TESTING OF CONCRETE IN NORWAY AS RADIATION PROTECTION SHIELDING

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ABSTRACT

The concrete in nuclear power-plants plays not only the structural role, but also the role of shielding material that has to absorb neutron and gamma irradiation. Concrete consists mostly of aggregates, Portland cement and water. The final properties of the concrete are affected by the mixing ratio of the components, the quality and composition of the local aggregates and the water used. A major influence on physical and mechanical properties is given by the water content in the concrete. The gamma irradiation is being absorbed at the passage through concrete, what can induce water radiolysis in the material and consequently chemical reactions leading to changes of the concrete phase composition and thus the hydration degree decrease. It negatively affects the mechanical properties, and enhances shrinkage of the cement paste. Neutron radiation has a swelling effect on the properties of crystalline material such as the aggregates of concrete. There is limited data available on the microstructural, mechanical and physical changes in concrete due to radiation. IFE, Norway has developed a concrete irradiation test program where concrete can be irradiated under controlled and monitored conditions in the JEEP II research reactor. The hot laboratory has standardized and adapted techniques applicable to study microstructure, physical and mechanical properties of fresh and irradiated concrete.

1. Introduction

This paper presents the constituents of concrete and the impact of gamma and neutron radiation on their structures, enlightens the importance of expanding the knowledge of microstructural, mechanical and physical changes of concrete due to radiation and eventually presents installations and capabilities at IFE, Norway to successfully perform irradiation of concrete samples and subsequent testing.

Today concrete is used to a great extent as biological shielding and as structural support for the vessels of LWRs and for interim storage facilities because of its good shielding capacity, good structural support, good resistance to elevated temperatures and relatively low construction cost. The concrete supporting NPPs is exposed to neutron and gamma radiation. Short term exposure of concrete to radiation at relevant levels is not considered to cause harmful deterioration to the material although extension of operating reactor life time and subsequent increased gamma dose/neutron fluence will eventually cause property changes of the concrete that may be of significance.

1.1 Purpose

The purpose with the concrete program at IFE is to enable controlled and monitored irradiation of old and new types of concrete samples and to perform subsequent testing to expand the knowledge of the microstructural, mechanical and physical changes of concrete due to radiation.

1.2 Background

Concrete is a composite material with aggregates, cement and water being the main constituents. Aggregates are bound together by fluid cement paste that hardens over time. Depending on the chemical and mineralogical composition and the mixing ratio of the different constituents it is possible to vary the strength, density, chemical, thermal and shielding properties of concrete.

The properties of concrete change over time due to changes in microstructure caused by slow hydration, crystallization of amorphous parts and due to reactions between the aggregates and the cement paste. Also changes in the local environment i. e. temperature, humidity, chemical attacks and radiation exposure have an effect on the microstructure. [3]

Aggregates
Aggregates have a structure that is normally of crystalline nature. The aggregates could be coarse or fine in size, dense or light in weight, and consist of different rock types with different mineralogical composition (siliceous, calcareous). Normal weight aggregates (limestone, granite and sandstone) are commonly used as biological shielding in PWRs while heavy weight aggregates (magnetite, barytes, ferrophosphorus) have been used in support structures and shielding in BWRs. High hydrogen content (mainly due to chemically bound water), dense aggregates and boron containing aggregates improve the shielding properties. [1]

Cement paste – Cement and water
The most commonly used cement in concrete structures for shielding purpose is Portland cement which consists of a mixture of oxides of mainly calcium, silicon and aluminium. Cement paste is obtained by mixing cement and water to form hydration products, air voids and capillary pores. The structure of the cement paste is a mixture of nonstoichiometric amorphous together with needle or plate like crystals.

The main hydration products of Portland cement paste consists of [1]:

- Calcium silicate hydrate ($C_3H_2S_3$) – Nonstoichiometric amorphous structure that binds the components together
- Calcium hydroxide (CH) – Needle- or plate shaped crystals
- Ettringite ($C_6AS_3H_{32}$) – Needle shaped crystals

The water content of concrete has a large impact on the properties. Most of the water of concrete is contained in the cement paste and appears as non-evaporable (chemically bound in the layers of cement paste) and evaporable (physically adsorbed onto the surface of the cement paste layers and free water in pores) and it changes with temperature and/or relative humidity.

Additives
There are several mineral and chemical additives available to further modify the properties of concrete. Mineral additives are used as supplement to improve cement properties, lowering costs and/or recycling wastes. Examples of mineral supplements are fly ash (by-product from coal fired power plants), silica fume (by-product from production of silicon and ferrosilicon alloys), ground granulated blast furnace slag (by-product from steel production) and metakaolin (dehydroxylated form of the Al and Si rich clay mineral). Chemical additives can be accelerators to speed up the hydration process, retarders to slow the hydration process, air entering agents to increase durability especially freeze-thaw cycle, plasticizers to improve workability, corrosion inhibitors and pigments.

