Capillarity in Concrete Disposal Vaults and Its Influence in the Behavior of Isolation Barriers at El Cabril Low and Intermediate Level Radioactive Waste Disposal Facility in Spain - 9015

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ABSTRACT

El Cabril is a disposal facility commissioned in 1992 for Low level and Intermediate Level Radioactive Waste (LILW). Most waste is stored in 11 m^3 concrete overpacks, placed inside 24 x 20 x 10 m concrete vaults. Beneath the disposal vaults, an inspection drift has been built containing 0.01 m^3 control tanks that collect eventual seepage water from each vault. After 10 years of operation, small quantities of water started to be collected in the control tanks of some vaults. After thorough investigation, tests, and modeling effort, capillary rise was identified in the origin of this phenomenon, together with evaporation and condensation caused by temperature differences between the concrete blocks and the vaults wall surfaces, causing a sort of wick effect. With the support of research institutions as Instituto Eduardo Torroja (CSIC-IETCC), Instituto Jaume Almera (CSIC-IJA) and Technical University of Catalonia (UPC), a set of experiments as well as models were developed to study these processes and their effects in the concrete barriers and the potential migration of radionuclides. The Thermo-hydraulic model predicted two seasonal peaks (winter and summer), and has a good quantitative co-relation with the amounts of water collected. According to the model, this process will not be significant in the long term, once the vaults will be covered by an earthen cap. The experimental work on the influence of this phenomenon in the different degradation mechanisms and the reactive transport models show a potential surface damage with a depth of two millimeters in 80 years, a period much longer than the expected duration before construction of the engineered cap.

INTRODUCTION

ENRESA is the Spanish organization in charge of the long-term management of all categories of radioactive waste and is responsible for decommissioning the different nuclear installations. El Cabril Low and Intermediate Level Radioactive Waste (LILW) disposal facility was commissioned in 1992, and its main objective is the disposal of all the waste in this category produced in the country. A number of auxiliary installations were built, such as treatment and conditioning installations, waste characterization laboratories, a concrete containers fabrication plant, laboratories, etc. An additional installation specifically intended for very low activity waste was very recently commissioned at the same site. The term waste management does not only refer to the disposal operations but also to a complete system including provisions for setting the waste acceptance criteria, verification of the waste characteristics and control of their production, transfer, collection and transport. It also includes a number of support activities, among which a continuous effort of performance assessment improvement should be stressed. As a part of this effort, ENRESA maintains a fruitful co-operation with various research institutes, and the study of the behavior of the concrete engineered barriers has been considered a key element for understanding the performance of the whole system. The Institute Eduardo Torroja (IETCC) has been working on concrete barriers durability from the initial specification of materials to the development of assessment models, carrying out an extensive experimental work [1]. The department of Geotechnical Engineering and Geosciences of the Technical University of Catalonia (UPC) is supporting ENRESA in the hydrological studies of El Cabril site and modeling of water flow in repository conditions [2]. This work makes use of hydrogeological tools applied to a concrete environment taking into account on the one hand the results of the studies performed on concrete characteristics and evolution, and on the other hand the influence of the water content and movement in different steps of the life of the structures under consideration.

The aim of this paper is to present studies and models that assess the performance of the disposal facility. To do so, we first give a general description of the facility, the different phases in the evolution of the facility and the main scenarios considered in the performance assessment. Then, we present the basis for the conceptual models; we describe the characteristics and constitutive laws used in the water flow model. We present the experimental work to improve the knowledge of the water transport characteristics and for the calibration of the model. We also present the geochemical model used to assess chemical evolution of the system, a summary of the experimental work carried out in this area to validate and feedback the model. We end the paper with a brief discussion of the main results and the conclusions.

THE DISPOSAL FACILITY

The disposal facility is a multi-barrier system designed and built to minimize water ingress through the waste, and thus to minimize radionuclide leaching and transport to the geosphere, the biosphere and finally to humans. Usually the following sets of barriers are considered: the engineered barriers, including waste packages (waste form, backfilling grout and container), vaults, cap, etc.; and the geosphere, providing additional retention and dilution in case of a failure of the artificial barriers. The engineered barriers have as main roles: to minimize water ingress and to allow for the collection of infiltrated water, thus helping to control properly the behavior of the entire facility; other roles are the minimization of the probability of intrusion and the retention of radionuclides.

Figure 1 includes a scheme of the disposal system: most waste packages are 11-m^3 reinforced concrete containers with 18 steel drums in which waste are conditioned forming a cementitious matrix. 320 of such concrete containers are placed inside a larger structure called a vault. Once a vault is completed, a closing slab is built and the assembly is coated by means of an impervious painting forming the so-called provisional covering. Once the existing 28 disposal vaults are filled-up, or at least after completion of the vaults in a particular zone, a multi-layer engineered cap will be placed to minimize water percolation and protect the disposal vaults from weathering.

