The Development of Concrete Packages for Geological Disposal of B- and TRU Radioactive Waste: Collaboration Between ANDRA and RWMC

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ABSTRACT

A cooperation program on long-term concrete disposal packages solutions for ILW-LL has been developed between Andra (French National Radioactive Waste Management Agency) and RWMC (Japanese Radioactive Waste Management Funding and Research Center). The main application of this cooperation program has been high retention ability packages (confinement and durability) for hulls and end pieces in CSDC canister. Respective package designs differ slightly. The RWMC package is based on Ultra High Performance Concrete monolithic package manufactured by continuous placing. Andra package designs are based on High Performance Concrete: one option is a monolithic type package; another option investigates the performance of concrete junction with small poured concrete lids.

The paper focuses on respective approaches and cooperation in two specific areas: thermal crack prevention design and associated tools, and manufacturing results (full scale and small scale mock ups).

Each partner has consolidated his own approach and benefits from the experience and expertise feedback of the other partner on similar problems. Cooperation is fruitful especially in knowledge and methodology consolidation, and in the package industrial feasibility performance check.

INTRODUCTION

ILW-LL waste result mainly from spent fuel reprocessing (e.g.: hulls and end-pieces) and from the operation of research centers. France and Japan share the need to find solutions for such ILW-LL waste disposal in geological strata. The solutions require the use of a waste disposal package that complies with repository long-term requirements, and achieves unit waste grouping and standardization for the handling process.

For the ILW-LL waste, disposal packages made of concrete are the solution considered by Andra in France for deep geological disposal in clay or granite. It is also a solution investigated by RWMC for Japan. It is also considered a solution investigated by RWMC as an alternative technology for geological disposal in Japan. The package for long-term confinement is required for poor geological condition, e.g. high permeability or high hydraulic gradient because the design and location of the disposal site of the TRU waste of Japan has not been selected yet.

This common interest has been the basis of cooperation between Andra and RWMC. This cooperation has been focused on challenging research and industrial feasibility areas. A common field of investigation for high retention ability (confinement and durability) is concrete package solutions for disposal of hulls and end pieces. RWMC has developed a package design for a 60 000 years lifetime, and Andra has explored the feasibility of an alternative package design for a 10 000 years lifetime objective.

The comprehension of the difference in the designs has been a first field of mutual information. Then, the high level of requirement has developed the need for similar research and industrial feasibility work on concrete package crack prevention, and on manufacturing feasibility.

This paper describes the respective approaches and the mutual benefits of cooperation on concrete waste package development: it recalls first the package designs, and then shows the development in crack prevention analysis and manufacturing capability and some package performances.

CONCEPT

The framework of the studies for deep geological repository is defined by national approaches. Andra and RWMC have developed their packages accordingly. We present below the respective design objectives and the associated packages. We will put an emphasis on high retention ability and long term performance package for hulls and end pieces, which has been a key part of the collaboration.

