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Experimental Performances of a Non-cracked Concrete Wall in Air Permeability and in Accidental Conditions

BILLARD Yvan[1)], DEBICKI Gerard[1)], COUDERT Laurent[2)]

[1)] INSA de Lyon, URGC Structures, Villeurbanne, France
[2)] EDF/SEPTEN, Division Génie-Civil, Villeurbanne, France

ABSTRACT

The presented experimental research investigated the behaviour of a concrete wall, with a local zone very permeable to the air, in situation of accident. The high level of permeability in the concrete was obtained for one specimen with a porous concrete having connected pores (intrinsic permeability of $10^{-16}m^2$).

The aim of this work was to study comparatively, in laboratory, the permeability of a non-cracked concrete wall under two conditions. A cylindrical specimen of 1.3 m of thickness was used. No appreciable stresses were applied on the concrete. The first conditions was at ambient temperature, under an increasing pressure (till 0.42 MPa) of the air applied on a face of the specimen, the other one been at atmospheric pressure. The second condition was an accidental scenario with simultaneous effects of temperature and gas (a mix of air and steam) pressure applied on a face, the other one remaining at atmospheric pressure and temperature. During the test, the lateral face of the cylindrical specimen was thermally isolated and made leaktightness. So, an uni-dimensional experimental analyse was performed. The accident conditions consisted of a rise from ambient conditions to a temperature of 141°C and a relative pressure of 0.42 MPa (steam pressure of 0.377 and air pressure of 0.043 MPa) in 3 hours, the maximum values been kept constant for several days.

Thermocouples, pressure taps and moisture gauges were implanted in the specimens at the moment of the casting, to provide local information of the inner wall under the simultaneous effects of temperature and steam pressure. At the outside of the specimen, the chamber enclosed a condenser with humidity meter and thermocouple, so it was possible to quantify separately the saturated air flow with a flow-metre and the condensed water.

During the permeability test at ambient temperature, the field of pressure was affected by the variation of local permeability of the concrete. Furthermore, few movements of interstitial water inside the specimen induced an increase of the predicted outflow; no liquid phase appeared.

For the natural porous concrete, during accidental test, the field of pressure advanced slowly, the outflow progressively increased to obtain a maximum at 70 hours, after this time on the one hand the air flow rate decreased and became equal to zero, on the other hand the liquid flow rate was constant; at the end of the test, about 30 centimetres of the specimen were water saturated.

These experiments gave some indicators on the relations between air flow during a permeability test and gas (air +steam) flows during accidental test. They also offered experimental data to the calculation of hydrothermal performances of the wall during accident conditions [1].

KEY WORDS: Concrete wall, permeability, accidental conditions mercury porosity, sorption isotherm, air flow, liquid flow, hydraulic pressure, water saturation, transposition ratio.

INTRODUCTION

The function of a containment wall is to prevent the leakage of radioactive fission products into the environment in the event of an accident. For many Nuclear Power Plants (NPPs), containment wall construction is based on a single containment design, where the leaktightness function of the containment is ensured by a steel liner.

In French design, the 1300-1450 MWe NPP reactor building consists of a double concrete wall, which comprises an outer reinforced wall to assure protection against external effects, and an unlined inner prestressed concrete wall to provide the leaktightness function. Furthermore, the annulus between the two containments is maintained under slight depressurisation in order to suck in and filter potential leaks from the inner containment [2].

On the containment wall, the technical objective, in term of leaktightness, is to maintain the rate of gas escape under 1.5% by day of the confined gas volume during a LOCA (Loos Of Coolant Accident). As this criterion is not practically measurable, the compliance with the rule is evaluated by measuring the quantity of air leak, obtained during a periodical pressure test at ambient temperature. The level of pressure used is analogous at this one that could arise in case of accident. To improve the knowledge of the link between the two situations an experimental program was performed.

The aim of this work was study comparatively the permeability of a non-cracked concrete wall under an air permeability test at ambient temperature and under an accidental scenario with temperature. In the first section, the test conditions are introduced. In the second section, the structurally porous concrete used is presented, it was chosen to represent a flaw in proportioning concrete mixture, this was representative of very local zones on the containment wall. The third section summarizes the results and opens a discussion.