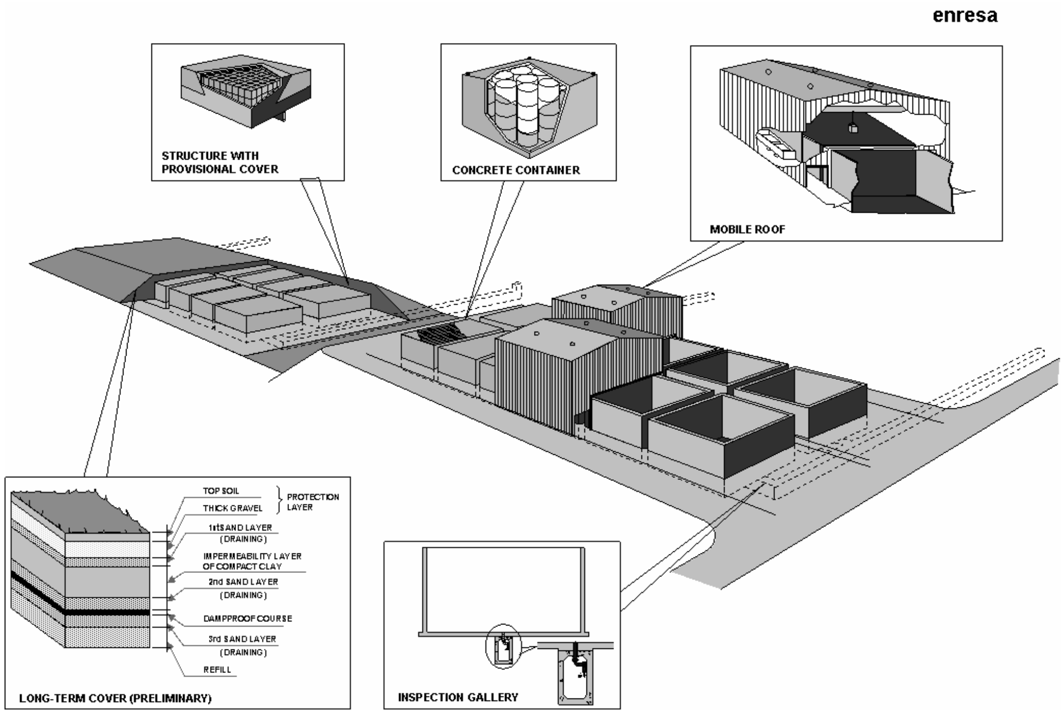

Figure 1- Scheme of the disposal system.

The vault in operation is protected by a mobile metallic shelter. Beneath each row of disposal vaults, an inspection gallery had been constructed containing a seepage system designed to collect any water from inside the disposal vaults in operation or sealed. The average design infiltration rate through the cap is 1.5 l/m^2y.

The site host rock is gneiss, and the depth of the water table varies with time and location from a few meters to tens of meters.

Concrete used in the construction of the vaults and containers are very similar. At the time, a classical Sulfate Resistant Ordinary Portland Cement (OPC) was preferred to new materials, because it was better studied and more experience on its behavior was available. Cement content was specified at 400 kg/m^3, water/cement (w/c) ratio was specified at 0.4 with a maximum allowed value of 0.42. A minimum characteristic strength of 35 MPa was adopted. Afterwards, fabrication experience showed that with these specifications, the typical strength was significantly higher and a more stringent requirement of 48 MPa was included, while real values are always around 62 MPa, with a standard deviation of 2.5 MPa

Phases considered in the life of the facility. Assessment scenarios

In a near surface disposal facility three main phases might be identified: the operational phase, when the waste packages are placed in the vaults; the surveillance phase, after the construction of the final cap, when a minimum monitoring of the facility may be expected ; and the post-surveillance period when surveillance of the facility is no longer assumed. The design criteria of El Cabril facility assumes a maximum surveillance period duration of 300 years and a durability design goal also set to 300 years. From a durability standpoint, these periods can be associated to different levels in the control and maintenance of the structures. This control may be assumed to be intense during operation, mostly passive during surveillance and practically inexistent during the post surveillance phase. These phases in the life of the structure also condition the water flow through the system and the saturation degree in different parts of the facility. During the operational phase, the structure is protected from weathering by an almost impervious film, but it is subject to insolation and temperature changes, that may create a wick effect, causing water evaporation and condensation in different parts of the vault (explained with more detail below). During the surveillance phase, water ingress from rainfall and surface water is limited by the engineered cap to a few millimeters per year. Water collection due to thermal differences coupled with capillary rise is precluded by the thermal insulation provided by the earthen cap. In the post-surveillance phase, the engineered cap is expected to degradate allowing an increase of water infiltration to the top of the concrete vaults in the range of natural recharge in the area.