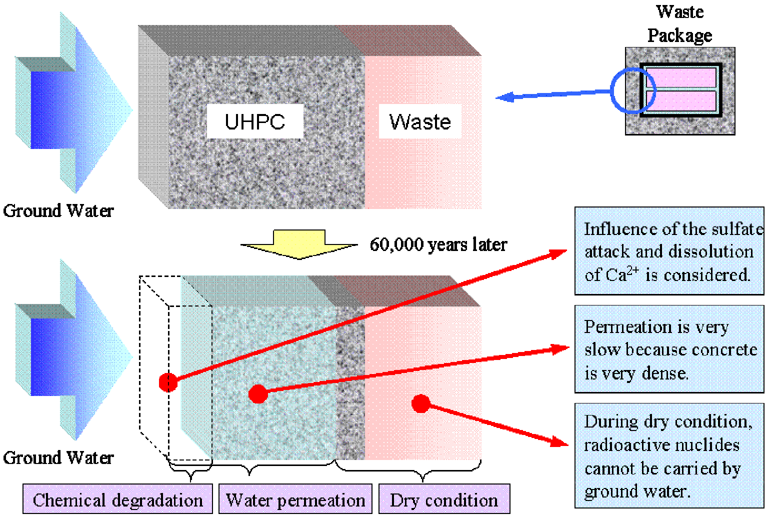
Concept of the Japanese packages

The reference packages in the 1st and 2nd progress report of the TRU disposal in Japan [1,2] has shown as the only concept to evaluate the performance of the repository, because the design and location of the disposal site of the TRU waste of Japan has not been selected. If the suitable geological and hydraulic condition is chosen, only mechanical performance during handling is required for the waste packages. On the other hand, to reduce the influences from low-sorption nuclides such as I-129 and C-14 was required for the condition with high permeability and/or high hydraulic gradient. It has been required the actual design considered the mechanical properties, handling, fall strength and so on. RWMC has been developing some concrete packages to prepare the options for various geological environment [3].

RWMC has developed two concrete packages for 200 litter drums and one for hulls and end pieces canister, almost the same as CSDC, for desirable condition. One package for drums is similar to the standard package design in France and it is made from ordinary reinforced concrete with the gas-vent system using the gas-permeable mortar [4]. Another one for drums is reinforced high performance concrete package that can contain radionuclides for 300 years. The other is the reinforced concrete package for canisters [4]. These packages have been designed with consideration of fabrication, handling, gas generation and falling accident [3].

RWMC has also developed a long-term confinement concrete package (LCCP). The target duration of this package is 60 000 years that is expected sufficient reduction effect of dose from C-14[3]. The package is made from ultra-high strength low permeable concrete (UHPC) with 200MPa compressive strength. The UHPC is a kind of the fiber reinforced reactive powder concrete.

The dimension of the LCCP is 1.8m×1.8m×1.6m and inner-steel-box housed 6 canisters horizontally are placed in the LCCP (shown in figure 2). The total weight is expected about 17 metric tons which is limited by the handling capacity of the fork lift truck. The dimension of the LCCP was decided in consideration of the handling in the disposal gallery shown in progress reports of the TRU disposal in Japan. The gap between the inner-steel-box and canister is filled with silica sand. Reduction corrosion of hulls and end pieces is very slow ($<5\times10^{-9}$m/year) under the alkaline condition expected in TRU repository [2], and also the volume of the gas generated by radiolysis of the UHPC is considered very small. More over, the air space in the sands moderates any potential increase of gas pressure due to those hydrogen releases. Minimum thickness of the concrete wall of LCCP is set 20cm which is expected sufficient to confine the radionuclide for 60 000 years from the results of the calculation.



Influence of the sulfate attack and dissolution of Ca^{2+} is considered.

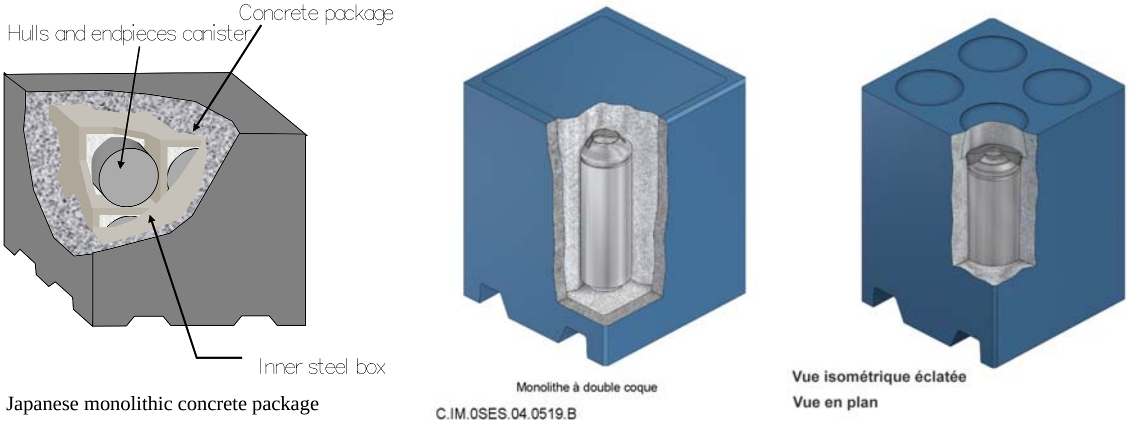
Permeation is very slow because concrete is very dense.

