ACES

Towards Improved Assessment
of Safety Performance for LTO of Nuclear
Civil Engineering Structures

Řež, Czech Republic
November 7 - 9, 2022

ACES Mid-term Workshop
Book of Abstracts

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ABOUT ACES

ACES addresses the EURATOM Work Programme 2019-2020, dedicated to Nuclear Fission and Radiation Protection Research (H2020 NFRP-2019-2020). Specifically, the proposal addresses the following work programme topic: A - Nuclear Safety - NFRP 1: Ageing phenomena of components and structures and operational issues.

The main objective of ACES is to advance the assessment of safety performance of civil engineering structures by solving the remaining scientific and technological problems that currently hinder the safe and long-term operation of nuclear power plants reliant on safety-critical concrete infrastructure. Proper understanding of deterioration and ageing mechanisms requires a research strategy based on combined experimental and theoretical studies, following a multidisciplinary approach, and utilizing state of the art experimental and modelling techniques. Material characterization at different length scales (i.e. nano, micro, meso, and macro scales) is necessary, focusing on the physical understanding of the degradation processes (e.g. neutron and gamma radiation, internal swelling reactions, liner corrosion, etc.) as well as physical phenomena (drying, creep, shrinkage, etc.), and their influence on macroscopic mechanical properties and structural/ fuanctional integrity of the components.

The ACES project aims at having a significant impact on the safety of operational Gen II and III NPPs and impacting the design of next-generation plants. ACES will improve the understanding of ageing/ deterioration of concrete and will demonstrate and quantify inherent safety margins introduced by the conservative approaches used during design and defined by codes and standards employed through-out the life of the plant. The outcomes from ACES will therefore support the LTO of NPPs. This will be achieved by using more advanced and realistic scientific methods to assess the integrity of NPP concrete infrastructure. The project will provide evidence to support the methods by carrying out various tests, including large scale tests based on replicated scenarios of NPPs.

ACES engages 11 partners from five EU Member States (BE, CZ, FI, FR, SI) and two non-EU countries (UA and USA).

1. Partners

2. International Partners

PROGRAMME

Monday 7. 11. 2022		
Visit to Research Centre Řež		
8:00 – 9:15	Registration in KC ÚJV	
9:15 – 9:25	General welcoming	
9:30 – 12:00	Visit to facilities	
12:00 – 13:00	***Lunch***	
1st Presentation session – EUG view		
13:00 – 13:15	General welcoming	
EUG talk Session I.		
13:15 – 13:40	LTO in Czech Republic and regulatory requirements in ageing management	Antonín Kříž (SÚJB)
13:40 – 14:05	Ageing of concrete and beyond that during LTO	Pekka Välikangas (STUK)
14:05 – 14:30	Containment liner issues – Operational experiences Ringhals NPP – Unit 3	Johanna Spåls (Vattenfall)
14:30 – 14:55	Ageing management and monitoring of concrete structures at CEZ NPPs	Jan Stepan (ÚJV/ČEZ)
14:55 – 15:15	***Coffee break***	
EUG talk Session II.		
15:15 – 15:45	Perspective on ageing of concrete infrastructure and the challenges for LTO regarding concrete infrastructure	Madhumita Sircar (US NRC)
15:45 – 16:15	Challenges and Lessons Learned from LTO Implementation for Civil Infrastructure	Samuel Johnson (EPRI)
16:15 – 16:45	Irradiation impact of concrete cores from the biological shields of Oskarshamn 1 and 2	Ulrik Brandin (Oskersham)
18:00 – 21:00	**Project dinner at the Vienna House Diplomat Hotel**	

