Irradiation effects on reactor concrete structures

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Keywords

Concrete, neutron irradiation, minerals, degradation, MOSAIC

Abstract

As the US Light Water Reactor (LWRs) fleet age, irradiation and environmental effects may degrade concrete structures within the reactor cavity of nuclear power plants (NPPs). Concrete components provide structural support and serve as a containment barrier and radiation shield. Among the most important constituents of concrete are the aggregates and cement paste phases. These two phases deteriorate due to different factors, aggregates swell due to the presence of neutron irradiation and the cement may lose water due to gamma-ray induced hydrolysis. The authors will present a series of results from different characterization techniques (i.e. TEM, XRD, XRF, EBSD and ellipsometry) and Fast Fourier Transform (FFT) micro-mechanical simulations using MOSAIC that demonstrate the effects irradiation, moisture, temperature, and constraint on reactor cavity concrete (RCC). The development of new numerical techniques and understanding of the irradiation effects in concrete are crucial for the assessment and life extension of the NPPs.

1. Introduction

Concrete is used as a structural material, containment, and biological shield of Nuclear Power Plants (NPPs). Other possible applications of concrete structures in nuclear applications include the radioactive waste storage and disposal facilities. Due to its proximity of the reactor core, some concrete structures in NPPs are more exposed to extreme environments; this particular section of concrete is known as reactor cavity concrete (RCC) (**Fig. 1a**). Cavity concrete is exposed to temperatures that can reach a maximum of 65˚C [1] and neutron and gamma irradiation. These environmental effects can alter the mechanical, chemical and physical properties of the constituents of concrete, **Fig. 1b** shows an example of the typical microstructure of concrete.

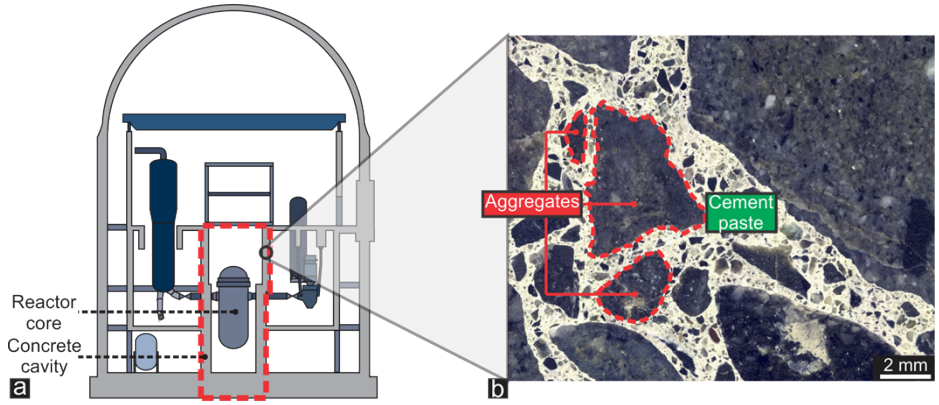

Fig. 1 Concrete Pressurized Water Reactor (PWR) containment, location of reactor cavity concrete and microstructure of concrete. **Fig 1a.** Illustration of cavity concrete and reactor core, **Fig 1b.** Typical microstructure of concrete

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Most of the aggregates used in RCC are thermally stable at the normal temperature conditions of NPPs [2]. On the other hand, the cement paste can lose moisture due to the interactions of this material with gamma irradiation and heat transferred from the core promoting cracks in this phase [3]. The next ageing mechanism, neutron irradiation, can produce dimensional changes in the minerals and rocks that constitute concrete. This phenomenon is known as radiation-induced volumetric expansion (RIVE). In addition to aforementioned deterioration effects, chemical reactions such as alkali-silica reaction and interactions with the steel reinforcement can contribute to the degradation and strength reduction of RCC. With the aging of the US NPP fleet, environmental effects on concrete has received renewed interest. As NPPs exceed the initial license period of 40 years (**Fig. 2**), the possible extension of operation and requisite license renewal depends upon the reliability of the concrete cavity structures among other aging issues. Although concrete is a well-known engineering material, the NPP environment produces microstructural and mechanical changes that are not commonly found in civil infrastructure applications. In this manuscript, the authors describe a how Energy-Dispersive x-ray Spectroscopy (EDS) and x-ray fluorescence (XRF) are used to characterize the microstructure of concrete samples.