TEST CONDITIONS

Two processes are coupled together under accidental conditions: moisture and heat transfer. One process cannot be considered without the other simultaneously. In order to study the behaviour of the containment wall under the simultaneous effects of temperature and steam pressure, and in particular the effect of air and steam propagation through the concrete, a cylindrical specimen has been used to perform a one-dimensional analysis of the phenomena. The test equipment simulates a reactor containment wall subjected to permeability test or hydrothermal loading.

The cylindrical concrete specimens had a diameter of 0.5 m. Their thickness is the same as that of an EPR nuclear containment (1.3 m), so the thermal properties and leaktightness behaviour are modelled with a scale ratio of 1.

Test equipment

The specimen was vertically put into place and laterally enclosed by resin injection between concrete and metallic shell. This ensures the hydric leaktightness. A thermal insulation lead to a quasi-homogeneous temperature range on the planes normal at the specimen's axis of symmetry.

An autoclave was placed on the concrete surface at the top of the specimen. A control system set the accident conditions of temperature and pressure (which was produced by water vapour). At the base ("extrados" of the concrete specimen), a system consisting of a gas flow meter, humidity meter and condenser allowed the separation and quantification of the gaseous and liquid parts of the outgoing fluids.

Thermocouples (18), pressure taps (8) and moisture gauges (8) were implanted in the specimen at the moment of casting. They provide local information on the specimen, and are mostly distributed in the first 30 cm of the concrete. All gauge connections exit the concrete specimen laterally. The pressure tap consists of a copper pipe connected to a pressure gauge located outside the specimen. Water content measurement in the concrete specimen is performed by examining the electrical resistance of the moisture gauges [3]. The value W_{tot} (kg per cubic metre of concrete), obtained during the test with the help of gauge calibration performed prior to the test, corresponds to the quantity of locally evaporable water (if the concrete was dried in an oven at 105°C).

Test programme

A preliminary test (with reference T1) of permeability, with dry air, gave the characteristics of permeability and the type of flow through the specimen. In this case, the used method consisted to proceed by stages. The imposed pressures on the exposed face were successively 0.1, 0.26 and 0.42 MPa, the other face was at atmospheric pressure. The change of pressure was made when a constant rate of output appeared. So the duration of the stages was very long to be sure that a constant regime was obtained.

In a second time, an accident scenario (with reference T2) was applied. During the tests, the lower face of the specimen is kept at ambient conditions in the collection tank. The upper face is subjected to thermo-hydric loading. The imposed experimental conditions on the exposed face are detailed hereafter. The conditions accounted for the capabilities of the autoclave, which limited the kinetics of the pressure and temperature rises.

The scenario T2 involved two phases. The first phase consisted of a controlled rise in temperature till 141°C with heating in the autoclave and production of water vapour simultaneously, this during 2 hours, at this time the temperature was maintained waiting to reach the pressure of saturated vapour (0.377 MPa), that took 40 minutes more. At this time, the autoclave contained only vapour. The second phase started one hour and twenty minutes after, with the insertion of dry air in the autoclave to obtain the pressure of 0.42 MPa. This situation was maintained constant during 220 hours with the control system. The ratio of gas mix ($mass_{vapour}$ / ($mass_{air}$ + $mass_{vapour}$)) was equalled to 62% on this stage. This was to simulate in a realist way the gas mix present in the reactor during an accident.

THE CONCRETE WALL

The thermal properties and leaktightness behaviour are studied with a scale ratio of 1. The challenge was to realise a large specimen relatively homogenous giving an air output around 10 to 50 normal litres by hour and square metre under a pressure gradient of 0.42 MPa, at ambient temperature.