Tuesday 8. 11. 2022		
2nd Presentation session – ACES working progress		
9:00 – 9:05	General welcoming and Agenda	
ACES WP5 Session		
9:05 – 9:30	Progress report on Mesoscale numerical simulation	Yuliia Khmurovska (CTU)
9:30 – 9:55	Pre- and post-irradiation characterization of irradiated aggregates in CVŘ	Alica Fedoriková (CVŘ) Patricie Halodová (CVŘ)
9:55 – 10:20	Neutron transport, gamma irradiation and NDT of ACES samples	Petr Štemberk (CTU)
10:20 – 10:45	Concrete damage under radiation - modelling approach	Sicong Ren (VTT)
10:45 – 11:00	***Coffee break***	
ACES WP4 Session		
11:00 – 11:25	Creep and shrinkage concrete database covering 1700+ mixes	Vít Šmilauer (CTU)
11:25 – 11:50	Constitutive behaviour of VERCORS concrete in severe accident situation.	Herman Koala (EDF)
11:50 – 13:15	***Lunch***	
3rd Presentation session – ACES working progress		
ACES WP3 Session		

13:15 – 13:40	Microstructural and mineralogical characterization of concrete subjected to ASR and DEF	Tri Phung Qoc (SCK/CEN)
13:40 – 14:05	Interaction between the swelling due to ISR and creep due to bi-axial compression constraints	Georges Nahas (IRSN) Rita Tabchoury (IRSN)
14:05 – 14:30	Ongoing study of the correlation of expansion between large mock-ups and laboratory specimens for ASR and DEF	Yushan Gu (VTT))
14:30 – 14:45	***Coffee break***	

ACES WP2 Session		
14:45 – 15:10	Crevice experiments	Valdir De Souza (SCK CEN)
15:10 – 15:35	PEC techniques and experiments	Sokratis Iliopoulos (ENGIE)
15:35 – 16:00	Phenomenological modelling of embedded steel corrosion in concrete	Elina Huttonen-Saarivirta(VTT) Anssi Laukkanen (VTT)
16:00 – 16:30	**Closing of workshop**	

Wednesday 9. 11. 2022 Project WP meeting	
Technical meetings (It will take place in the premises of the Research Centre Řež)	
8:30 – 11:30	Work-package meetings WP 2, WP4 and WP5
11:00 – 12.00	Lunch
12:00 – 15:00	Work-package meetings WP3

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LTO IN CZECH REPUBLIC AND REGULATORY REQUIREMENTS IN AGEING MANAGEMENT

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ABSTRACT

Each nuclear facility will one day reach the moment when it exceeds its planned lifetime and, depending on its condition, it either ends its operation or continues to operate in the LTO mode. For the Czech Republic, the operating limit is set at 30 years. However, in order for a nuclear facility to be commissioned even after its planned lifetime, the facility must still meet the requirements set by the legislative framework. From this point of view, the LTO requirements are closely related to the aging management program. The aim of the presentation is to acquaint the participants with a short introduction to nuclear facilities in the Czech Republic and further on with the development and current status of legislative requirements in relation to long-term operation and the aging management program. In the final part, examples of the impact of the applied requirements on devices that are already in long-term operation will be presented. The issue will be presented from the point of view of the regulator authority.

KEYWORDS: regulatory, ageing managemant, long-term operation, requeriments, legislation

AGEING MANAGEMENT OF CONCRETE AND MODELLING IN PRA – REGULATOR POINT OF VIEW

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ABSTRACT

This presentation introduces regulatory point of view concerning ageing management of concrete structures of nuclear power plants and nuclear utilities in relation to radiation and nuclear safety. Nuclear utilities are presented briefly in connection to the title of this presentation.

STUK issues safety guides (YVL) to support the fulfilment of radiation and nuclear safety regulations in Finland. The ageing of concrete and the corresponding safety goals related system of YVL guides is presented. Oversight of ageing management is discussed from the safety guide YVL A.8 point of view. Requirements for ageing management of concrete structures traditionally focus on the design and construction phases since most of the relevant findings related concrete structures of nuclear power plants arise during that time. Today in Finland there is an ever increasing need to study ageing management also from the long-term operation (LTO) point of view. Ageing management issues during construction and lifetime of civil structures are discussed in addition to corresponding research needs. Cases for probabilistic risk assessment (PRA) studies are reviewed for typical post tensioned reinforced concrete containments and for typical reinforced concrete spent fuel water pools. PRA studies are based on clear identification of physical barriers. Corresponding design goals and monitoring are modelled in order to prove the fulfilment of the safety of utilities and environment.