During dry condition, radioactive nuclides cannot be carried by ground water.

Fig. 1. The concept of long-term confinement of LCCP package

Fig. 1 shows the concept of the long-term confinement of LCCP. The water permeation was thought to be limited by the low water permeability (4×10^{-19}m/sec) of UHPC. The value had been obtained by the CIP method [5]. Duration of the water tightness of the package was evaluated by the water permeation and chemical degradation coupling calculation that includes increase of porosity by Ca-dissolution and exfoliation by ettringite generation [5]. Voids, cracks and placing joints of the concrete are thought to be the pathways of migration of radionuclides. To avoid the placing joint and crack prevention are considered as the determinant technology of this concept. The porosity of the UHPC is about 5vol% which is significantly lower than that of ordinary cementitious material. The pore in the UHPC won't be expected to be pathway of water and radio nuclides from the result of numerical simulation with the percolation theory[5]. To avoid the placing joint, continuous placing manufacturing methods have been developed.

Continuous placing uses the high fluidity and slow hardening characteristics of UHPC. The feasibility of the continuous placing was confirmed by the small-scale manufacturing. Because the hydration heat and shrinkage during hardening are expected to be causes of crack generation, RWMC has been developing the prediction calculation method for the thermal stress during hardening of concrete.



Japanese monolithic concrete package

Fig. 2. RWMC and Andra package designs for long-term performance: application to hulls and end pieces

Concept of the French packages

Andra has developed a standard ILW-LL waste disposal package which suits the requirements for deep geological repository in France[6]. Among the inventory, hulls and end pieces are characterized by a high proportion of radioactive gases (H-3, Kr-85 and C-14) and of long life radioisotopes such as Nb-94, Zr-93 and Cs-135. For those hulls and end pieces in CSDC canisters (15% of French ILW-LL inventory), it is therefore worth exploring the feasibility of alternative concepts for an enhanced long-term containment capability, similar to the RWMC concept.

Andra has developed two variant designs with enhanced long-term containment capability, which can be compared with RWMC designs. Their specific purpose is to delay radionuclide migration toward the exterior for several millennia (objective: 10 000 years). The other main functions of these variant designs are shared with the standard design: the disposal package must minimize the remaining internal and external voids in order to limit the long-term deformation in the geological massif due to lithostatic pressure. It also contributes to reversibility by the choice of materials that are relatively inalterable over periods of at least a century. Other functions are assigned such as handling requirements and standardization and the contribution to the integrity of the primary package in case of dropping.

In order to minimize voids two package design options are obligatory: i) rectangular geometry to limit the empty space between adjacent containers when stacked in disposal drifts, ii) a “massive” solid container limiting the volume of the internal voids.

The disposal package overall design is a parallelepidal shape concrete container weighing less than 25 metric tons. It is an irradiating object, requiring handling with forklifts under radiological shielding. It can contain up to 4 primary packages, to limit the total handling weight, reduce the size of the handling drifts in the repository, and optimize the arrangement of the containers. The disposal package is lifted from below and includes slots under the body for insertion of the fork.

The specificities of the variant design is to meet the long term containment performance objectives, which requires very low diffusion from the disposal package but also long-term mechanical integrity. The minimum thickness of the body wall and the lid necessary for durability and containment performances is 150 millimeters. The mechanical resistance is set to the lithostatic pressure of 12 MPa. The required minimum thickness of 150 mm with the selected geometry justifies the mechanical strength at a uniform lithostatic pressure of 12 MPa

The disposal package variant design has been detailed for hulls and end pieces in CSDC canisters. It accommodates 4 CSD-C in a concrete enclosure measuring approximately 1.5 × 1.5 m by 2 meters high, for a total weight of 12 metric tons. Two options that differ in their closure system have been considered: the "CPCC" with lid concrete jointing and the "monolith MDC" with a uniform monolithic "cast" around the CSDC.

