Concrete aging in containment building and deep geological disposal facilities: the odoba project

Christophe Marquie, Benjamin Richard, Alexandre Dauzeres, Georges Nahas

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CONCRETE AGING IN CONTAINMENT BUILDING AND DEEP GEOLOGICAL DISPOSAL FACILITIES: THE ODOBA PROJECT

Christophe MARQUIÉ[1], Alexandre DAUZERES[2], Benjamin RICHARD[3], Georges NAHAS[4]

[1] ODOBA Project Leader, Institut de Radioprotection et Sûreté Nucléaire, IRSN, Cadarache, France (christophe.marquie@irsn.fr)
[2] Head of the Structural Performance Modeling and Analysis Laboratory, IRSN, Fontenay- aux-Roses, France (benjamin.richard@irsn.fr)
[3] Head of the Research Laboratory for Migration and Interactions in the Geosphere, IRSN, Fontenay- aux-Roses, France (alexandre.dauzeres@irsn.fr)
[4] ODOBA Scientific Advisor, IRSN, Fontenay- aux-Roses, France (georges.nahas@irsn.fr)

ABSTRACT

Concrete is widely used in nuclear facilities (Nuclear Power Plants, Deep Geological Repository) and participate to ensure their safety. Aging may deeply impact the mechanical and containment properties of structures made of either concrete or reinforced concrete. Present knowledge regarding concrete pathologies is mainly based upon small-scale and separate effect experiments at laboratory level. Within this context, IRSN started the ODOBA international program. Its main objective is to improve the understanding of phenomena related to aging, to assess and qualify Non Destructive Examination and to develop and validate numerical models to predict pathologies evolutions at structural scale. ODOBA experimentation is mainly performed in Cadarache (South-East of France) on the ODE platform and consists of large-scale concrete specimenspecimen, highly instrumented. As today, 17 specimens representing containment building issue, were cast. DEF, ASR and coupled ASR/DEF are studied. The majority of the specimens will be submitted to accelerated aging by immersion in heated water pool. Some specimenspecimens are reinforced with steel rebars. First deformations are foreseen at the beginning of 2020. Today, ODOBA partners include US-NRC, CNSC (Canada), Bel V (Belgium), VTT (Finland) and NRA (Japan). NSC (China) should soon sign the ODOBA agreements.

CONTEXT

Nuclear Power Plants (NPP)

There is a general worldwide trend which lies in increasing the operating life of Nuclear Power Plants (NPP). In France, reactors were originally designed for a 40-year operating life. EDF wishes to extend it to 60 years. In some countries, there are plans for 80 years of operation. The new facilities, like EPR in Flamanville, are designed from the beginning for 60 years of operation.

Therefore, it is necessary to assess the ability for each component of the NPP to fulfil its safety requirements all along this extended period and assessmentof the adequacy of the maintenance and repair program carried out by the operator.. The issue is particularly sensitive for non-replaceable components such as the containment building.

The containment building is the third and last safety barrier between the radioactive materials and the environment. The containment building is both designed to withstand mechanical loading (plane impact, internal pressure after a severe accident, earthquake…) and to confine radioactive materials (leak-tightness).

Concrete pathologies were already observed on some plants in the World (Gentilly-2 in Canada, Seabrook in USA, affected by Alkali Silicate Reaction (ASR),

As aging could affect the safety margins concerning the containment building, there is an international concern about the evolution of concrete characteristics with aging, leading to R&D works. Within this context, IRSN decided to launch an ambitious research program called ODOBA devoted to study the concrete pathologies.

Deep Geological Repositories (DGR)

In France and some countries (Finland, Belgium, Canada…), the chosen option for long term depository of high activity waste is deep geological repository. Concrete may have a functional and safety role during operation and reversibility period, where removal of waste packages is “easy”. For the French CIGEO facility, this period should be at least 100 years.