In the safety assessment, the normal evolution scenario of the facility derives from the definition of the periods in the service life of the structures. The design characteristics of the different components of the system are considered as essentially maintained until the end of the surveillance period (although sensitive analysis to early failures is also performed). An analysis of the different physical and chemical processes was performed to define the main degradation mechanisms, but its description is out of the scope of this paper. It included the study of all the attack mechanisms described in the specialized literature and included freeze and thaw, carbonation, chloride, sulfate, etc as well as the migration of potential aggressive agents contained in the waste forms, such as chloride, sulfate and borates.

SERVICE LIFE MODELS

A simplified model for assessing the service life was initially adopted based on simple rules. After analysis, a number of processes that could impair engineered barrier lifetime were considered negligible in the disposal conditions and the site characteristics, or excluded after an intense control. The control implemented went beyond the regulatory requirements in the selection and supply of materials and aggregates. For instance, freeze and thaw were not considered important at some 400 m above the sea level in Southern Spain and alkali aggregate reactions were excluded after tests and X-Ray diffraction assay of aggregate supply. An intense experimental tests program was also established in support of the service life model. The aim of the models was to justify that the initiation period before depassivation of reinforcement steel was longer than the service life objective. Carbonation was considered as a controlling mechanism and modeled with a square root of time function. Chloride diffusion from the waste packages was modeled in 3D to verify that depassivation thresholds were not overpassed in the period under consideration.

One of the aspects with potential significance in the processes controlling the long-term behavior of the structure is the water content and water flow that may have significant influence in the transport mechanisms. In the above-mentioned simplified models, mainly diffusion mechanisms in a water saturated concrete matrices were considered for the scenarios related to chloride ingress. Average diffusion coefficients were applied for carbonation process taking into account the local environmental conditions prevailing. On the contrary, for leaching and transport of radionuclides a much higher artificially forced flow through the disposal system was adopted and, hence, dispersion and advection were of much higher importance. This apparent contradiction is one of the reasons justifying the effort in model improvements of the different attack mechanisms. The development of an improved water flow model is a first step in this approach.

A more detailed carbonation diffusion in buried conditions, while the environment of the vault interior is connected to the atmosphere only through the connection to the seepage piping system (see figure 1), demonstrated this process to be negligible. Chloride and sulfate flux from the water table during the operational period is under consideration due to the reduced wick effect observed and described later. Leaching and diffusion of calcium has been intensively tested and the experimental results are being incorporated in the detailed model. Potential attack from substances contained in the waste packages, that previously was tested and modeled in diffusion models are also being considered in the integrated model of which the water flow model explained here is a first task. Freeze and thaw were also taken into consideration due to the humidity conditions determined by the models

WATER CONTENT AND WATER FLOW CHARACTERISTICS

Capillarity and pore structure of concrete

Concrete and cement paste are porous materials with hygroscopic characteristics. Condensation in a capillary is produced at a lower relative humidity than 100%. The relative humidity h_r and the capillary pressure P_C are related through the Kelvin or Psychrometric law:

$$-P_C = (P_L - P_G) = \frac{RT}{MV_{SL}} \ln h_r \qquad \text{(Eq. 1)}$$

The pressure difference in the meniscus of a capillary is given by the Laplace's Law:

$$P_G - P_L = \frac{2\sigma}{r_{men}} \qquad \text{(Eq. 2)}$$

Thus, the relative humidity is related to the capillary radius through the Kelvin-Laplace Law:

$$\ln h_r = \frac{-2\,\sigma\,M}{RT\rho_L\, r_{men}} \qquad \text{(Eq. 3)}$$

Where P_L and P_G represent liquid and gas pressure; R is the gas constant (8.3143 10^{-3} kg MPa/mol K); T is the temperature; M represents the molar mass of the fluid; V_{SL} the specific volume of the liquid; ρ represents the fluid density; σ represents the surface tension of the liquid (σ= 0.0729 N/m for water at 20ºC); and r_{men} the meniscus radius, equal to the pore radius for a wetting fluid like water. Pore sizes in concrete range from nm to few µm, providing high capillary suction heads when saturation degrees are not very close to 100%. So, in buried conditions high saturation degrees may be expected.