1.3 Impact of radiation on concrete
Concrete used as structural support and shielding in nuclear power plants is exposed to neutron and gamma radiation. Both types of radiation will interact with the concrete in different ways and depending on the constituents of the concrete mixture it will be more susceptible to neutron radiation or gamma radiation.

Neutron radiation effect on concrete

When a neutron enters a shielding material inelastic and elastic scattering processes occur until the neutron slows down to energy where it is only absorbed. Each scattering process involves a neutron collision/interaction with a nucleus of the shielding material where the neutron is absorbed, a new neutron is emitted by the nucleus and the nucleus moves. If the incoming neutron is fast, the nucleus will in addition to a neutron emit gamma radiation and if the neutron is thermal it will be absorbed. As nuclei are moving, the lattice spacing of the shielding material may change. The neutron interaction will cause more significant changes in dense and crystalline materials than in amorphous, porous materials. Therefore the effect will be more accumulated in the aggregate rather than the cement paste. Neutron radiation of aggregates may cause lattice defects and convert the crystalline structure to a distorted amorphous structure. The specific gravity and volume of the aggregate increases and could introduce stresses and micro crack formation of the concrete. Furthermore the radiation induced conversion from crystalline to distorted structure leads to higher chemical reactivity of the aggregate. Neutron radiation on cement paste will have the same neutron-nucleus interactions although the damage is not severe enough to change the cement paste properties because of the high porosity and internal structure. [1, 2]

Gamma radiation effect on concrete

Gamma radiation has a significant impact on the cement paste. The reason is that absorption of gamma energy can decrease the water content by two mechanisms; radiolysis of the water and gamma heat generation. Loss of water causes shrinkage and could result in shrinkage cracking. Dehydration occurs at high temperature when the chemically bound water is released. The elevated temperature caused by gamma heating of the concrete can lead to phase transformations and if the temperature changes are fast also to spalling. These effects may lower the strength, stiffness and ductility of the concrete. The gamma heating may also introduce a temperature gradient of the concrete that could be damaging on a structural level and on a micro structural level it could cause differences in thermal strain between aggregate and cement paste that could lead to large stresses at the interface followed by micro cracking of the cement paste. [1, 2]

2. Capabilities at IFE

There is limited data available on the microstructural, mechanical and physical changes in concrete due to radiation. Much of the data may not be relevant for LWR concrete structures, since tests performed at high fluence (>$1\text{x}10^{19}$ n/cm^2) also have reached temperatures above 100℃ and/or have been conducted with samples that are not typical for LWR concrete structures. [3] Existing data is difficult to compare due to the differences in constituents of the concrete, mixing ratios, specimen size, temperature and humidity condition during the tests.

Concrete is a complex material with the microstructure changing over time and with changes in the local environment. There are many parameters to take into account for determining the properties and the changes in properties of concrete. Experimental set ups need to be carefully designed and evaluated in order to ensure that the effects from specific parameters are studied on representative sets of samples.

IFE has developed a successful program to perform irradiation of concrete under controlled and monitored conditions (relevant for LWR concrete structures) followed by standardized and adapted non-destructive and destructive techniques to characterize the physical and mechanical property changes of fresh and irradiated concrete.

2.1 Concrete irradiation

The irradiation is performed in JEEP II, a 2MWth research reactor located in Kjeller, Norway. Temperature has a large impact on the property changes of concrete and therefore it is important to irradiate the samples at low temperature that is relevant to LWR concrete structures. JEEP II provides the advantage of having a moderator at low temperature (50-

55℃). The temperature of the irradiated samples will reach a higher value due to gamma heating although not higher than 80-90℃ in the center.

The neutron flux levels in JEEP II are:

- $3.5x10^{12}$ $n/cm^2/s$ for E>0.1MeV
- $1.5x10^{12}$ $n/cm^2/s$ for E>1.0MeV

Test rigs can be designed and constructed to comprise different types and dimensions of concrete samples. There is possibility to equip each test rig with on-line LVDT based measurements of specimen stack elongation that provide information on swelling in terms of axial expansion of the concrete stack. There is a magnetic core spring loaded against the concrete column end sample and the movement is sensed by LVDT.

A center line thermocouple for temperature measurements will be installed and the rigs are further equipped with fluence monitor wires to determine the neutron fluence and with gamma thermometers to determine the gamma dose after irradiation.