KEYWORDS: Ageing management, nuclear facilities, concrete structures, PRA

CONTAINMENT LINER ISSUES, OPERATIONAL EXPERIENCES RINGHALS NPP – UNIT 3

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ABSTRACT

The containment building is a gas-tight shell around a nuclear reactor and primary circuit. The building is primarily designed to prevent or mitigate the uncontrolled release of radioactive material to the environment in operational states and in accident conditions. Ringhals Unit 3 is a Pressurized Water Reactor (PWR) and the containment building is a prestressed concrete structure with a steel liner. The larger part of the liner is embedded in concrete.

During a periodic test of the containment at Ringhals Unit 3 (containment leakage test) in 2016, a leakage through the concrete wall was found. The test was approved but an investigation was needed to find out the cause of the local deviation. The leakage was in an area where the liner is embedded in concrete. During the following years, actions were taken to find the cause of leakage, and finally, in 2020 a hole caused by corrosion was found in the embedded liner. The corrosion was caused by a wooden stud that had been wedged against the liner since the time of construction. During the search for the cause, different Non-Destructive test methods were used but none of them were able to detect the degradation of the liner.

The liner was repaired, and additional areas were checked to make sure that it was not a common mistake. No more deviations were found. A new containment leakage test was performed with an approved result and no local deviations were found.

KEYWORDS: Containment building, Corrosion, Embedded liner, Leakage test

AGEING MANAGEMENT AND MONITORING OF CONCRETE STRUCTURES AT CEZ NPPS

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ABSTRACT

The presentation is focused on the current state of ageing management and monitoring of concrete structures at NPPs operated by CEZ. An overall overview of the inspection methodology is provided, as well as examples of specific problems solved within the framework of the ageing management of concrete structures

PERSPECTIVES ON AGEING OF CONCRETE INFRASTRUCTURE AND CHALLENGES FOR LONG TERM OPERATION

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ABSTRACT

Most U.S. reactors have been granted a renewal of license to extend their operation from 40 to 60 years. The U.S. Nuclear Regulatory Commission has begun the subsequent license renewal process, reviewing license applications that would extend those reactors' operating lifetimes by an additional 20 years (80 years total) if approved. To support licensing decisions, the NRC initiated many research activities including Radiation Effects on Concrete Structures, Creep and Creep-cracking of Post-tensioned Concrete Containment Vessel (PCCV), and Alkali-Aggregate Reaction (AAR).

This presentation focuses on radiation effects on concrete structures. Reactor operation beyond 60 years (long-term operation) is expected to accumulate neutron fluence and gamma dose to levels that can potentially cause some degradation of the concrete bioshield and reactor pressure vessel (RPV) support structures. Past research indicates that the radiation degrades the concrete's physical and mechanical properties. Further research is ongoing to evaluate the safety performance of the RPV support structures.

This presentation also summarizes NRC's confirmatory research on PCCV creep and AAR.

KEYWORDS: Radiation effects on concrete, Radiation transport through concrete, PCCV Delamination, AAR

IRRADIATION IMPACT OF CONCRETE CORES FROM THE BIOLOGICAL SHIELDS OF OSKARSHAMN 1 AND 2

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ABSTRACT

Effects of radiation concerning concrete is a potential degradation mechanism from a perspective of LTO.

The level of exposure of the biological shield in a Pressurized Water Reactor, PWR, environment is higher than in a boiling Water Reactor, BWR, both neutron radiation and ϒ-radiation must be considered regard the biological shield. The critical levels are on 1x1019 n/cm2 for neutron fluence and 1x108 Gy for dose of ϒ-radiation.

The consequence will thus be that a critical level of the fluence in a crystal structure becomes for a population of concrete types a critical area. This effect can be seen in published data on the effect of compressive strength by increased fluence, where the relative compressive strength at first seems unaffected, but subsequently gradually tends to be reduced by increased fluence. The γ-radiation is thus more damaging to the aggregate than the reinforcement, the neutrons have an adverse effect on both concrete and reinforcement where a shift in transition temperature for brittle cleavage fractures occurs in relation to elevated temperatures.