Expressing equation 2 in terms of head (m), the capillary or matricial potential and the capillary suction head can be written as follows:

$$\phi_C = -\Psi = \frac{2\sigma}{\rho g r_{men}} \qquad \text{(Eq. 4)}$$

The capillary potential is dominant in materials where porosity is mainly formed by small capillaries, except for relative humidity very close to 100%, and pore distribution is of paramount importance.
The concretes being studied have been subject to a sound characterization program, including a number of capillary absorption tests, used to verify concrete quality. This program also included an important number of mercury intrusion porosimetry tests for determination of pore size distribution. Median pore diameter is very constant around 0.02 µm, corresponding to condensation at 90% humidity or 15 MPa equilibrium capillary suction.

Usually, capillary suction versus state of saturation at a given temperature and for different materials (concrete, host rock) is represented through retention curves. The retention curve can be mathematically expressed using several different conceptual models. A very usual expression is that by Van Genuchten (1980) [3], relating the effective saturation S_e (as compared to the saturation state at a given low-humidity reference state) to the capillary potential ϕ_C . ϕ_0 represents the air entry value; n and m are form parameters of the retention curve, where usually a value of $m = 1- 1/n$ is adopted.

$$S_e = \left[1 + \left(\frac{\phi_c}{\phi_0}\right)^n\right]^{-m} \qquad \text{(Eq. 5)}$$

Permeability of concrete

The main parameter characterizing the permeability of a porous material is the intrinsic permeability K_{int} (m^2). The definition of the intrinsic permeability coefficient derives from the Hagen-Poiseulle's equation. Permeability to gases should be determined in dry conditions, but this would damage the specimen and thus it is measured at specified low humidity (e.g. 50%), while permeability to water is determined under full saturation.

$$K\,\text{int}(gas) = \frac{Ql\eta}{At} \cdot \frac{P}{(P_1 + P_2)/2} \cdot \frac{1}{(P_1 - P_2)} \qquad \text{(Eq. 6)}$$

$$K\,\text{int}(liq) = \frac{Ql\eta}{At} \cdot \frac{1}{P_1 - P_2} \qquad \text{(Eq. 7)}$$

Where P is the pressure, at which the volume Q is measured. P_1 and P_2 are the test pressures above and below the specimen, A and l represent the sectional area and the length of the specimen, and η the dynamic viscosity.

Other permeability coefficients are also used as those in Darcy's equation

$$V = -k\nabla P = -\frac{K}{\rho g}\nabla P = -K\nabla H \qquad \text{(Eq. 8)}$$

These Darcy's coefficients and the intrinsic or saturated permeability are related through

$$K_{\text{int}} = k\eta = \frac{K\eta}{\rho g} = \frac{K\nu}{g} \qquad \text{(Eq. 9)}$$

Where P is the pressure (Pa), H represents the head (m), V (m^3/m^2s) is the flow per surface unit in the material or Darcy's velocity, η the dynamic viscosity ($1.01.\ 10^{-3}$ kg/ms for water at 20ºC), ρ represents the liquid density (1000 kg/m^3), g the gravity acceleration (9.81 m/s^2), and ν the kinematic viscosity ($1.01\ .\ 10^{-6}$ m^2/s at 20ºC). Thus, for water at 20ºC:

K (m/s) = $9.71.\ 10^6\ K_{int}$ (m^2) ≈ $10^7\ K_{int}$ (m^2) (Eq. 10)

In unsaturated conditions, the permeability to water decreases because the larger pores are full of air and the water path is restricted. This decrease is also related to the pore size distribution and thus to the retention curve. In this model, the modified Van Genuchten - Mualem model equation (Van Genuchten, 1980 [3]) is adopted.

$$K = K_s\sqrt{S_e}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad \text{(Eq. 11)}$$

Where K represents the permeability in the given conditions; K_s the saturated permeability; S_e the effective (in relation to a reference volume content of liquid) state of saturation; and m a characteristic parameter for which the same value than in the retention curve is usually adopted.

The flow of water in porous media

The flow of water will be a function of the hydraulic level or potential. This total potential will be the sum of the different potentials, including gravitational, capillary, osmotic, air pressure and envelope due to mechanical loads transmitted to the fluid, usually expressed in terms of head (meters).

$$\phi = \phi_g + \phi_c + \phi_\phi + \phi_a + \phi_e \qquad \text{(Eq. 12)}$$

The generalized Darcy's equation may be shown as follows:

$$V = -K\nabla\phi \qquad \text{(Eq. 13)}$$

The gravitational potential represents the geometric head; the capillary or matricial potential is the reverse of the capillary suction (Ψ) expressed in terms of head. The osmotic, air pressure and envelope (due to mechanical loads transmitted to the liquid) potentials are not considered here.