The first option ("CPCC") is based on proven technology with a prefabricated body and closure by poured concrete forming plugs above each individual compartment for primary packages (fig 2). To obtain a high quality plug, an ultra high performance prefabricated concrete slab is placed in the tapered opening above the primary package and the concrete walls of the body are deactivated (improving the permeability and mechanical strength of the bonding).

A single high performance concrete formulation (~ 90 MPa) was selected for all the container components (plug and body). Components of the formulation (cement, aggregates, …) have been chosen on the basis of scientific studies recommendations for long term durability of concrete. Mechanical reinforcement is exclusively ensured by stainless steel fibers based on the calculated acceptable mechanical stress loading.

The second option (Monolith MDC) is a dual solution. It consists of a monolith built in a concrete shuttering. A concrete prefabricated outer box (as a shuttering) is first manufactured. The CSDC are laid in this box. Then, a monolithic filling of the inside of the concrete prefabricated box is achieved. This option has been selected instead of a pure monolithic approach, because no reliable solution of continuous filling was found. The scope of solution was restricted because it had to take into account a high performance concrete self-placing fiber reinforced formula.

A solution with single support for each CSDC has been developed for scale 1 manufacturing and performance testing.

CRACK PREVENTION

Crack prevention in long term high retention ability packages is a major concern, shared by Andra and RWMC. Both organizations have developed tools to calculate and estimate the crack risk. The needed data on concrete characteristics has been provided for the UHPC and for the HPC selected for the package designs.

Those tools use models in order to simulate the behavior of concrete in its early age (first days). They take into account the hydration of concrete, the thermal and the mechanical evolutions. They have been used for package development as described here below.

RWMC's crack prevention approach and manufacturing principles

In Japan, the thermal stress analysis tool had been developed to evaluate the crack generation of the thermal stress caused by hydration heat [7]. This analysis was composed of four parts of the hydration analysis, the thermal analysis, the structural analysis, and the crack assessment. The crack assessment is evaluated by the probability distribution depending on the crack index (Ratio of tensile strength of concrete / tensile stress)[8]. Relation between degree of hydration and characteristic of strength growth were acquired experimentally. The relationship between hydration and hardening is understood by the results of the measurement of total calorific value by conduction calorimeter and measurement of strength, and thermal stress on the hardening time was evaluated.