During irradiation the rigs are connected to channels for gas sampling and for monitoring the pressure. The pressure gauge provides data on gas release by means of measurements of the capsule inner pressure.

Heating tests can be performed parallel to irradiation tests with same type of samples being subjected to the same temperature history as the irradiated samples, although no radiation will be applied in the heating tests. The ovens for heating test are connected to a joint system where the temperature follows the temperature in the irradiation test rigs. On-line monitoring systems are installed in the heating test rigs, similar as to those described for the irradiation test rigs.

Finally concrete control samples from the same batch, only kept in normal conditions (20℃, 60%Rh with no heating or radiation applied) should be measured for comparison.

2.2 Testing of concrete

The hot laboratory is located in Kjeller next to the JEEP II reactor building. After irradiation the test rigs are cooled down in a pond next to the reactor until transport to the hot lab takes place. The concrete shielded cells at the hotlab are equipped with necessary instruments and tools for safe opening of the test rigs without damaging the concrete samples. The samples are brittle and all procedures involves little handling to limit the risk of small fragments and powders to fall off. When the samples are not handled they are kept in air tight aluminium containers to limit exposure to humidity in air.

Visual inspection, mass and dimension measurements

The hotlab has a setup for visual inspection and high resolution photos of the irradiated concrete samples to examine for deposits, micro cracks, visual degradation etc. A balance with 0.001g precision is available for mass measurements. Data loggers, probes and specimen holders are available to perform high precision measurements of height and diameter.

Gamma scanning

The lab is equipped with an ORTEC digital spectrometer and HPGe detector. Gamma scanning of concrete reveals qualitative information on the gamma emitting activation products.

Neutron radiography

Neutron radiography is a photographic technique that uses neutrons instead of visible light to image an object. The neutron imaging is performed in a specially constructed channel connected to JEEP II using neutrons from the research reactor. The imaging process is based on neutron attenuation and the difference in contrast will be a result of material specific properties of neutron attenuation. There are several methods for neutron imaging however the dysprosium foil technique is commonly used at JEEP II. The method is non-destructive and will provide imaging of specimen integrity and water/moisture uptake and distribution of the concrete.

Ultrasonic measurements
There is possibility to perform ultrasonic measurements of the concrete. Ultrasonic testing is a non-destructive technique based on the propagation of ultrasonic waves in the object or material tested. In most common applications, very short ultrasonic pulse-waves with center frequencies ranging from 0.1-15 MHz, and occasionally up to 50 MHz, are transmitted into materials to detect internal flaws such as micro cracks or to characterize materials.

Drying of samples
The water content has a large impact on the mechanical properties and the tests should be performed at same conditions. Continuous changes in humidity and temperature makes this difficult and therefore the lab is equipped with a shielded furnace to perform controlled heating, long time drying and cooling of the samples with chemically inert gas flow in order to reduce the water content before performing additional measurements and tests on irradiated/heating tested concrete.

Mechanical testing
The lab is equipped with semi shielded instruments for measurement of the static modulus of elasticity in compression and for measurement of the compressive strength. The instrument holders have been modified to fit irradiated concrete samples of different dimensions.

Microstructural characterization
Microstructural characterization of concrete is performed with LOM (Leica DMI 5000 M) and SEM (JEOL JSM 6100). An integrated EDS in the SEM allows for semi quantitative element analysis.

Thermal gravimetric analysis
Changes in physical and chemical properties are determined by interpreting registered mass measurements as function of temperature change or as a function of time for desired conditions (gas, flows, temperature etc.).

3. Summary/Conclusion

There is limited data available on the microstructural, mechanical and physical changes in concrete due to radiation. Results from irradiation tests of concrete are specific to the type of concrete used and in addition the complexity of concrete in terms of having a microstructure that changes over time and with changes in the local environment make testing and evaluation of concrete degradation due to radiation challenging. There are many parameters to take into account for determining the changes in properties of concrete.

Facilities at IFE, Norway, provide possibility to irradiate old and new types of concrete samples at conditions that are relevant to LWR concrete structures, with subsequent testing. Irradiation test rigs are designed to comprise different types and dimensions of concrete samples and the rigs are instrumented to enable on-line monitored measurements of specimen stack elongation and temperature. A gas sampling system is connected that also allows for monitoring the pressure. In addition fluence monitor wires to determine the neutron fluence and with gamma thermometers to determine the gamma dose after irradiation are installed.

The Hotlab is equipped to perform non-destructive and destructive tests to determine the microstructural, mechanical and physical changes in concrete due to radiation.

4. References

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