Concrete specimen

The use of a high ratio W/C (> 0.75) gives the possibility to obtain high permeability on the vertical direction of the concrete specimen which becomes hydrated. During pouring and setting of concrete, the relative displacements of solids in suspension, which tend to move downward under the earth's gravity, produce many capillary pores positioned vertically. If this direction is parallel to the gas flow, this leads to a high permeability. Nevertheless, this method has the disadvantage to give very inhomogeneous permeability, between the top and the bottom of specimen.

The mixture proportion of the concrete are given in table 1, a large proportion of fine aggregate with superplasticizer reduces the bleeding. Furthermore, the bottom of the moult was water permeable during the setting to improve the specimen homogeneity.

The form removal was made 24 hours after placing. Then, the specimen was wrapped laterally by a plastic film to stop the mass exchanges between the concrete and the environment, the planes faces at the top and the bottom staying in contact with the air. A cure of 28 days was made at ambient temperature (20 ± 2°C) with 95% of relative humidity. The test was realised 3 mouths after the cure.

Table 1. Mix proportions (kg/m^3), and slump of the concrete used

Sand (0-5 mm)	Gravel (5-10 mm)	Cement CEM I 52.5	Filler	Water	Superplasticizer	Water / Matrix	Slump (cm)
1096 kg/m^3	651 kg/m^3	200 kg/m^3	40	198	1.78 kg/m^3	0.825	12.5

Qualification of concrete

This section regroups general information on the concrete. The porous network, the material properties of mass transfer and the initial state of humidity was studied.

The compressive strength was 15.3 MPa. The free water content for saturated concrete at 20°C was about: 7.4 % of the dry mass. The dry bulk density was 2068 kg/m^3.

The test of mercury porosity gave the characteristics of the connected porous network. The total porosity obtained by this method was 20.3%. The figure 1 shows the cumulative pore-size distributions for several dried specimens took on the large specimen after the tests T1 and T2. A classification of the grading characteristics is introduced on the table 2. The results show the presence of two porous structures. The first one includes a great volume of pores having an average pore diameter of 0.07 µm, it could be an empty space between the hydrates. The second one has a greater volume of pores (diameter around 1 µm). The high W/C ratio was at the origin of the last network described. From these observations, it appears that the concrete used has a more spacious porous network than ordinary concrete.

Table 2. Grading characteristics of the porous network, in percentage.

Micro-porosity d < 1 µm	Meso-porosity 0.1 < d < 0.63 µm	Macro-porosity 0.63 < d < 125 µm
38.9 %	19.9 %	42.2 %

The experimental values of sorption isotherm at ambient temperature obtained for the concrete are reported on Figure 2. The type of got curve suits with macro-porous solid. It is notable that there is no stable stage for the high relative humidity. In the macro pores, the capillary condensation can take place only for the very high humidity. Before reaching this high humidity zone, a large part of porous network stays only partially filled with liquid. Moreover, the hysteresis curve (desorption for the upper part and sorption for the lower part) runs continually through all the relative humidity field.

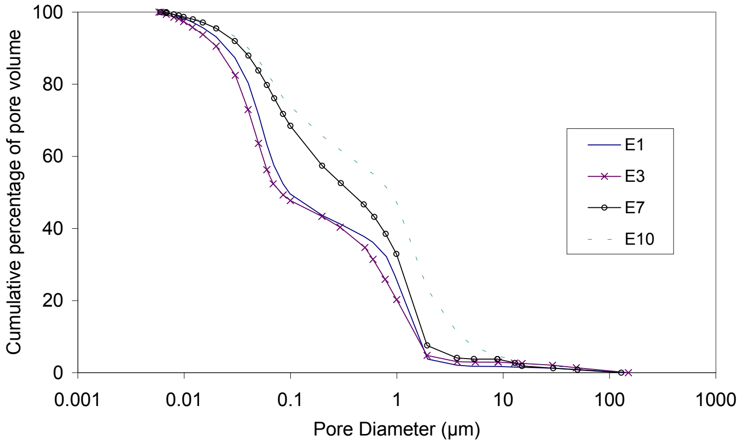

Fig. 1 Cumulative mercury pore-size distribution for several dried specimens of concrete