Xx

CONCRETE AGING

Degradation of concrete due to aging might be the result of several phenomena:

- Irradiation: high neutron or gamma dose can lead to important reduction of concrete mechanical properties. Considering the irradiation level needed for such effect, Field (2015), it should be addressed only for some reactor designs (structural concrete close to the primary vessel) and for very long operation life (more than 60 years). This point is of little concern for the French containment building.
- Shrinkage/creeping: these phenomena lead to decrease the post-tensioning tendons for pre-stressed containment building. This issue was studied by IRSN, Hilaire (2014) and the validation of the mathematical model is carried out in EDF VERCORS mock-up,, Masson (2015). Concrete pathologies:
    - Freeze/thaw: considering climate conditions on French NPP’s site, this isn’t an issue in France.
    - Corrosion (rebar or tendons): the destruction of the passivation layer due to high pH of the cement paste can lead to corrosion of rebar or tendons (pre-stress) and thus to drastic evolution of traction capability. The main cause can be carbonation (decreasing of pH by reaction with carbonic gas) or chloride ion attack (from sea spray for seaside NPPs).
    - Internal Swelling Reactions (IWR): chemical reactions in the concrete create “swelling” products in the solidified concrete matrix from chemicals already present in the concrete. The Alkali-Silica Reaction (ASR) concerns reactions between the alkali species in the cement paste and reactive form of silica in the aggregates (e.g. opal). The Delayed Ettringite Formation (DEF) is a thermally activated reaction linked to the sulphate content. Usually DEF is the result of high temperature at early age (>65°C) but can also result from “late” heating.
    - External attack from species in solution in the pore or ground water, e.g. External Sulfatic Attack (ESA), acid attacks (Boric acid)…
    - Leaching of concrete by water.

Most of these phenomena can take years to begin (incubation period) and may evolve for decades, see next figure. For example, the Chambon dam in France was built in the 30s and, today, the stabilisation phase isn't still reached, Chulliat (2017).

They can lead to cracking, deformations, evolution of mechanical and transport properties. For example, in a laboratory study on DEF, Al Shamaa (2012), a 23% diminution of compression strength and a 30% diminution of the Young modulus were observed for an expansion of 0.2%. Also, the permeability increased by a factor close to 20. Even without direct impact on concrete properties, induced deformation might lead to loss of functionality (like alignment of access doors).

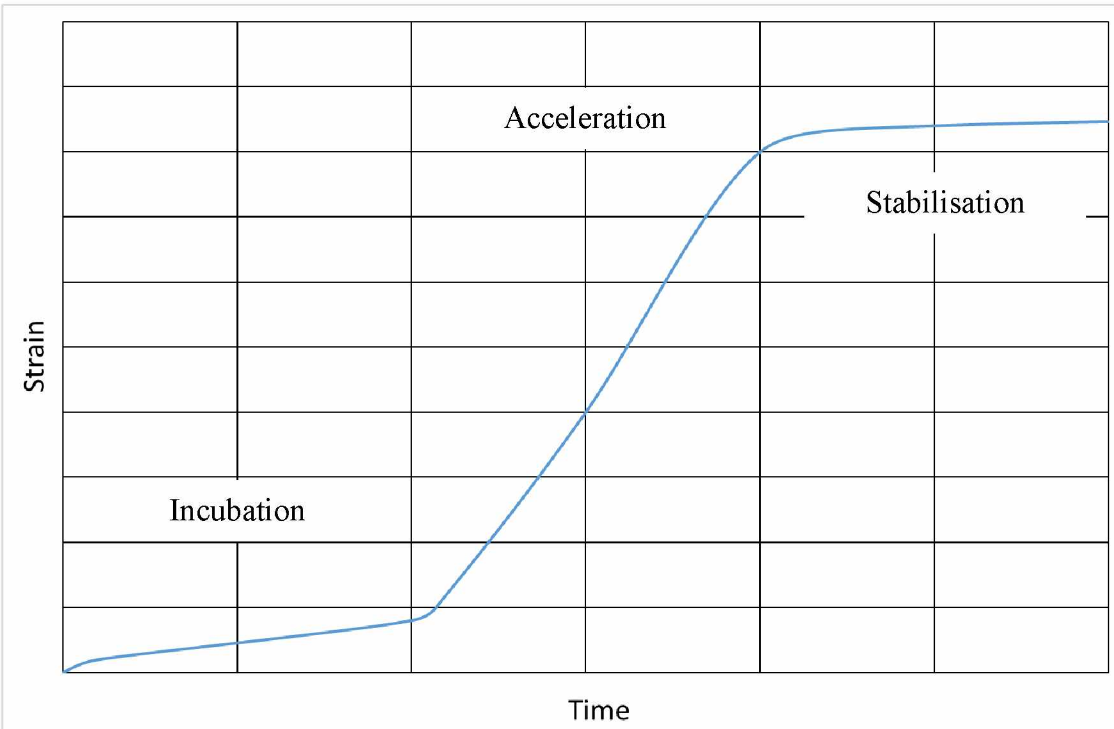

Figure 1. Typical Pathology evolution (arbitrary units)

As today, few nuclear facilities are affected by concrete pathologies, like Gentilly-2 in Canada (ASR), Seabrook in the USA (ASR), Tihange-2 in Belgium (ASR, carbonation and suspected DEF)… More might be affected in the next years. So, assessment of remaining years of safe operation for containment buildings or repository is of key importance.