WATER FLOW MODEL

Two different conditions are considered, when the vaults are uncapped and thus subject to direct insolation and temperature variation, and after the construction of the approximately 3 m thick engineered cap. For reasons of brevity, and because it can be compared with observations, only the operational period flow model is presented. The calculation for the situation after capping shows that no water will be collected in this period, due to both the thermal insulation and the thermal inertial effect of the earthen cap.

Water collection and conceptual model

Water percolation tests through the impervious painting have been carried out, no percolation could be detected. Nevertheless, small amounts of water have been collected in the control system, even in summertime with zero precipitation and low water table level. To explain this unexpected situation (larger amounts of water were foreseen, but the generation mechanism was penetration through the roof) a hydraulic model was developed by Saaltink et al [4] [5]. The conceptual model can be summarized as follows: two seasonal cycles are defined. During the summer cycle the outer wall of the vaults are heated. There is a delay and attenuation in the heating up of the concrete containers inside the vault. These containers have a 0.02 m gap from the walls surface. This air gap provokes a jump in temperature and allows a flux of water vapor from the wall surface onto the containers surface. The balance of mass and energy in the system shows an evaporation at the wall pores, which provokes an important capillary suction and a capillary rising (wick effect) from the water table, modeled 3 m deep, based on the hydrogeological surveillance of the site. The water vapor flows to the containers, condensing at the pores and increasing their saturation. When 100% humidity is reached at the surface, the condensed water drips down at the containers' surface. In wintertime cycle, the process is inversed. Walls are colder and there is evaporation in the containers concrete, with diffusion of water vapor to the walls surface, increasing the saturation state, decreasing the capillary suction, and thus permitting liquid flow from the walls pores to the water table. Once 100% saturation is reached, some liquid is condensed at the surface and collected in the control tank. Figure 2 shows amounts of water collected in the seepage system of vault number16 (the one with a larger volume collected)

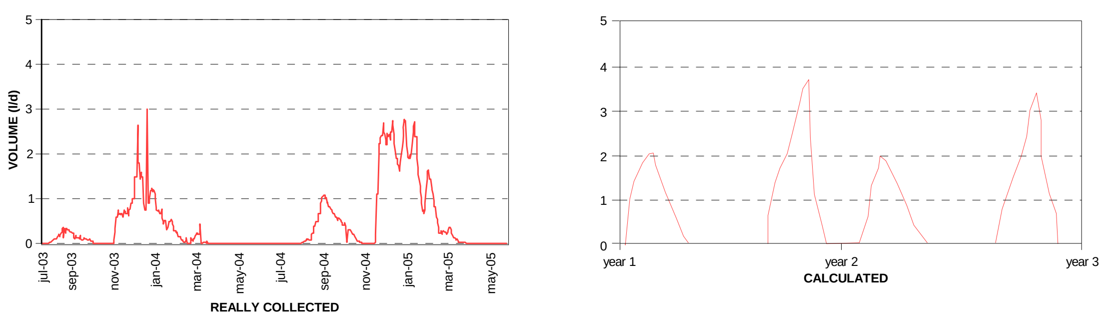

Figure 2- Water volumes collected in the seepage system (Total flow mL/day vs. date). The left figure shows the water collected in vault number 16, where this phenomenon was identified. The right figure shows the calculated with the model.

Numerical model

This conceptual model has been verified with a numerical model using CodeBright code [6]. This code allows the simulation of water (liquid and vapor) and heat transport as well, in unsaturated media, and has been applied successfully to this type of processes. Different variables are related through constitutive laws expressing the dependence of the properties (density, viscosity) in the various phases (liquid, gas) to the state variables (temperature, pressure). Among these constitutive laws, we stress some of them: Darcy's Law for water and gas flows, Fick law for vapor diffusion, retention curves for the relation between suction head and saturation, and Kelvin law to express the relation among humidity, temperature, and capillary pressure.

The model was developed in two steps. First, a 1D model [4] was carried out to study the feasibility of this process, and afterwards a more detailed 2D model [5] was performed. Figure 7 shows the finite element net used in this development