It could not be any control on the microstructure of concrete during cement hydration. At this time, many phenomena induced heterogeneities within the specimen. To simplify, we consider that the main variations was caused by the earth's gravity as explained before. To explore the field of permeability along the large specimen, a core drilling

(∅ = 0.15m) was made on the large specimen. Along the core obtained, several (14) specimens (∅ 0.15 x 0.05m) were taken to realise standard permeability tests (on dry concrete). The measures gave the possibility to calculate the intrinsic permeability using the concept of Klinkenberg [4]. The figure 3 shows a non-uniform profile of obtained permeability, the upper part having a lower permeability. The values obtained in the lower part came from the design of the bottom element of the moult.

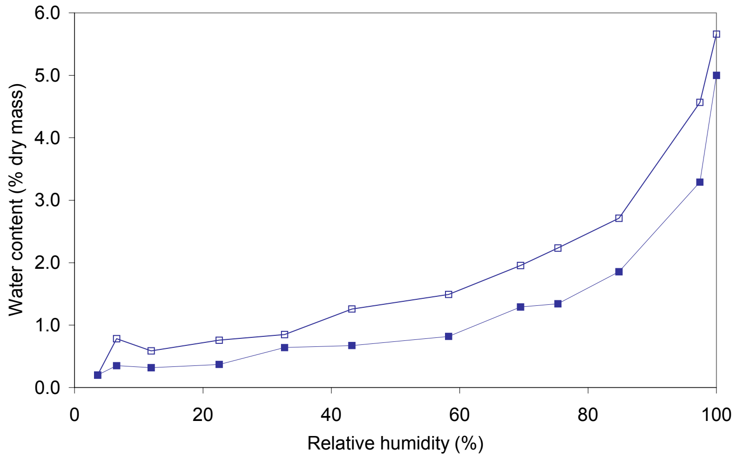

Fig. 2 Experimental values of sorption isotherm of concrete tested, at ambient temperature

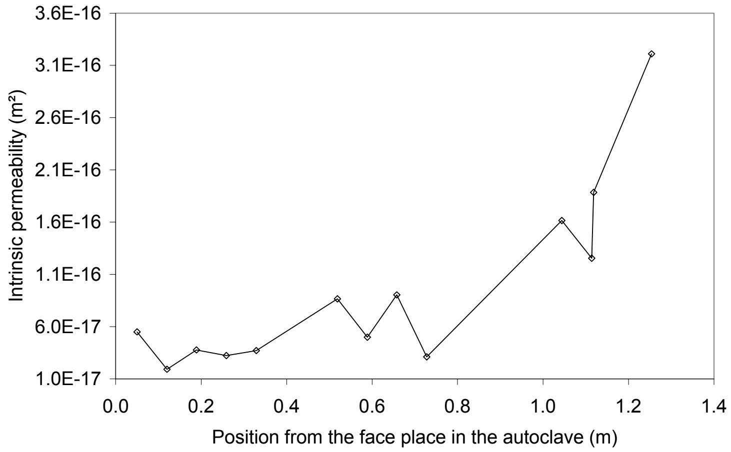

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Fig. 3 Profile of the intrinsic permeability

The results given the scenario 2 could only be interpreted after accounting for the specific initial condition of humidity inside the specimen prior to the test. To characterise the initial hydric state of the concrete, values given by the humidity sensors were collected before testing. Figure 4 presents the humidity contents within each specimen. The humidity ratio was determined with the quantity of locally evaporable water giving by the resistive sensors and the sorption curve. The positions of the sensors within the concrete are represented on the horizontal axis, the origin having been positioned on the face placed in the autoclave. The layers of concrete close to the surfaces present a slightly lower humidity due to the natural authorised drying on the plane faces.

WALL BEHAVIOUR UNDER TEST CONDITIONS

The tests were performed as described before.