STATE OF KNOWLEDGE

Within this context, the OECD/NEA (Organization for Economic and Cooperation Development/Nuclear Energy Agency) decided to launch the ASCET (Assessment of Structures subject to Concrete Pathologies) Workshop in 2014. A first phase of the workshop (ASCET Phase I – 2014-2015) was devoted to establish a state of knowledge and recommendations for research, code modelling and regulation.

The ASCET Phase I workshop, OECD (2015), concluded among others:

- Material testing based on cubic or cylindrical samples is not sufficient and can be misleading regarding the overall structural level.

- Concrete restraint due to the presence of reinforcement and pre-stressing, as well as boundary conditions in the case of concrete expansion, significantly modifies the behaviour in terms of ultimate capacity and displacements.
- The relevance of the use of reduced-scale specimens cured in chambers under uniform environmental conditions for the assessment of real structures is questioned. The real structures are not in such conditions: the degradation mechanism as well as the temperature and humidity are not uniformly distributed.
- The structural condition is rarely the consequence of a single degradation mechanism, unlike in a laboratory environment. Real structures are exposed to simultaneous actions of several degradation mechanisms, and it is not easy to assess their contributions in an overall structural condition.
- Due to difficulties in performing core drilling and other destructive methods in nuclear facilities, non-destructive tests should be developed to identify the damaged zones, the damage magnitude and the impact on the overall structural behaviour.

THE ODOBA PROJECT

Objectives of the ODOBA Project

Considering the importance of the pathologies potential effect on the durability of the nuclear structures in line with the long term operation extension, IRSN started the ODOBA project. Its objective is to address particularly “scale effect”, coupling between phenomena and effects of concrete confining (rebar or pre-stress) on pathologies. The final objective will be to develop and qualify numerical tools for prediction of structural behaviour of concrete affected by pathologies. It also studies the possibility to detect pathologies and monitor their evolution by non-destructive means. Mainly, the ODOBA project is based on experimentation on large concrete specimens on the ODE platform. The key parameters are:

- the concrete formulation: cement and aggregates types and content, water/binder ratio…
- the accelerated aging protocols,
- the concrete confinement: reinforcement, post-tensioning.

The ODE Platform

In Cadarache, in South-East of France, IRSN has built an outdoor 1,700 m² experimental platform called ODE, with a capacity of about 60 large concrete specimens. Each specimen has approximatively the following dimensions: 2 m high, 1 m thick (typical thickness of containment building wall) and about 4 m long. The specimens are instrumented with embedded sensors to follow temperature (thermocouples), deformation (vibrating string or optical fibre) and stress (strain gauges), humidity…

Alongside this “classic” instrumentation, more innovative means are studied: optical fibber measurements, pH sensors…

Periodic core sampling are performed in order to determine mechanical (compression and traction resistance tests), chemical (alkali, portlandite, sulphate and reactive silica content…) and physical (microstructure, porosity, permeability, diffusivity…) properties evolution.

Accelerated aging protocols

In order to assess the behaviour of concrete for 60 years or more of operation, it is necessary to apply accelerated aging processes. These processes have to be qualified (representativeness of the process, determination of accelerating ratio) and feasible for large concrete structures.

For ASR and DEF, some laboratory accelerating processes have been defined such as LCPC protocols, Fasseu (1997) and Pavoine (2007). However, that kind of process cannot be applied to the large structures planned for ODE as they imply a strict control of humidity and temperature and are defined for specific sample size. Moreover, these processes are developed for designing new structures in order to avoid such pathologies.