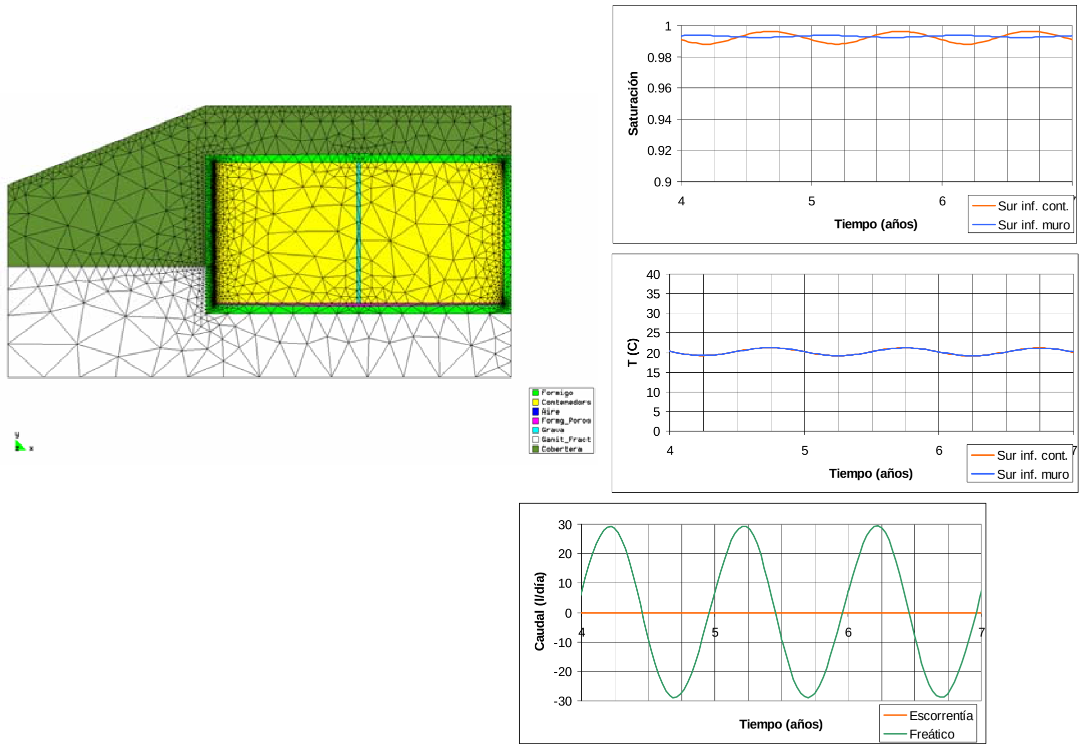

Figure 3 - Finite elements of the model of a disposal vault and the host rock beneath. The figure shows the representation of a vault after building the final engineered cap.

The model shows that the calculated temperature differences between the inner surface of the Wall and the outer surface of waste containers reach 5ºC. This difference activates the mechanism of water rising and descent from/to the water table and the collection of condensates as well. The model calculated volumes show a similar pattern than the real volumes collected (see figure 2) and, and the model also predicted the appearance of water in the summer season, before its occurrence. The initiation of water collection at the beginning of each seasonal episode is clearly related to the evolution of the atmospheric temperature.

A sensitivity analysis was performed. The model appeared sensible to the variation of the retention curve parameters and to the permeability of concrete. The influence of the water table depth, the temperature values or the gap distance seemed lower. We also calculated the influence of a number of potential corrective measures to prevent water collection at the retention recipients. Some of them seem successful (e.g. backfilling with fine sand to eliminate temperature differences; painting of containers and walls; taking the paint off on the external surfaces of vault walls). Other measures appear as ineffective (thermal insulation seems insufficient; decrease of water table level is only feasible in insufficient depth; painting only containers or walls eliminates water collection in one of the seasonal episodes, while larger volumes can be expected in the other season). The construction of the final engineered cap, more than two meters thick, will prevent water collection at the control recipients because of two reasons: the decrease of the magnitude of the temperature changes because of the thermal insulation and inertia given by the cap, and the retention by the earthen materials placed around the vaults. In this situation, there is an interchange of water mass between the water table and the systems, following the temperature variations, with a nil balance along the year [7].

REACTIVE TRANSPORT MODEL

From the identification of the causes of this phenomenon, the issue of its influence of the behavior of concrete barriers, due to the potential accumulation of aggressive ions: sulfate or chlorides or to the leaching of calcium by the condensate water. To improve the preliminary models, a reactive transport model was developed by Ayora et al [8], based on the water flow model previously described.

The model uses CODE-BRIGHT RETRASO [9] geochemical calculation code. It is superposed to the water flow model, in its 1D version. The model considers the conservation of mass (equation 14) at each node. The rapid reactions are represented in equilibrium through de mass action law (equation 15). Other reactions are represented by their kinetics (equation 16).

$$\frac{\partial(\vartheta u_j)}{\partial t} = \nabla \bullet (D\nabla u_j) - \nabla \bullet (q u_j) - \sum_m \nu_{jm} R_m \qquad \text{(Eq. 14)}$$

$$X_i = K_i^{-1}\gamma_i^{-1}\prod_{j=1}^{N}(\gamma_j C_j)^{\nu_{ij}} \qquad (i = 1,2...N) \qquad \text{(Eq. 15)}$$

$$R_m = \mathrm{sgn}\left(\log\left[Q_m / K_m\right]\right) A_m k_m f(\Delta G) \qquad \text{(Eq. 16)}$$