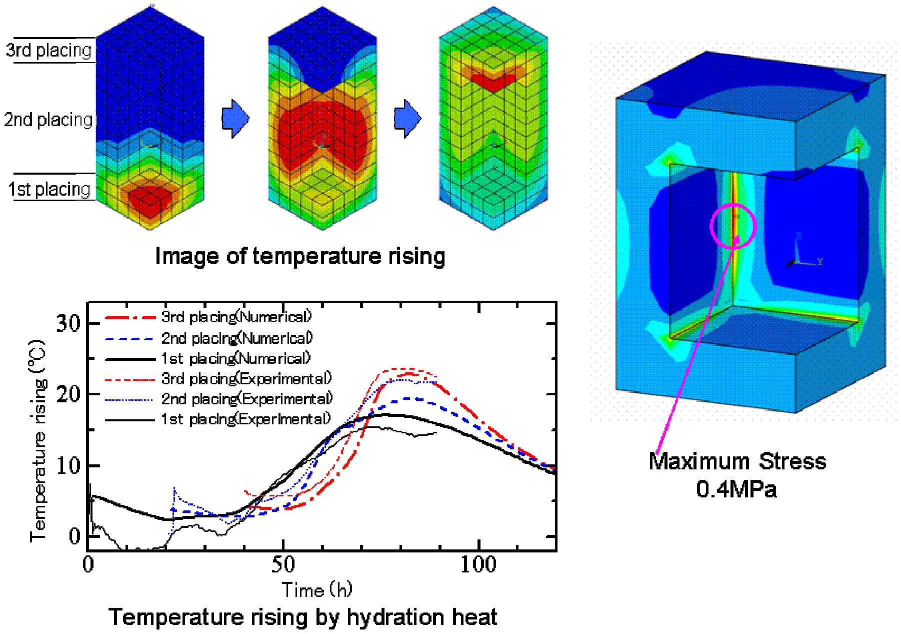


Fig. 3. An example of the results of thermal stress analysis

Fig. 3 shows the evaluation result in the small-scale model condition as one example of the evaluation with the thermal stress analysis tool. The crack index of the part of maximum stress was approximately 1.5, which meant the probability of the crack generation expected as about 20% in the ordinary concrete. The part of the maximum stress was agreed with the cracking part of the small-scale manufacturing.

Therefore the RWMC design and manufacturing principles for long-term confinement are to avoid crack risk and also to avoid the placing joint. RWMC planed to make the LCCP as a monolithic package without placing joint. So, as the manufacturing of monolithic concrete package in usual industrial way had been thought to be difficult, the continuous placing method was developed. The thermal cracks were prevented by the optimization of the pouring and curing condition such as the pouring time, curing temperature and so on by using the results of thermal stress analysis. The inner buffer was inserted between inner-steel-box and LCCP to defuse the hazard of cracking caused by the shrinkage of UHPC. The effect of the inner buffer was confirmed by the 10cm×10cm×40cm scale specimen[8].

Andra's crack analysis modeling and full scale assessment

In France, two models are available for crack analysis. Early age behavior of concrete is based on complex multi-physical and multiscale phenomena. The prediction of the cracking risk and the residual stresses in the hardened concrete structures is still a challenging task. The first model (OXAND SA) has been used on preliminary mock-ups and for comparison on the RWMC small scale UHPC mock up. This model shows a quite good agreement with experimental data. It can be improved with more accurate basic data given by a better concrete acknowledgment (i.e., Young modulus, autogenous shrinkage) The second model developed by ENS LMT-Cachan has been used for some mock ups and the full scale packages.

ENS LMT proposes a practical method to characterize the material parameters on the construction site and to identify a macroscopic model from simple tests. The identified model can then be used to predict the cracking risk and the residual stresses in a massive structure. Concrete at early age is considered as a poro-visco-elastic material with physical and mechanical parameters depending on the hydration degree ξ. As phenomena are strongly non linear, an incremental procedure (with three steps at each time increment) is implemented in a three dimensional finite element code. Such a chemo-thermo-mechanical model identified with simple lab test enables the determination of the cumulated damage and the residual stresses in any complex structures.

Step 1: Calculation of the degree of hydration at each node at time t_n with chemical affinity $A(\xi)$ and Arrhenius law for the thermodynamic force driving hydration:

$$\dot{\xi} = A(\xi)\times\exp\left(\frac{-E_a}{R\times T(t_{n-1})}\right)$$

Step 2: Resolution of the heat equation at time t_n to determine the temperature at each node:

$C\frac{\partial T}{\partial t} = div\left(k(\xi)\times\underline{grad}(T)\right)+\dot{Q}(\xi)$ with $\dot{Q}(\xi)$ the hydration heat source

Step 3: Mechanical computation at time t_n of the total strain and the damage function D:

$\dot{\varepsilon} = \dot{\varepsilon}_{elastic} + \dot{\varepsilon}_{creep} + \dot{\varepsilon}_{thermal} + \dot{\varepsilon}_{shrinkage}$ with

$\varepsilon_{elastic} = \frac{1+\nu}{E(\xi)\times(1-D)}\sigma - \frac{\nu}{E(\xi)\times(1-D)}tr(\sigma)I$ the elastic strain coupled with damage D (macrocracking occured when D=1). Such a model can be identified through compressive and flexural tests,

$\varepsilon_{creep} = J(\xi,t)\times\sigma$ the creep strain based on a Maxwell viscoelastic model. Creep function can be identified through a passive restrained shrinkage test (ring test in our case),

$\dot{\varepsilon}_{thermal} = \alpha(\xi)\times\dot{T}$ the thermal strain;

$\varepsilon_{shrinkage} = \varepsilon^{\infty}_{shrinkage} \times \xi$ the autogeneous shrinkage. Free shrinkage tests provide the material parameter.

