the repair material. In our case, we considered phases I and II concretes as a unique material because no significant permeability difference could be highlighted between the two of them.

Following the proposed scheme, the total flow rate throughout specimen $Q_T$ is equal to the addition of the flow rates coming through concrete $Q_C$ and junction zone $Q_J$:

$$Q_T = Q_C + Q_J. \tag{3}$$




**(a)** Specimen configuration **(b)** Proposed scheme

**Fig. 11** Comparison between the specimen configuration (**a**) and the proposed scheme for the evaluation of the junction zone permeability (**b**)

**Table 5** Estimation of the junction zone permeability $k_J$ on the basis of the experimental results (the junction zone width $e$ is assumed to be equal to 100 μm)

| Preparation type | CD | SA | MA | Unit |
|---|---|---|---|---|
| Total permeability $k_T$ | $3.4 \times 10^{-17}$ | $4.4 \times 10^{-17}$ | $8.6 \times 10^{-17}$ | $m^2$ |
| Concrete permeability $k_C$ | $2.0 \times 10^{-17}$ | | | $m^2$ |
| Junction permeability $k_J$ | $1.2 \times 10^{-14}$ | $2.1 \times 10^{-14}$ | $5.9 \times 10^{-14}$ | $m^2$ |
| Ratio $k_J/k_C$ | $\sim 600$ | $\sim 1,000$ | $\sim 3,000$ | – |

Using Eqs. (1) and (2) this writes:

$$k_T\left(1+\frac{b_T}{\overline{P}}\right)S_T\frac{P_i^2-P_o^2}{2\mu L P_o}=k_C\left(1+\frac{b_C}{\overline{P}}\right)S_C\frac{P_i^2-P_o^2}{2\mu L P_o}+k_J\left(1+\frac{b_J}{\overline{P}}\right)S_J\frac{P_i^2-P_o^2}{2\mu L P_o}, \tag{4}$$

where $S_X$ corresponds to the cross-sectional surface area ($m^2$) of the zone X (X ∈ {C, J,T}). Assuming that the width of the junction zone was smaller compared to the specimen diameter, one can calculate the surfaces as follows:

$$S_T=\pi\frac{D^2}{4};\ S_J\approx De;\ S_C\approx\pi\frac{D^2}{4}-De, \tag{5}$$

where $D$ and $e$ are the specimen diameter (113 mm) and the junction zone width (unknown value), respectively. Eq. (4) is true whatever be the gas pressure, so that one can arbitrarily choose the value of $1/\overline{P}$ to facilitate the intrinsic permeability evaluation. The best choice is $\frac{1}{\overline{P}}=0$; this yields to

$$k_T\left(\pi\frac{D^2}{4}\right)=k_C\left(\pi\frac{D^2}{4}-De\right)+k_J\,(De)\,. \tag{6}$$

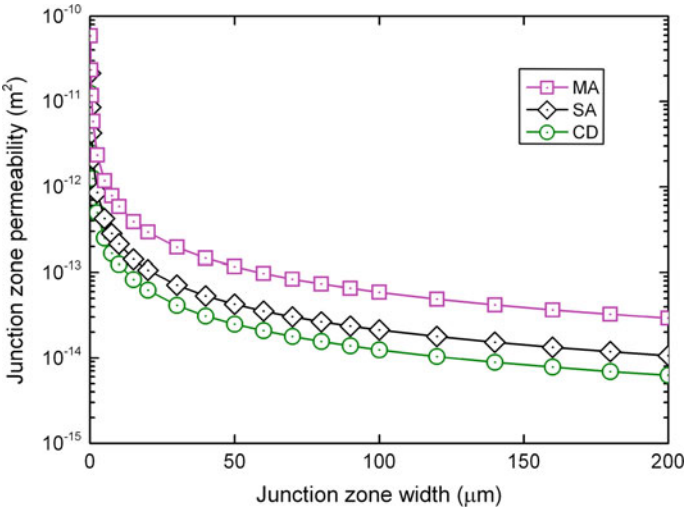



**Fig. 12** Variation of the junction zone permeability $k_J$ as a function of its width $e$

The permeability of the junction zone $k_J$ then becomes

$$k_J = k_C + \frac{\pi D}{4e}(k_T - k_C)\,. \tag{7}$$

By means of the mean permeability values obtained experimentally from the joined specimens (Table 5), we could estimate the intrinsic permeability of the junction zone $k_J$ as a function of its width $e$. The resulting curves (Fig. 12) are monotonically decreasing: the larger the junction zone, the lesser the permeability. Moreover, according to the conclusion drawn earlier, for any given width of the junction zone, the surface retarder (CD) allows minimizing the permeability, whereas medium sandblasting (MA) yields the highest value. Assuming a width of the junction zone as $e = 100\,\mu m$ (note that we did not verify the same) allows quantifying the increase in concrete permeability within the junction zone: the latter was found to be multiplied by $\sim$600, $\sim$1, 000, and $\sim$3, 000 for surface retarder (CD), strong sandblasting (SA), and medium sandblasting (MA), respectively (Table 5).

## 5 Conclusion

We studied the feasibility of a concrete waste package for radioactive waste management with a special focus in long-term durability and radionuclides' confinement. The latter mainly relies on the concrete transfer properties: the lower the better. We used gas permeability as the relevant durability indicator.

We worked on concrete samples cast in laboratory as well as samples cored from a real waste package cast and kept in industrial conditions. The results showed that the permeability measured using the "laboratory-cast" samples was lower ($1.0 \times 10^{-17}\,m^2$). The value obtained using samples cored from a real waste package manufactured in industrial conditions was higher ($3.4 \times 10^{-17}\,m^2$). We believe that this increase is representative of the difference between the laboratory and industrial placing and curing conditions.

The presence of construction joints between the prefabricated body and the four poured closure lids was identified as the major threat to radionuclides' long-term retention. As a consequence, we used joined specimens and three surface preparation methods (surface retarder, medium, and strong sandblasting) to test the bonding between the two specimen parts. The results showed that permeability increases whatever be the surface treatment used. The most efficient method appeared to be the one using the surface retarder.

For each surface preparation technique, we evaluated the increase of permeability within the junction zone using elementary homogenization. For the width of a junction zone equal to 100 μm, the permeability of the junction zone was estimated to be from 600 to 3,000 times greater than the permeability of concrete according to the surface preparation.

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