Experimental observations and discussions

During the air test (T1), the flow output measured, Q_{tot}, was essentially dry air, at ambient temperature, while the mass of vapour stayed under 0.4% of Q_{tot}. The curve (on figure 5), giving the output flow according to the pressure, shows an increase of flow more important than those expected with Hagen-Poiseuille law (linear link between Q_{tot} and $\Delta P^2 = [(P_1)^2 - (P_2)^2]$), when the effective pressure exceeded 0.26 Mpa. After the stage at 0.42 MPa in the autoclave, several stages were made before coming back to atmospheric pressure on the two faces. Those stages put in evidence the reversibility of the phenomenon and so the material structure was not modified. Although the humidity sensors manifested no variation, local water transfer in the pore system could explain this phenomenon. Pihlajavaara [5] made the same observation: an unexpected increase of the gas flow through the porous material when a threshold pressure was exceeded. The threshold could be dependent on capillary pressure and the level of humidity within concrete.

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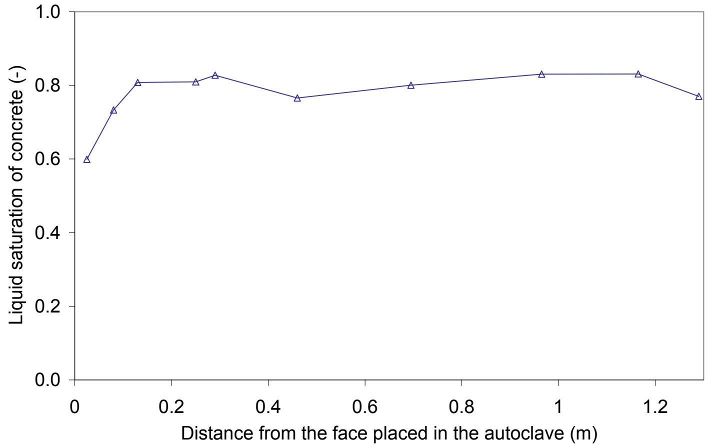

Figure 4 Variation of humidity content before testing

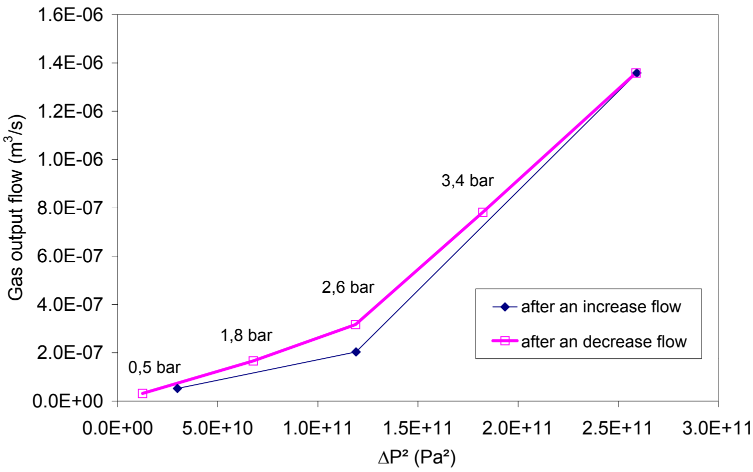

Fig. 5 Gas output flow according to variation of pressure during the air test (T1)

The Klinkenberg's concept (or the Carman's concept) allows to distinguish the different characteristics of the gaseous flow in the concrete ([4], [6]): during this air test (T1) the molecular contribution (noted Q_{mol}), i.e. slip flow and Knudsen flow, was around 9% of Q_{tot}: the Klinkenberg's parameter b*, indicative of the porous network fineness, was equal to $9.2.10^3$ Pa. This slight contribution of Q_{mol} to the total flow confirms the mercury porosity results which indicated that the gaseous flow would be mainly governed by a more spacious capillary network than ordinary concrete. Note that b* coefficient here corresponds to a humid state (the decrease of liquid saturation induces indeed a bigger contribution of the micro-pores to the total gas flow and also an increase of b*).

The pressure fields measured were clearly non-linear (Figure 6). The intrinsic permeability profile of the concrete specimen confirms this convexity (see Fig. 3); almost a linear form - slightly concave - would be obtained with a uniform permeability.