At unit Oskarshamn 1, commissioned in 1972, the samples were taken in 1990 after approximately 20 years of operation, from the upper edge of the biological shield. At unit Oskarshamn 2, commissioned in 1974, the samples were taken in 2014, after approximately 40 years of operation, from the Main Circulation Pump Shield, MCP-shield.

In order to inspect possible degradation on the concrete with reference to effects of radiation, concrete core samples were taken and sent for material analysis to a laboratory.

Other materials analyses completed also indicate that the structure of materials should be assumed as unaffected after the above-mentioned periods of operation.

Testing performed at Oskarshamn 1 and 2, both BWR, strengthens the theory concerning that degradation of the concrete does not occur from radiation below the threshold value.

KEYWORDS: Irradiation impact, concrete, biological shield, MCP-shield

PROGRESS REPORT ON MESOSCALE NUMERICAL SIMULATION

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ABSTRACT

Concrete structures, such as biological shields of nuclear power plants, may be subjected to ionizing irradiation. Since concrete biological shields protect humans and environment from the exposure to radiation, these structures should satisfy the most stringent requirements in terms of durability and possible damage. It is known that the radiation-induced volumetric expansion of aggregates is the primary concrete deteriorating factor under irradiation conditions. Therefore, the radiation-induced volumetric expansion of aggregates needs to be predicted in order to estimate the service life of existing nuclear power plants as well as in order to choose appropriate materials for new nuclear power plant construction.

This work presents a progress report on Mesoscale numerical simulation of Radiation-Induced degradation of rocks, which are commonly used or potentially may be used as coarse aggregates in concrete biological shields of European nuclear power plants.

Nonlinear 2-D Rigid-Body spring model was implemented in in-house software in order to perform numerical analysis. Exact mineral composition of rocks was adopted from the Rietveld refinement of powder X-Ray diffraction data and used as an input for numerical simulation. The numerical model also takes into account irradiation temperature, neutron fluence and neutron spectrum of the used reactor. In order to validate the numerical model, the radiation-induced volumetric expansion obtained from the numerical simulation was compared with the experimental results on irradiated samples with identical mineral composition. The experimental results were obtained using three different techniques, namely helium pycnometry, water pycnometry and using Vertex 251HM MicroVu with touch sensors and optical profilometry. Numerical and experimental results show good correlation.

KEYWORDS: Neutron irradiation, Numerical simulation, Radiation-Induced Volumetric Expansion, Rigid-Body Spring Model, Radiation-Induced Volumetric Expansion

PRE- AND POST-IRRADIATION CHARACTERIZATION OF IRRADIATED AGGREGATES IN CVŘ

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ABSTRACT

The interest on ageing of concrete as structural material in nuclear power plants (NPP) has received increasing attention in the latest years, because of the increasing operational NPP lifetime. The main consideration is that, due to a radiation environment that lasts for decades, the concrete structure may gradually lose strength. This can be induced by damages due to periodic temperature changes, to irradiation effects such as volumetric expansion of the aggregates, and to irradiation-induced water radiolysis which results in loss of water and hydrogen generation within the concrete structure.

To predict the behaviour of concrete with increasing time of irradiation, quantification and modelling of the radiation effects on concrete main constituents are required. The aggregate composes up to 70% of concrete total volume and its behaviour under radiation has a direct impact on degradation of in-service concrete components in NPPs. The main role of Research centre Rez within the framework of the ACES project is to characterize how irradiation affects the concrete dimensional stability and strength, by means of irradiation of different types of aggregate that were used for construction of existing nuclear facilities. The irradiation of aggregate specimens was done in the LVR-15 test reactor in Research Centre Řež for two sets of samples, one with target fluences of 8.22E+18 n/cm2 (>1MeV) signed as Low dose and the second one to target fluence of 1.83E+19 n/cm2 (>1MeV) signed as High dose. Pre- and post-irradiation examinations contains non-destructive and destructive testing in Hot Cell facility in CVR and is carried out to study the phenomena involved, quantify the extent of aggregate damage, and build up an understanding of the concrete aging process.