Where θ represents the water content; u_j is the concentration of component j; q is the water advective flow, υ is the stechyometric coefficient, R the reaction velocity, X_j is the concentration of the secondary component; K_i is the chemical equilibrium constant, γ_i and γ_j represent the activity and C_i the concentration of the primary component; sgn means the sign of reaction; Q represents ionic activity product; k_m is the kinetic constant of reaction; A_m is the mineral surface; and $f(\Delta G)$ represents the kinetic variation with saturation state.

A specific development was made for Calcium-Silica-hydrates (CSH) dissolution kinetics, due to the lack of literature. CSH is represented in this model as solid solutions (Lichtner-Carey). There was some discussion about this hypothesis. Kinetics and even composition of CSH is controversial. Nonetheless, we advanced in the model, although we have launched tests in order to better understand and model the CSH dissolution and its influence in the leaching of Calcium.

The model gives the concentration at different nodes and time of the main components and calculations were extended for a period of 20 years (the time expected before covering with the engineered cap. Afterwards, results were extrapolated to 80 years. Degradated thickness of concrete after this period was assessed in 2 mm. This result is consistent with experimental results described in next chapter, although this verification is only for a single measurement and experimentation and modeling are nor finished.

This model was also adapted to the migration of radionuclides, as a case study additional to the official Safety case. Potential migration through the roof and walls due to advection caused by with water interchanges with the water table had not been previously taken into account. This was of special interest in the case of Tritium that could pass from the waste containers to the walls in the form of steam. The disintegration constant was simulated as a chemical kinetic factor. Tritium calculated concentration in the water leaving the system reached 1.4 Bq/L after 50 y

EXPERIMENTAL WORK

Experimental work on thermo hydraulic characteristics and model verification

A number of tests have been implemented [10] to improve the calibration of the model and to go deeper in thermo hydraulic characterization of concrete, especially on those parameters to which the model is sensible.

On one hand, two full size disposal vaults have been instrumented with temperature and humidity sensors (thermocouples, thermo-hygrometers, psychrometers) installed at different heights and positions: internally for a disposal vault in operation; and externally in the case of a disposal vault already sealed.

On the other hand, a program is under way for enhancing the previous characterization of concrete mainly focused on permeability and retention curves. This includes the direct measurement of intrinsic permeability, in some case in combination with the study of calcium leaching by the water traversing the specimen; the determination of absorption isotherms by equilibrium at different humidity levels in ambience controlled by different dissolutions and using desiccators; and determination of suction in triaxial pressure cells and membrane cells. The triaxial cell has been also used [11] for determination of relative permeability under unsaturated conditions. The tests confirmed an intrinsic permeability in the range of 10^{-18} m^2. They have given a number of retention curves or sorption isotherms; the absorption curve seems coherent with those used in the model. They also fit with those adjusted from the results of mercury intrusion porosimetry. Nonetheless, the hysteresis found is more important than in other curves from literature, deserving more tests. In addition, we have done some attempts to co-relate permeability coefficients to easier-to-determine capillary absorption coefficients, although more tests are needed to extract validated conclusions. The program also included the verification of thermal conductivity in different saturation states.