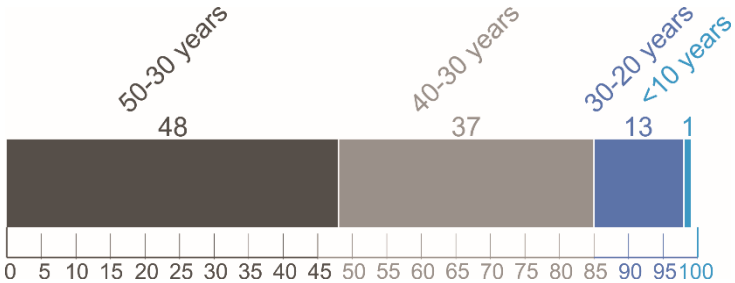

Fig. 2 Time of current U.S. NPPs at the end of 2018 [4].

2. Materials and methods

Elemental maps were taken from a concrete sample with two different techniques: XRF and EDS and Energy-Dispersive x-ray Spectroscopy (EDS). The XRF scan was performed using an IXRFS Systems Atlas µXRF whereas a FEI Versa 3D dual Beam equipped with an Oxford detector X-Max 150 was used for the EDS scan. The parameters for each technique are summarized in Table 1.

Table 1. XRF and EDS scan parameters

Technique	Acceleration voltage (kV)	Current
XRF	50	600 µA
EDS	20	8 nA

3. µXRF and EDS elemental analysis results and discussion

Elemental maps provide unique spatial information of the composition of concrete and mineral samples, moreover, this type of data allow for the identification of the location of the different phases of concrete. Information of elemental maps can be used to calculate the compositions of the different constituents of concrete. In this study two scans were obtained from a bulk sample of concrete, **Fig. 3** shows an XRF map (**Fig. 3a**) as well as an EDS map (**Fig. 3b**). The EDS map was acquired at the region highlighted at the top of the XRF illustration (**Fig. 3a**). Both techniques are non-destructive techniques that can provide chemical information with little to no sample preparation. Like any other characterization technique, XRF and EDS have advantages and disadvantages. XRF elemental maps scan larger areas such as large aggregates and cement paste areas. Although EDS maps cannot resolve large areas, this technique is capable of pinpointing details that require more resolution such as small particles or interfaces between the cement paste and aggregates, i.e. higher concentrations of Ca around aggregates (**Fig. 3b**). By combining these two techniques it is possible to assess the microstructure of bulk samples of concrete and individual minerals, rocks or other small features at multiple resolutions. Composite minerals do not normally influence the mechanical performance in civil

applications, however, these heterogeneous phases can promote differential cracking and failure of individual aggregates by the effect of RIVE.