For the purpose of evaluation and comparison of aggregate properties before and after irradiation, this procedure was designed for examination:

1. Photographic record of samples in five different positions for visual control
2. Weight and precise dimension measurement
3. Water and helium pycnometry for volume and density measurement
4. Ultrasonic pulse method to determine time of flight and dynamic E-modulus
5. Mechanical testing – compressive strength measurements (destructive)
6. Microstructure characterization including light optical and scanning electron microscopy
7. X-ray diffraction for evaluation of structural and mineralogical changes

The results will help to explain the causes and mechanism of the Radiation-induced volumetric expansion phenomenon (RIVE). The obtained experimental data represent one of the basic inputs to the calculations and simulation of the behaviour of irradiated concrete.

KEYWORDS: Aggregates, Minerals, Radiation-induced volumetric expansion, Neutron fluence, post-irradiation characterization

NEUTRON TRANSPORT, GAMMA IRRADIATION AND NDT OF ACES SAMPLES

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ABSTRACT

This contribution summarizes the progress in three areas of the ACES project, namely the irradiation fields characterization which includes the neutron, gamma, temperature and moisture content effects, then gamma irradiation and the NDT of ACES samples. Regarding the irradiation fields, a model of the reactor core of the first fuel loading of the VVER-1000 at the Temelín NPP in the Czech Republic, which belongs to the ČEZ company, was developed according to the available data and technical documentation. The model is three-dimensional and includes the precise geometry and materials of the internals and also the concrete biological shield. The model is now available for analyzing the irradiation fields according to a given fuel loading. The modeling strategy will be further extended for analyses of the irradiation fields of the VVER-440 reactors. Regarding the gamma irradiation studies, the planned activities which were based on the acquisition of the concrete samples harvested for the gamma irradiation chambers in Sosny were altered into the more topical activities related to the effect of gamma ray radiation on the degradation of the bond between concrete and reinforcing steel. The gamma rays cause both the changes in hardened cement paste and the corrosion of steel. The interface transition zone then is of interest and will be studied intensively. Regarding the non-destructive testing of the rock samples, a new methodology was developed and will be tested on the rock samples. A series of longer rock samples of the length of 2 cm was prepared so that the effectiveness of the developed method could be quantified more easily. The developed method is intended for measuring the mechanical parameters of the rock samples.

KEYWORDS: Neutron irradiation, Gamma ray irradiation, Concrete-reinforcing steel bond, NDT, ultrasonic testing, mechanical properties, rock samples

CONCRETE DAMAGE UNDER IRRADIATION – MODELLING APROACH

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ABSTRACT

Micromechanical models applied previously imply that the prevailing failure mode at microstructural level is the tensile failure. A new straightforward anisotropic plastic damage model has been developed to tackle the tensile failure at microstructural scale. To model alss the crack closure under compression, unilateral condition has been included in the model. Derivation is based on the idea of strain decomposition into elastic and inelastic parts - where the inelastic part is due to crack opening. The model has been derived and implemented in MFront environment. Preliminary numerical simulations with amitex FFT solver show that the proposed model is capable to tackle the failure of concrete. Later on, the damage model wil be merged with concrete creep and shrinkage model. Also, benchmark studies with FE software will be done as well. In parallel, we utilize phase field damage model within the micromorphic framework to address scale dependent development of the crack networks. The mechanics (visco-plasticity) and phase field are coupled in terms of free energy, which allows future implementation of creep and plastic constitutes inside depending on the outcome of the main developments of the contribution/project.

KEYWORDS: Anisotropic of damage of Concrete. Unilateral effect, FEM, FTT Phase-field.

CREEP AND SHRINKAGE CONCRETE DATABASE COVERING 1700+ MIXES

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ABSTRACT

Creep and shrinkage characteristics of concrete present an important input for design, construction phases, deformations, stress redistribution, prestress loss, maintenance or service life assessment. Due to high variability of mix designs and raw materials, considerable scatter of concrete properties exists. For the purpose of model benchmarking carried out within ACES project, a MySQL database has been assembled, being now the largest in the world. The majority of input data originated from Northwestern Creep & shrinkage database, over 100 new mixes were added from other sources including VeRCoRs concrete mixes.