The Andra's approach has been to use the models in order to help design packages with low crack risk. The model predictions were used to help in positioning the instrumentation in the mock-ups and in the full-scale packages. The demonstration program with full-scale manufacturing has provided detailed results with instrumentation including temperature and very precise extensometers (vibrating wires): micro deformations of a few µm are accurately detected. It has helped in improving the understanding of the phenomena and in fine-tuning of the models in relation with the concrete properties and the package shape and characteristics. These models have been assessed during the package demonstration program in 2004 and 2005. They provide a good evaluation of the crack risk zones. It is however still very difficult to predict accurately the occurrence and importance of a crack. The program is now able to set up sensors at the key places into a demonstrator to monitor the concrete early age behavior. Some curves that indicate the strain versus time show clearly the microcracking.

Mutual benefit

The RWMC/ANDRA cooperation has led to compare a simulation made by Andra/Oxand with the results of RWMC small scale mock up. The temperatures curves are in good concordance. The UHPC data was not fully available, which explains that the mechanical behavior couldn't be reproduced. However, the simulation was able to confirm the influence of factors such as hot curing, and buffer placing.

This comparison confirms the possibility to use model for guidance in preliminary designs, but also emphasizes on the importance of having good data on concrete behavior. It shows that the present know how only enables to underline crack risks, and that further development studies are needed in order to improve the prediction capability of simulation tools.

The use of instrumentation on mockups and full scale demonstrators in UHPC and/or HPC is really important to validate the models used. It enables to cover a wide range of high performance concrete materials. A share between Andra and RWMC on the concrete data and instrumentation results will help and save time in improving the model's prediction accuracy.

MANUFACTURING

Small scale manufacturing (RWMC)

The feasibility of continuous placing method and the manufacturability of monolithic concrete package were confirmed by the small scale (60cm scale) manufacturing. Because the traces of the hanging wires and/or molds would remain as pathways of the water and radionuclides, the continuous placing method, shown in figure 4, was developed. The continuous placing method uses the difference of hardening time between accelerated UHPC and normal UHPC. The lower accelerated concrete and upper normal concrete were placed continuously, and the hanging wires were removed when the lower concrete hardened. Temperature and strain sensors were set on and into the model to detect the cracking and the tensile strain and temperature were measured during and after curing. After the manufacturing, some drilled cores were gathered from the sidewall of a model to verify the position of inner-steel-box.

The generation of the crack was determined by the results of the surface observation and the outputs from the strain sensors.

Some small cracks (0.3 to 0.5mm in width) were observed in the models of the case of large thermal gradient (in hot water curing) and no inner buffer. The place of cracking was almost the same position estimated by the thermal stress analysis. The abruptly change of the tensile strain was observed in the case of the cracked model. The discontinuity of the strain was considered to be caused by cracking[8].

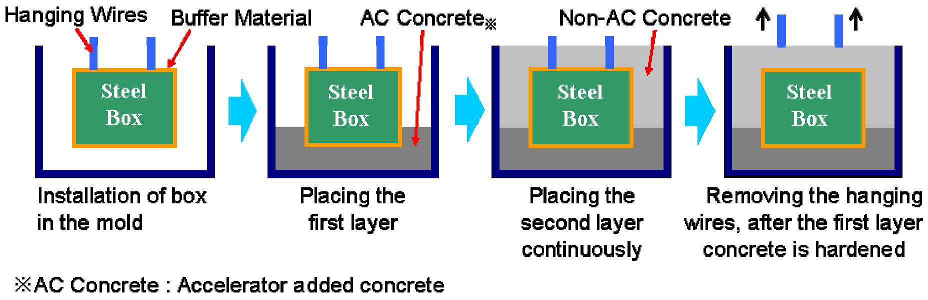


Fig. 4. Scheme of the continuous placing method

In the room temperature curing, no cracks on the surface and no discontinuity of the change of strain were observed. The surface observation and strain measurement is going on, and no cracking have been observed after 2 years from pouring.