Considering the phenomena linked to ASR and DEF evolution and feasibility issues, coupled immersion-drying and temperature cycling is proposed. The ODOBA specimens are placed inside a pool with heated water, with a mixing pump to avoid temperature stratification. Depending on the studied pathology, chemicals might be added to water, e.g. alkali to avoid leaching for ASR or sulphate to develop ESA. Feasibility of such protocol was validated during a PhD study, Jabbour (2018), for ASR or DEF, for a given geometry of concrete specimen and for specific concrete mix.

A final qualification of aging processes will be obtained by having some specimens submitted to a natural aging during the 10-year experimentation planned period and to compare with core sampling on actual structures affected by pathologies. It is also planned to build concrete specimen representative of existing structure affected by pathology to compare results obtained on the ODE platform to measurement from the real structure.

Non-Destructive Examinations

The validation of NDE means in order to detect and monitor the evolution of pathologies is an essential objective of ODOBA project. At early stages, there is some evolution of concrete features such as porosity, Young Modulus and micro-cracking. That kind of evolution should be detectable by NDE means (acoustic measurement, radar or resistivity).The use of different technologies is required in order to discriminate from other evolutions like concrete saturation.

Usually, NDE are developed and used for near-surface exploration. As ASR and DEF can occur from the centre of the structure, it is necessary to adapt and validate NDE in order to inspect in depth around 50 cm inside the concrete.

A first step is devoted to the development and qualification of non-linear acoustic methods. Then it is planned to study resistivity methods.

For acoustic development, a progressive approach was chosen from small laboratory-scale specimen to ODOBA specimens. A first set of 7x7x28 cm^3 samples were casted to evaluate sensitivity of different acoustic methods for detection of DEF. Then, intermediate scale samples (40x40x70 cm^3) is used before implementation on large ODOBA specimens.

The small-scale specimen showed that, in laboratory conditions, acoustics method were not efficient to detect DEF at early stages (up to 0.2% deformation), Ouvrier-Buffet (2019). However, it is not excluded to detect DEF at larger scale where deformations are not free and will cause micro-cracking. Previous studies showed the possibility to detect ASR by acoustic means, Boukari (2015).

At medium scale, two type of specimen are studied. In the first one, ASR degradation is simulated by a sandstone ball placed at the centre of the specimen. Sandstone is known to have a strong non-linear behaviour that should be similar to ASR gel one. The objective is to develop non-linear acoustic tomography to detect and locate (at a known place) the sandstone ball. Then, a second specimen was casted with an ASR-affected insert inside an inert concrete. Results are expected by the end of 2019 summer.

At last, a specific ODOBA specimen was casted which is designed to develop ASR and in the upper part DEF. Sandstone balls were also embedded. Results are expected in 2020.

Status of the Project

The first 5 specimens were cast at the end of 2016. Since then, 12 other specimen were cast, all devoted to containment building conditions. The first specimens devoted to wasted management facilities are planned in October 2019.

A first specimen is a “non-pathological” specimen that is used as a reference specimen evolution without any pathology.

Seven specimens are devoted to the study of ASR. All specimens are based on the same concrete formulation but with different aggregate types: formulation A is made of reactive sand and non-reactive coarse aggregates whereas formulation B is made of non-reactive sand and reactive coarse aggregates. That will allow to study the effect of aggregate size of ASR development in large structure. The effect of reinforcement (typical NPP reinforcement rate) is also studied.

Table 1: ODOBA ASR specimens

Specimen Name/date of casting	Without reinforcement		Reinforced	
	Nat. aging	Acc. aging	Nat. aging	Acc. aging
Formulation A: reactive sand	BA 9/29/2016	CA 11/9/2017	DA 9/29/2016	EA 11/9/2017
Formulation B: reactive coarse aggregates	BB 11/16/2016	CB 11/20/2017		EB 9/10/2018

One specimen (HA) is devoted to the study of DEF triggered by a late heating of the concrete, like concrete near steam pipes in a containment building. PhD work is ongoing to define heating conditions. Heating is planned in 2020.

One specimen (ZA) is devoted to NDE mean validation (see above) and is affected both by ASR and DEF.

Eight specimens are devoted to the study of DEF. Two concrete mixes (B and C) are studied. For each mix, two early age conditions were simulated: a first one with a heating up to 80°C (T1) and a second one up to 70°C (T2). But the same "efficient energy" EE ($\int(T - 65°C) \cdot dt$) was kept for both conditions. One specimen of each formulation is reinforced.