The presentation will show database statistics and data mining for autogenous shrinkage, drying shrinkage, uniaxial basic creep and uniaxial total creep. Benchmarking against models B3, B4 and MC2020 will illustrate high scatter of results, coefficient of variation, and long-term (asymptotic) behavior. The differences between traditional Portland cements and current blended cements will be briefly discussed. The database presents an indispensable tool for uncertainty quantification, which is of paramount importance for structure reliability among nuclear facilities.

MODELING OF VERCORS CONCRETE BEHAVIOR UNDER SEVERE ACCIDENT SCENARIO

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ABSTRACT

VERCORS concrete is a standard concrete representative of the concrete used in the double-walled containment buildings of nuclear power plants. This study is part of the deepening of knowledge on the behavior of VERCORS concrete under accidental thermo-hydro-mechanical loading conditions. The objective is to implement and calibrate a creep model able to reproduce the instantaneous, transient and delayed deformations of concrete experimentally observed .The implemented viscoelastic model, based on the works of [Manzoni et al.,2019] and [Sellier et al.,2016], allows within the framework of classical poromechanics to partition the total external applied stress into two components; an effective stress corresponding to the part of the total stress that is applied on the solid skeleton; In the proposed rheological model, this component is represented by an association of a spring for the elastic strain, a Kelvin chain for viscoelastic creep and a Maxwell chain for purely viscous creep. The second component of the total stress corresponds to the water pressure allowing to take into account the effects of changes in capillary and disjunction pressure. During a temperature increase, an additional creep strain has been experimentally observed and under certain thermo-hydric conditions, the amplitude of this compressive strain is such that the concrete, instead of expanding under the effect of temperature increase, contracts instead. In order to take into account this transient strain in the model, a viscous deformation rheologically linked to the Maxwell chain was defined. The kinetics associated with this additional creep strain is driven by a micro-diffusion equation of water from concrete nanopores to capillary ones. Finally, a thermo-hydric coupled orthotropic damage model has been defined to take into account the microstructural part of the drying creep of concrete. The model has been implemented following an implicit scheme under MFront and tests have been performed via Code_Aster. The computational results show a good ability of the model to simulate the macroscopic creep of VERCORS concrete in temperature.

KEYWORDS: thermal transient creep, viscoelasticity, orthotropic damage, consolidation process

MICROSTRUCTURAL AND MINERALOGICAL CHARACTERIZATION OF CONCRETE SUBJECTED TO ASR AND DEF

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ABSTRACT

In the context of work package 3 of the ACES project, three concrete mock-ups were cast by IRSN and placed under specific conditions to evoke internal swelling reactions in concrete, specifically delayed ettringite formation (DEF) and alkali-silica reactions (ASR). After conclusion of the experiment, the mock-ups were cored for characterization. This presentation details the microstructural and mineralogical characterization of some of these cores. The microstructural characterization of the cores reveals that fractures are generated in each material, with either ASR gel or ettringite infilling. Due to the infilling of the fractures, the pore size distributions of the cores do not significantly differ from one another. Similarly, the mineralogical composition of the cores is similar with the exception of the nature of the siliceous aggregates used in the DEF core. The crystallization of ettringite was noticed in all cores, but only in those subject to DEF conditions was the crystallization of ettringite in fractures noticed, a strong indication of DEF.

INTERACTION BETWEEN THE SWELLING DUE TO ISR AND CREEP DUE TO BI-AXIAL COMPRESSION CONSTRAINTS

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ABSTRACT

Internal swelling reactions (ISR) can lead to the degradation of concrete due to expansion induced by such chemical reactions. They classically include the Delayed Ettringite Formation (DEF), the Alkali-Aggregate Reaction (AAR) and the occurrence of both simultaneously. The DEF may be developed in massive concrete structures under specific conditions, such as nuclear power plants that contain prestress reinforcement. Containment vessels are in France biaxially prestressed, which leads to concrete creep.

Recent research works show the importance of the effect of prestressing on the reduction of swelling due to ISRs, or even its cancellation for certain values of prestressing. These phenomena must therefore be studied and quantified, especially if the operating life of these facilities needs to be extended.