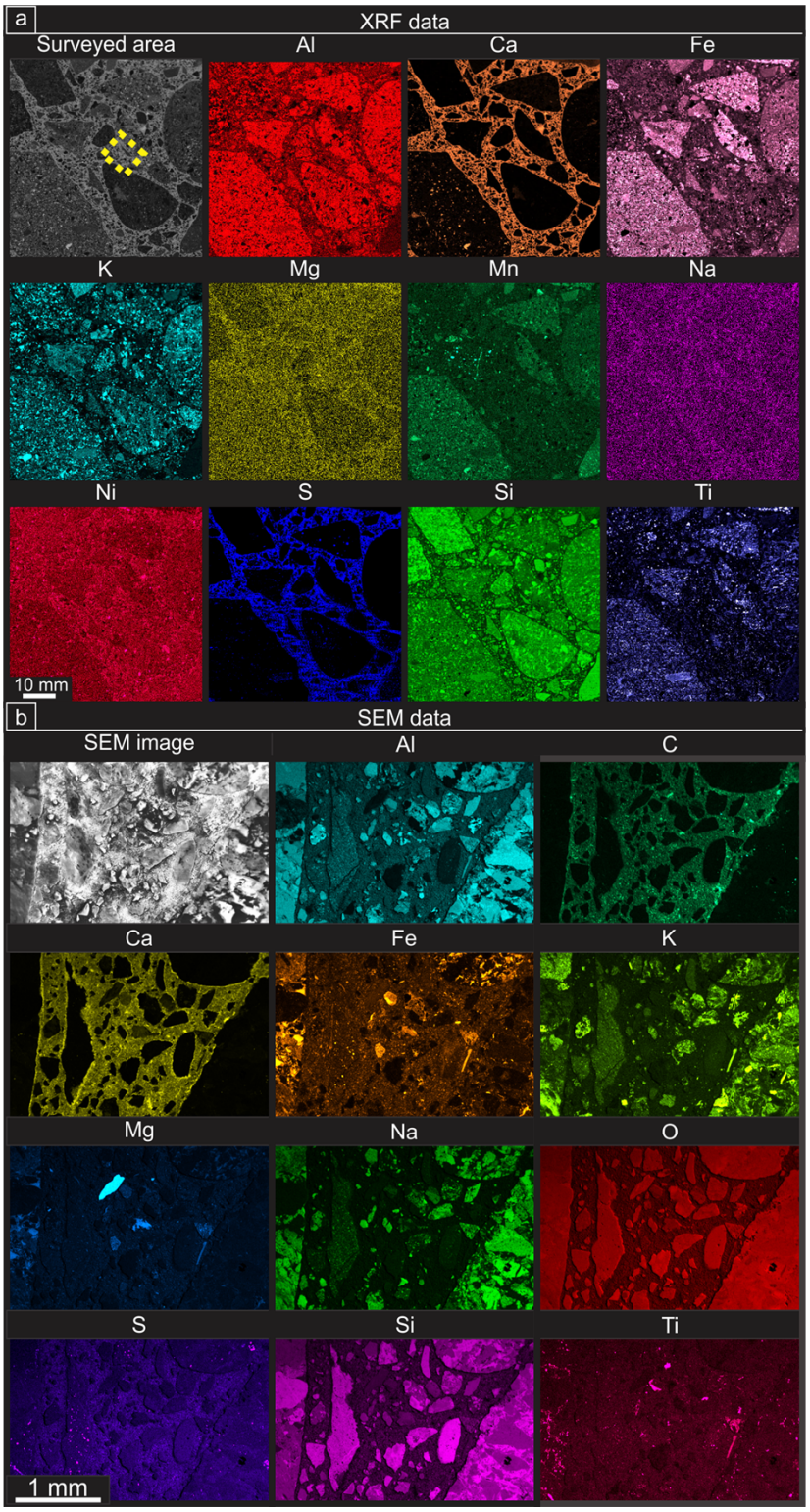

Fig. 3 XRF elemental maps of a bulk concrete sample. **Fig. 3a XRF** elemental maps, **Fig. 3b EDS** elemental maps of the yellow highlighted region in XRF surveyed area

4. Future work

EDS and XRF are powerful techniques that can be used to characterize the chemical composition of concrete. Furthermore, these techniques can be adapted to study other important aging mechanisms that affect concrete for example alkali-silica reaction. The information used in this study can also be processed and used in the Microstructure-Orientated Scientific Analysis of Irradiated Concrete (MOSAIC) [5], this software is capable of identifying the different phases of concrete. Moreover, this information can be used to create models of the microstructure of concrete. Specifically, MOSAIC can perform simulations of concrete microstructures subjected to neutron fluence and different temperatures conditions. An example of the common input and outputs of MOSAIC are illustrated in **Fig 4**. In order to capture and identify the phases of concrete, it is necessary to rely on an extensive database that contains the composition and irradiation performance of each individual phase. Part of the effort of the authors has been to collect and create the Irradiated Mineral, Aggregates and Concrete (IMAC) database [6, 7]. MOSAIC also accepts other inputs such as electron backscatter diffraction (EBSD) or ellipsometry measurements, which can be used to identify the orientation of the aggregates. By combining the aforementioned techniques, the results presented in this manuscript and the IMAC database, it is possible to create realistic simulations of the stress state and conditions of the microstructure of cavity concrete.

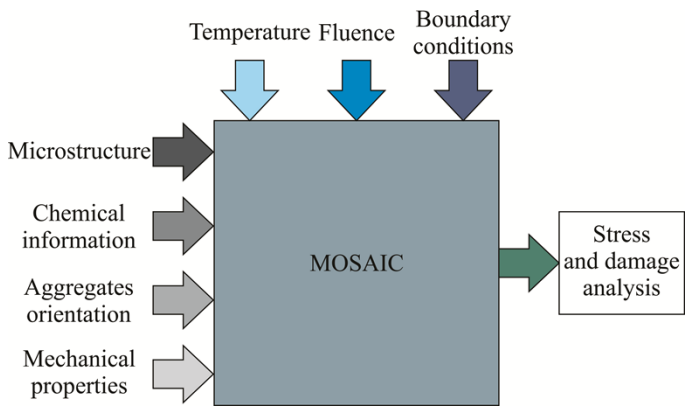

Fig. 4 Common inputs and outputs of MOSAIC

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Acknowledgments

Oak Ridge National Laboratory is managed by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 for the U.S. Department of Energy.