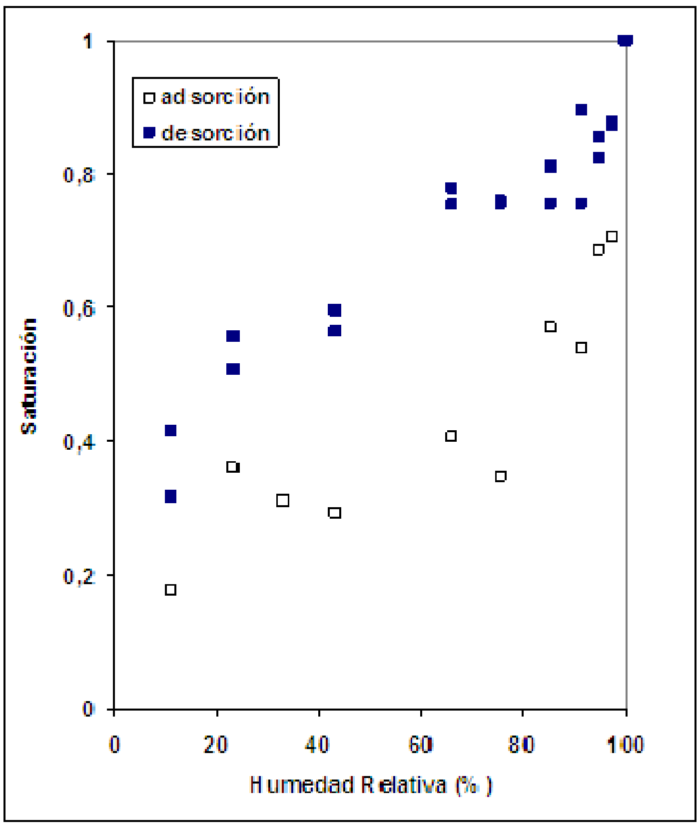

Figure 4 - Sorption Isotherm (Saturation vs. equilibrium relative humidity) obtained at 20ºC by IETCC for El Cabril Containers' concrete

In connection to this, the planned experimentation on the final cap design was completed with the inclusion of temperature, heat flow, hygrometric, psychrometric, deformation, etc. sensors in a test engineered multi-layer cap. The aim of this large-scale test is the verification of the design of the cap and the hydraulic model. The cap (in two sections with slight differences) has been built on a concrete structure representing the upper half of a vault. The sensors are embedded in the concrete and in the different layers of the cap. The selection of sensors was based on the expected saturation states, in accordance to the preliminary design.

Leaching of Calcium

Potential leaching of calcium driven by the condensate led to a number of tests focused on Calcium leaching, although also valid for other purposes in some cases, such as permeability. Resistance to leaching was studied [12] through static tests (type ANSI ANS 16.1 1986), column test, and with water permeation through the concrete matrix. During the tests the leachate is analyzed, and the specimen is tested for surface hardness, resistivity and by ultrasounds. After the end of the test, the specimens are subject to X-Ray diffraction, Thermo gravimetric, Intrusion porosimetry, Elemental analysis, and microscopy. The tests are carried out on the reference concrete and other three concrete specifications. Some of the specimens have also been analyzed by Particulate induced X-Ray (PIXE). The results show a deterioration of the first two millimeters with a significant increase of porosity and a change in the pore size distribution, a change in chemical composition, total lose of portlandite,

Chloride and sulfate

In the medium term, the water lost in the system (collected in the seepage system), although in small quantities, provokes the absorption of water from the water table and a concentration of ions. The local water has low concentrations of both ions, but the potential increase could impair the structures. In addition to the model development described above, specific work has been performed in the verification of depassivation threshold for chlorides and the consequences of sulfate concentration.

Concrete specimens have been put with their bottom submerged in water with different concentrations of chloride and sulfate, the lateral surfaces were isolated, and the upper one subjected to evaporation, controlling the temperature and recording the humidity.

After more than three years, no deterioration or efflorescence has been observed. The cement was specially selected for sulfate resistance. The resistance to sulfate of the material has been recently verified by Koch-Steinegger tests (by immersion in 4.4% sulfate dissolution, in groundwater, and calculation of a corrosion factor), and by ASTM C-452-02 to check the expansion in a saturated gypsum solution.

Freeze and thaw

Cordoba Province in Southern Spain has a warm climate and freeze and thaw consideration is not required in the Spanish Concrete Structures Code, because of the low probability of freezing together with high humidity. Nevertheless, the winter night temperature can go down to -5ºC, and the thermo hydraulic model showed the possibility of having this temperature together with 100% saturation in the outer surface pores. Because of that, two actions were performed: drilling small specimens (10 mm diameter x 40 mm deep) out of the walls of the older vaults (sealed in 1994) for visual inspection and mechanical testing, and carrying out freeze and thaw resistance laboratory tests on the concrete used.

Laboratory tests were based on CAN/RILEM standards for slab tests, directed to structural damage and surface damage. The specimens are subjected to freeze and thaw cycles. The evolution of the time length of an ultrasonic pulse provides information on the degradation. Then, visual inspection is performed for surface damages.

CONCLUSIONS

A service life model has been developed for the LILW disposal facility of El Cabril. The development of the model relies on an extensive research program and in a quality assurance scheme. The experience has shown that the engineered barriers have behaved as assumed in the previous models except in the case of the influence on temperature changes that have generated a not foreseen movement of water from and to the water table. The life assessment of real engineered barriers has to consider the different materials and elements. The ground and the water table have to be taken as an integral part of the multi-barrier isolation system. Water flow in very low permeability materials like concrete is not easy to model. However, a model representing the water flow and water content in the disposal vaults has been developed and compared with real conditions. The model developed for the chemical evolution of Calcium fits with the experimental data. The experimental work has been extended to have more data to validate the model. The model itself is also in a continuous improvement process. Coordination between modelers and experimental research is a key aspect.

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