This work aims to carry out an experimental program under realistic conditions to study the coupling effect of ISR and creep. Innovative testing frames have been specifically designed for this study to induce a biaxial compressive stress state. Preliminary studies were done, and they verified the good functionality of the biaxial frames for concrete creep test. These tests allowed to assess the reliability of the optical fiber strain measurements as well as the associated data acquisition system. The experimental program has already been launched and concrete specimens were cast. The specimens were immerged in water and heated to 38°C for one month after an autogenous cure. Half of the concrete specimens were loaded biaxially, while the remaining half were left unloaded to measure their free swelling. To be representative of the history undergone at the early age of a massive structure, a temperature cycle in a climatic chamber under humid conditions is applied to concrete specimens to ensure the development of the DEF.

KEYWORDS: Internal swelling reactions, creep, biaxial creep frame, delayed ettringite formation, optical fiber.

ONGOING STUDY OF THE CORRELATION OF EXPANSION BETWEEN LARGE MOCK-UPS AND LABORATORY SPECIMENS FOR ASR AND DEF

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ABSTRACT

As laboratory studies of internal swelling reactions are usually performed on small-size samples, the obtained data is not able to reproduce the real condition to which the massive concrete structures are submitted. In order to correlate the behaviour of real-scale massive structures and the conventional laboratory samples, multi-scale experimental investigations of swelling reactions including ASR, DEF, and ASR+DEF were performed at IRSN. The objective of the current study is to analyse the obtained data and correlate the behaviour of real-scale massive structures with the residual expansion of core samples. The final target of this study is to provide recommendations for predicting the long-term concrete expansion of massive structures based on residual strain analysis. The residual expansion of core samples extracted at the beginning of the expansion is much higher compared to the swelling of mock-up blocks, and the swelling of mock-ups at different heights shows an obvious difference as well. This may be induced by the difference in moisture degree, leaching of alkali, temperature gradient, restraint effect from the metal plate, and the generation of micro-cracks in core samples due to the high-speed action of the drill. As the residual expansion of the core samples extracted at the later stage of expansion shows no significant effect of the height of extraction, it is indicated that the microstructure of materials is homogeneous along the height, and the restraint effect from the metal support is the main reason leading to the different expansion in blocks. A mechanical model taking into account the restraint effect and the damage of concrete is proposed in this study. The calculated results and the corresponding analyses are presented as well.

KEYWORDS: ASR/DEF, massive concrete, core samples, ultimate expansion, restraint effect, expansion pressure.

CREVICE CORROSION MECHANISMS OF STEEL LINER IN CONCRETE OF CONTAINMENT BUILDINGS

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ABSTRACT

Crevice corrosion mechanisms in containment buildings are also studied in this project through different corrosion experiments. SCK CEN approach combines electrochemical methods such as potentiodynamic polarisation (PP), Tsujikawa-Hisamatsu Electrochemical (THE) and long-term open circuit potential (OCP) to understand the possibility of crevice corrosion occurring and its mechanisms. The PP experiments are performed to obtain input information for the THE method. The THE method is used to nucleate (induce) crevice corrosion in a controlled way and determine the crevice repassivation potential while the OCP tests are performed without applying any external potential. The crevice is formed by pressing the cement paste block or mortar (crevice former) on the surface of the steel specimen using a support rod. The experiments are being performed with and without the presence of a crevice former in oxic and anoxic conditions using two different pH solutions: (1) a high pH solution (sat. Ca(OH)2, pH~12.5) and (2) a low pH solution (0.005 M Na2CO3 + 0.015 M NaHCO3, pH~9.5). SCK CEN performs experiments under anoxic conditions with dissolved oxygen concentration lower than 1 ppb. The results from PP and THE methods under oxic and a preliminary result under anoxic conditions indicated that at high pH solution crevice corrosion did not occur and at low pH, corrosion attack was observed mainly outside the crevice region. For these conditions, it was not possible to determine the crevice repassivation potential with the THE method. However, experiments performed with high pH solution containing chlorides, crevice was generated and the crevice repassivation potentials under oxic and a preliminary result under anoxic condition were determined. Long term OCP performed in oxic conditions with a crevice former indicated that crevice corrosion occurred at low pH but not at high pH solution. The tests under anoxic conditions are on going and an overview on the status of the experiments is presented.