Manufacturing of full scale demonstrator (Andra)

Under a joint CEA-ANDRA program [9] approximately 20 full-scale demonstrators have been manufactured; they cover different designs. Eight units are dedicated to the enhanced containment design with B5 packages of hulls and end-pieces (CSDC). Six units of the CPCC design and two units of a monolith MDC design have been manufactured by end of 2005. The monolith MDC design is at an early stage of study and its manufacturing will not be detailed in this paper. The program has demonstrated the feasibility of manufacturing the CPCC design and has also provided significant experience in industrial conditions. The manufacturing steps and main lessons are given hereafter.

Upright casting was chosen for the prototypes to avoid the delicate step of turning the casting upside down. A metal mould was used to be able to produce at least 6 units and get close to industrial conditions. The mould of the prefabricated body consists of two parts: an "outer form" composed of an assembly of metal panels and a “core structure” to reserve space for the four internal compartments. In order to improve the facing, a geotextile is set on all the internal walls and the cylindrical cores. This material acts as drain for air and water in the walls. This is necessary because of the use of self-placing HPC concrete (no vibration), which induces risks of air imprisonment in the concrete.

The mould meets two main requirements: (i) sufficient rigidity to reach the very strict container dimensional tolerance, (ii) absence of induced faults (cracking due to the prevention of concrete shrinkage by the mould). The external formwork (side and bottom panels) consists of steel plates and thick stiffeners (30 mm plate for the mould bottom). The mould bottom was ground to ensure the flatness tolerance on the stacking surfaces. The geometrical tolerances on the external casing panels are ± 0.5 mm to ensure geometrical conformity of the finished object with respect to the functional requirement. The formwork is assembled by large diameter bolts and numerous positioning systems. Chamfers are provided to minimize sharp edges on the container after removal from the mould. The container geometry is relatively simple and smooth, but a sharp angle remains for the trunconic reservations of the lids.

The “core structure”, consisting of a structure from which 4 cores are suspended, ensures the two following specific functions: (i) maintaining the cores through flexible links to limit stresses during concrete setting, and (ii) molding of the horizontal plane which supports the lid. The cores are tapered for ease of removal from the mould. They are machined from solid castings.

Fig. 5. RWMC 1/27 model (left) and Andra CPCC manufacturing (right)

The manufacturing operations can be divided in three phases: casting and concreting, mould removing and curing. The container materials are carefully prepared; in particular the moisture content of the limestone aggregate is checked. After the mixing phase, the concrete is poured into a skip then positioned above the mould where it is slowly injected. An important holding point is to check that the spreading diameter of concrete at the Marsch cone is sufficient. If satisfactory, concrete is injected through a PVC tube at the bottom of the mould; the tube is gradually raised as the concrete fills. The concrete containers are then protected from drying and from air streams in the workshop by covering the entire formwork with a protective enclosure.

The removal of the formwork from the 4 cores is a delicate operation. The cores (metal cylinders) must be withdrawn at the proper moment to prevent damage to the fresh concrete by premature removal of the core, or possible adhesion of the cores due to concrete shrinkage. The correct period was determined by curing measurements, i.e. temperature monitoring to characterize changes in the concrete formula during curing until hardening to determine the moment for removal of the moulds. The temperature at the core of the concrete in the mould and the ambient temperature are monitored. For the CEM V formula used, the optimum period for withdrawing the cores will be between 27 and 34 hours after removal from the mould[1]. Once the 4 cores have been removed, the lateral forms are removed.

The container is put back under the protective enclosure then transferred out of the manufacturing area in order to allow removal of the fork recess moulds. The external facing of the container has a uniform appearance that is slightly grainy due to texture of the geotextile. The quality of the external facing improves the durability of the container notably by limiting migration phenomena Formwork geometry measurements before and after casting did not show any notable geometric variation between the initial form of the mould and the container. Fig. 5 shows an overall view of the CPCC demonstrator.