The main factor inducing a variation of mass transfers parameters is the liquid saturation of the porous network; now the sensors of humidity manifested no variation during all this air test phase. This aspect must be compared to the results obtained under accidental conditions (see next section) where the humidification of concrete will govern the kinetics of mass transfers.

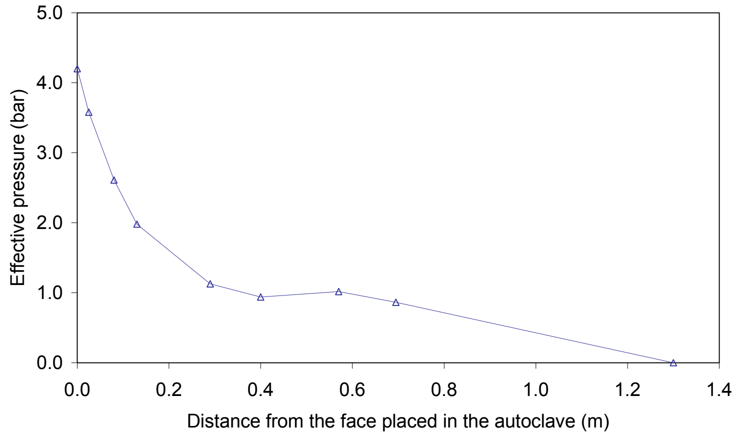

Fig. 6 Effective pressure field in steady flow ($P_{autoclave}$=4.2 bar) during the air test (T1)

During the air plus vapour test (scenario T2), the convexity of pressure fields was indeed more important because of the decrease of effective gas permeability with the increase of water content. This humidification progressed within this concrete specimen according a speed equal to 1cm/h during the first twenty hours to become gradually very slight when the colder zones were reached. Besides the information given by the moisture gauges, the pressure meters measurements were also an indicator of the progression of a hydraulic pressure field in the concrete corresponding to a saturated zone. Therefore two methods are presented on the figure 7 (from humidity sensors and from the pressure fields – hydraulic pressure notion, see [7]) to estimate the progression of humidification front within the concrete specimen.

Concerning the thermal transfer, about a hundred hours was necessary to obtain the steady state. At the end of solicitation, the 100°C isotherm reached around 20 cm from the face subjected to accidental conditions and the temperature at the lower face is around equal to 30°C.

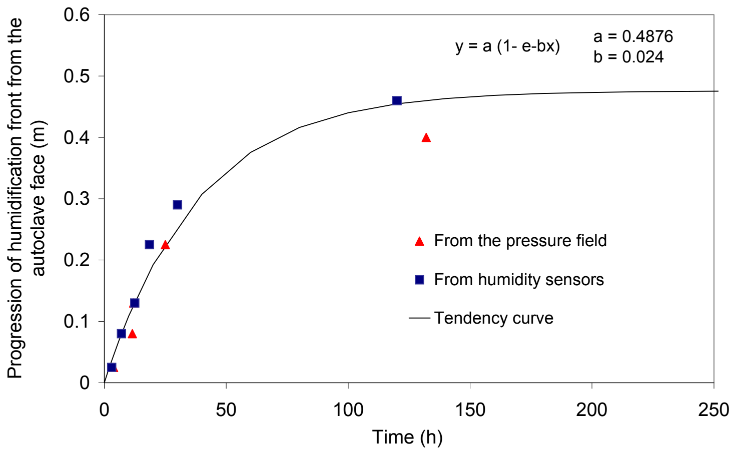

Fig. 7 Humidification of concrete specimen during the air plus vapour test (T2)

The gas flow measured on the extrados of the specimen was maximum (2.5 ml/min) at 70 hours, after that progressively decreased to become immaterial (Figure 8). This kinetics corresponds also to a decrease of the pressure field in the colder zone of the concrete specimen (following on from the saturated zone) after 70 hours. The gas output flow was mainly dry air coming from the autoclave during the transient phase; from thermodynamic tables (saturation vapour pressure and mixing ratio in relation to temperature), the results show a proportion of dry air mass flow which is about 38 times superior than the water vapour mass flow.