Table 2: ODOBA DEF specimens

Specimen Name date of casting	Thermal history at early ages	Without reinforcement		Reinforced	
		Nat. aging	Acc. aging	Nat. aging	Acc. aging
Formulation C	T_{max} = 80°C EE = 1500°C.h	HB 9/17/2018	IB 9/18/2018		KB 5/15/2019
	T_{max} = 70°C EE = 1500°C.h		IC 10/18/2018		
Formulation D	T_{max} = 80°C EE = 1500°C.h	HC 4/9/2019	IA 5/14/2019		KA 4/10/2019
	T_{max} = 70°C EE = 1500°C.h		ID 10/22/2018		

Concerning waste issue, two set of specimens are planned to be cast in October 2019.
The first set of three specimens (1x1x1.7 m^3) is devoted to the study of ESA. Sulphate may come from ground water or may be released from waste packages. The specimens will be immerged in a water solution with high content of SO_4^{2-} and Na^+.

The second set of three specimens (same size) is devoted to the study of the evolution of concrete properties, in particular transport properties, of a specimen place in calcareous water.

For next years, study of the coupling between ASR and corrosion or the development of pathology for pre-stress concrete is foreseen.

CONCLUSION

Within the frame of the extension of NPP operation life and the future construction of deep geological repository, IRSN has launched the ODOBA project to study the concrete pathologies and their impact at structural level. The ODOBA project is carried out with international partners: as today CNSC (Canadian Safety Authority), NRC (US Safety Authority), Bel V (Belgian Technical Safety Organisation or TSO), NSC (Chinese TSO), VTT (Finnish research centre) and NRA (Japanese Safety Authority).

In addition, a scientific support to IRSN is given by French academic laboratories: École Normale de Paris-Saclay, IFSTTAR (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux - French institute of science and technology for transport, spatial planning, development and networks) , LMA (Laboratoire de Mécanique et d'Acoustique – Mechanic and Acoustic Laboratory – University of Aix-Marseille) and LMDC (Laboratoire de Mécanique et Durabilité des Constructions – Mechanic and Durability of Constructions Laboratory – University of Toulouse).

The final objective of the ODOBA project will be to develop and validate predictive tools to assess the capability of containment building or structural concrete in DGR to safely operate for long periods of time.

The ODOBA project is planned for at least 10 years of experimentation. First results are expected in 2020.

REFERENCES

Al Shamaa M. and al. Coupling between mechanical and transfer properties and expansion due to DEF in a concrete of a nuclear power plan, Nuclear Engineering and Design, 270, 2014,p : 70-77

Boukari Y., Bulteel D., Rivard P., and Abriak N. E. (2015), "Combining nonlinear acoustics and physico-chemical analysis of aggregates to improve alkali-silica reaction monitoring," *Cem. Concr. Res.*, vol. 67, pp. 44–51

Chulia O., Grimal E., Bourdarot E. (2017), "The Chambon dam case", *Dam Swelling Concrete 2017*

Fasseu P. (1997), "Alcali-réaction du béton : Essai d'expansion résiduelle sur béton durci", *Projet de méthode d'essai du LPC n°44*

Field K.G., Remec I., Le Pape Y. (2015), "Radiation effects in concrete for nuclear power plants – part I: Quantification of radiation exposure and radiation effects", *Nuclear Engineering and Design* 282, pp 126-143

Hilaire A. and al. Modeling basic creep in concrete at early-age under compressive and tensile loading, Nuclear Engineering Design, 269, 2014, p.: 222-230

Jabbour J. (2018), "Méthodes d'essais de vieillissement accéléré des bétons à l'échelle des ouvrages", PhD thesis, Université Paris-Saclay

Masson B. and al. (2014), "VERCORS: A 1/3 scaled mockup and ambitious research program to better understand the different mechanisms of leakage and aging", *Fontevraud 8: Conference on Contribution of Materials Investigations and Operating Experience to LWRs' Safety, Performance and Reliability*; Avignon (France); 15-18 Sep 2014 (46081735 INIS IAEA 2015)

OECD/NEA (2015), ASCET Phase I – Final Report

Ouvrier-Buffet F. (2019), "Quantitative nonlinear and linear elastic properties of concrete affected by delayed ettringite formation at early stages", *Construction and Building Material*

Pavoine A., Divet L. (2007), “Réactivité d’un béton vis-à-vis d’une réaction sulfatique interne”, *méthode d’essai des LPC n°66*