KEYWORDS: Crevice, mortar, THE method, potentiodynamic polarisation, open circuit potential

PEC TECHNIQUES AND EXPERIMENTS

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ABSTRACT

In the framework of the ACES H2020 European Research Project and, in particular, Task 2.3 of WP2, the Pulsed Eddy Current (PEC) technique was evaluated for its feasibility to inspect corrosion in steel cylinder concrete pipes. The aim was twofold: a) identify commercially available PEC tools, define their technical specifications, assess their compatibility with a robotic manipulator and b) address the strengths and limitations of specific PEC probes. In the first case the products of two different manufacturers were researched and listed while in the second case laboratory size specimens (mockups) were designed and built. Six mockups were built in total. The mockups were replicating real pipe properties and included a steel liner and mesh. Mockups without mesh were also built for comparison purposes regarding interferences on the measurement results. Artificial defects were introduced in the steel liner of the mockups, in order to assess the detectability and the characterization potential of the technique. Four different sizes of defects were manufactured (100 mm, 75 mm, 50 mm and 25 mm diameter) with two different depths (1 mm and 2 mm). PEC assessment analysis included the experimental study of different parameters on the available mockups: equipment brands, probe types, interferences (mesh, border effect), lift-off and misalignment and scanning resolution (grid size). It was found that the systems of both manufacturers (Eddyfi and Maxwell) perform equally while small probes (i.e., small footprint) provide more accurate results compared to larger footprint probes. The presence of the mesh is influencing the results causing local distortion of the signals and wrong interpretation of material thickness losses. The borders have an equally negative effect on the mapping of the remaining thicknesses, while depending on defect size and location, they show masking of these defects. Concerning lift-off and misalignment, it was found that the higher they are the lower the sensitivity. The comparison of the 15 mm x 15 mm scanning grid with the 30 mm x 30 mm grid showed similar averaged thickness values and equal minimal values considering a tolerance of +/-0.1 mm. The latter implies that a bigger scanning grid is possible to use in real applications. Concerning detectability, it can be said that the minimum detectable defect is a cylinder of 25 mm diameter and 2 mm depth, this defect equals approximately 25% of the footprint volume of the smallest probe available. A third generation of probes is currently available on the market, this generation relies on array technology which improves the sensitivity by reducing the footprint.

PHENOMENOLOGICAL MODELLING OF EMBEDDED STEEL CORROSION IN CONCRETE

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ABSTRACT

Aging of critical components, systems and structures is important for the safety and long-term operation (LTO) of nuclear power plants (NPPs). Concrete structures are an essential part of NPPs, with tight integrity criteria. However, corrosion of steel embedded in concrete may challenge the integrity of concrete structures, like containment liner and steel cylinder concrete pipes. Improved understanding of corrosion phenomena on embedded steel structures can be achieved via phenomenological modelling. Particularly, the behaviour of steel associated with crevice corrosion mechanisms is of interest, as this topic has seen limited modeling efforts in the past. Similarly, it can be argued that typical corrosion models for concrete suffer from a high degree empirism, which is apparent in the large number of parameters and evolutional laws necessitating calibration, limiting their applicability and use in assessment of LTO performance and safety.

To address these, we present a modelling concept and a framework for constructing and developing corrosion models for steel embedded in concrete. We especially focus on explicit and full field microstructural modelling of steel-concrete system, this is foreseen ultimately to increase the applicability and interpretability of the modeling outcomes as direct comparisons to experiments are more straightforward. Our approach is based on introducing a multiphysical coupling to the respective mechanisms: electrochemistry, transport, corrosion reactions and thermomechanics, in the frame of microstructural modelling. This enables us to construct and tailor crevice corrosion models for steel-concrete systems. A simple analysis example is presented demonstrating the present work.

KEYWORDS: Corrosion, steel, concrete, crevice corrosion, electrochemistry, multiscale modelling