The measurements presented many oscillations mainly due to a low compression/expansion phenomenon of the gaseous volume located above the flow meters; the average curve was obtained using the *CurveExpert* program [8].

In spite of the pulverisation of a hydrophobic product on all the surfaces of the recuperative system, the drainage of condensed water to the precision scale begun only after 140 hours of test. The liquid flow measured became then globally constant (around 1.1 g/h.m²) what corresponds to the stabilization of the saturated zone progression from this moment (see Figure 7).

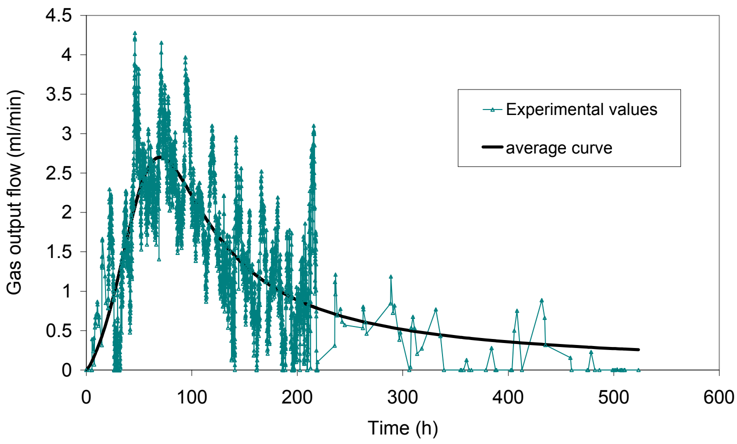

Fig. 8 Gas output flow during the air plus vapour test (T2)

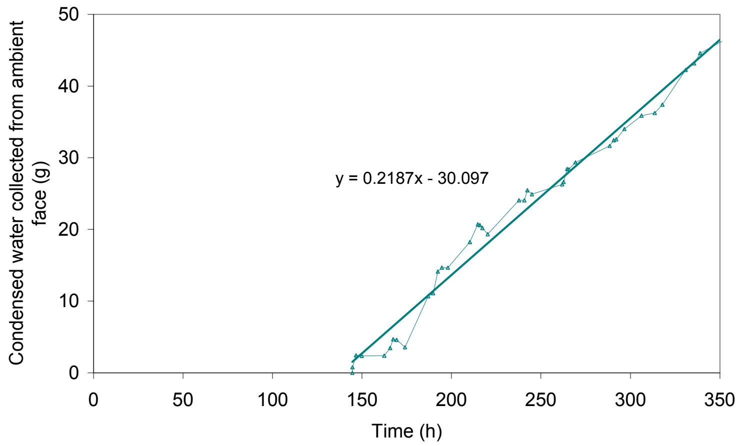

Fig. 9 Liquid water collected at the extrados during the air plus vapour test (T2)

CONCLUSION

The first laboratory test made the study of the permeability and the type of flow (laminar) possible through the wall realised with a porous concrete, without dimensional scale effect. The value of the flow output (about 25 Nl/h.m^2) was also obtained under leak test condition of reactor containment.

The profile of the intrinsic permeability along the specimen influence the field of pressure experimentally obtained.

The second test correspond to an accidental situation type APRP, with a stage at 141°C and 0.42 MPa maintained during 250 hours. This duration allowed to highlight several flow processes:

1) A saturated zone of liquid water appeared at the surface and progressed rapidly in a first time (20 hours), slowly after and were stabilised in the first 0.3 m.

2) The gas flow measured on the extrados of the specimen was mainly dry air coming from the autoclave during the transient phase. The gas flow was maximum (2.5 ml/min) at 70 hours, after that progressively decreased to become immaterial.

3) In spite of experimental difficulties, a constant liquid water flow was observed on the extrados (1.1 g/h.m2), after 140 hours.

Looking comparatively the flow outputs in the two cases studied, the ratio mass of air (obtained during the ambient leak test) upon the mass of air plus vapour and liquid (obtained during the accident condition with temperature and vapour) was much greater than one, between 10 and 22.

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