One CPCC package has been specifically instrumented to study the behavior of the concrete during its early curing phases (deformations and risks of cracking, induced by inherent and prevented shrinkage, during curing). The research program also includes numerical modeling of the physical and chemical changes in the cast concrete. Deformations are measured using vibrating-wire extensometers. This sensor technology is robust and durable. The installation procedure does not disturb the deformation fields in the observed areas. This type of equipment can be used to monitor the risk of cracking. The excellent precision and reliability of these measurements enables long-term monitoring.

This instrumentation was installed after modeling the areas with the highest potential mechanical stresses. It includes nine extensometers together with local temperature measurements for the body of the CPCC. It also comprises relative humidity and temperature measurements at the core of the concrete. Material characterization on test specimens helped to determine the free shrinkage of the concrete over time as well as its thermal expansion coefficient. The parameters were measured over a period of 10 months and show continual shrinkage over time and a close agreement between the measurements on the test pieces and on the packages.

One of the main results of this experiment is that the relatively large deformations recorded do not lead to the formation of microcracks. This is probably attributable to significant concrete creep arising from pouring without vibration.

Drop tests on full scale package

The program development includes a 6m high drop test of the CPCC package in order to check that the primary waste package (CSDC canister) is leak tight after a drop accident in the repository, and that the recovery of the waste package after the drop is feasible. The test has been conducted in May 2005 for the worst-case scenario for the primary waste package: a corner drop. The results are excellent: the 12-ton fiber reinforced disposal package staid in equilibrium on the corner, with some long cracks, but without rupture. The handling of the disposal package was possible after the drop, with no consequence on the package mechanical status. A slight deformation has been observed on the top part of the CSDC canister located in the drop corner.

Mutual benefits

The information exchange in manufacturing between Andra and RWMC helps each partner to evaluate the advantages of a solution or an approach he has not yet envisaged.

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[1] 27 hours corresponds to the end of the setting period with concrete at 25°C — and 34 hours corresponds to the temperature peak of the concrete during its hardening phase

For instance, the RWMC small scale UHPC monolithic package proved the feasibility of a monolithic approach. On this basis Andra has checked the feasibility of monolithic packages within the 2005 constraints: use of HPC concrete only and no intermediate packaging of the CSDC. Although the results were unsatisfactory, and have led to a variant approach (MDC monolith), Andra knows that future works can be launched to develop such a monolithic solution if needed, but that it requires further preliminary studies on the concrete and the waste prepackaging.

Another example of the value of this cooperation is that the development of a full-scale approach is now seen as a further step needed for RWMC. The Andra's experience has shown the importance of the industrial scale test in assessing the feasibility of a given design. Its results have been shared with RWMC. Such an experience provides a lot of information and underlines difficulties that cannot be foreseen in the R&D and conceptual design phase. The scale change and the industrial environment brings up new problems such as the raw material supply quality and preparation, the equipment adequation to the concrete volume (need for more than one single concrete batch), and the factory team ability to comply with severe requirements.

CONCLUSIONS

The development of concrete packages with a requirement of high retention ability and long term performance is a challenging task. Andra and RWMC have already carried out important work to define and demonstrate the feasibility of concrete package designs for that goal. The exchange of technical information has proven to be fruitful for each partner, although the design basis on concrete and manufacturing approach are not alike. The information has been used mainly in the evaluation method (crack assessment) and in the manufacturing approach.

Andra has demonstrated the feasibility of the high performance concrete package by the full scale manufacturing (no crack, but some small lid concrete jointings), but has still to assess its overall confinement performance. RWMC has shown the feasibility of the long-term confinement by the concrete package (UHPC monolith without crack), but has still to confirm this feasibility on full-scale experiment.

A continuation of cooperation has been decided in order to check for non-destructive examination methods (crack detection) feasibility on HPC and UHPC concrete. More generally, this cooperation will also seek further developments on full-scale demonstrators feasibility and performance assessment, both on HPC and UHPC concrete solutions.

AKNOWLEDGMENT

RWMC executed this research “Development of TRU Waste Disposal Package” under a grant from the Ministry of Economy, Trade and Industry of Japan.

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