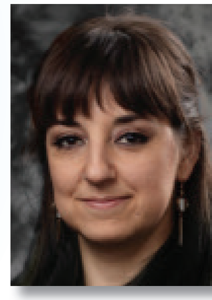
With Help from Artificial Intelligence, Advanced X-Ray Technology Can Measure Aged Concrete's Strength



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Although, concrete is a tough substrate and can last many decades, it is still affected by radiation. Deep inside walls of a nuclear structure that may be as much as two meters thick, neutrons emitted by a nuclear reactor can disrupt the crystalline structure of the quartz and other minerals embedded in concrete. Gamma rays break up water molecules in the cement that binds everything together. LWRS Program researchers at Oak Ridge National Laboratory are researching ways to examine concrete using x-ray computed tomography (XCT) and then using artificial intelligence (AI) to interpret the results. An approach is being developed to study and assess the long-term performance of concrete in nuclear power plants.

In light water nuclear reactors, concrete structural integrity is essential to ensuring safety and longevity of key structural systems. Reactor vessels are placed on concrete cradles, and inlet and outlet piping often rest on steel saddles embedded in the concrete. Maintaining the plant's structural integrity during an earthquake or accident depends on the concrete being structurally sound, even after being barraged by radiation for decades.

When neutron radiation breaks the crystalline structure of the rocks in concrete, they expand in different directions, causing cracks and a weakening of the bond between the aggregate and the cement. This radiation-induced volumetric expansion varies with the mineral composition of the rocks. Modeling and simulation, together with experimental efforts, provide insights into the damage and expansion of concrete under irradiation, although the analysis may be simplified due to the complexity of the concrete's microstructure.

Recently, simulations have become more realistic through the use of high-resolution characterization. XCT, a non-destructive technique, offers detailed three-dimensional (3D) insights into the internal structure of the concrete samples. This overcomes some of the challenges posed by other characterization techniques that are mostly two-dimensional (2D) and can be destructive. However, XCT has its own limitations because in the images, the aggregates and cement paste do not look very different from each other. This poses challenges for effective image segmentation, a crucial step for making a mineral map of the concrete, and then creating an accurate 3D reconstruction of the microstructure. Traditional, unsupervised segmentation techniques often fall short in distinguishing among the phases present in the material in the concrete microstructure XCT images.

To overcome these challenges, the approach described in this article leverages a branch of AI [1] called U-Net deep-learning-based approach, which improves traditional segmentation. A 2.5D (restricted to a 2D plane with little to no access to 3D) U-Net model [2] was developed allowing for learning 3D features from multiple neighboring slices of a 3D XCT volume without the need to perform model training used with an expensive 3D model. During the test, the model analyzes a few slices of the sample in the perpendicular direction to perform segmentation for every single slice in the 3D volume. Such an approach allows for capturing the 3D information while not incurring the cost of training and testing using a fully 3D model.

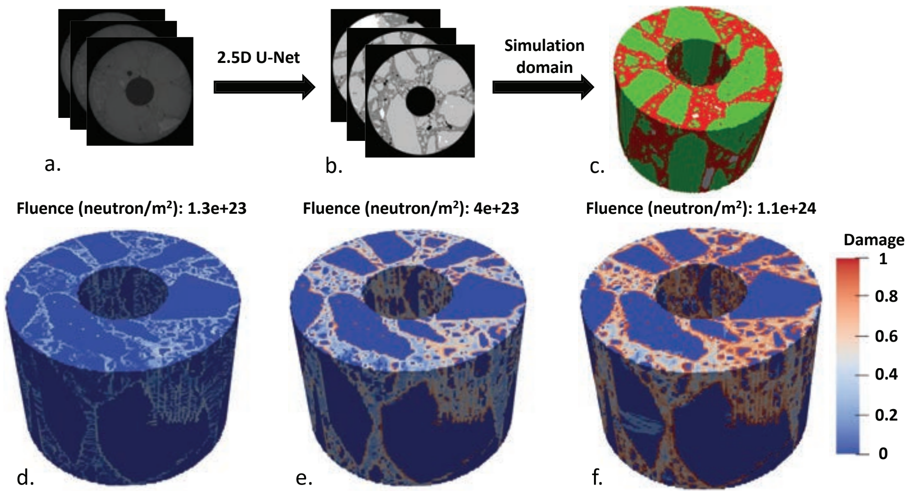

Figure 3. (a) Concrete microstructure XCT reconstruction slices. (b) Deep-learning-based segmentation of the XCT data in various phases. (c) 3D FEM volume. (d-f) Damage under various irradiation sources.

Using the 2.5D model, a computer can distinguish different phases of a material (in this case cement paste and aggregates) in a small set of annotated images (labeled images in a dataset), fewer than fifty, while AI takes over in analyzing the others. This method accurately analyzed hundreds of XCT data layers, with Ziabari's model achieving about 96% accuracy in distinguishing between the different phases of the concrete microstructure.

An example of XCT slices where the different components look very similar, and the corresponding deep-learning-based segmented microstructure, can be observed in Figure 3(a) and Figure 3(b), respectively. This accurate image segmentation facilitated a 3D representation, or digital twin (virtual representation of an object or system designed to accurately reflect a physical object), for concrete. Getting samples of irradiated concrete from an operating nuclear power plant is not always practical, but a computer model can estimate the amount of damage at various radiation levels. A digital twin can then be used to create a detailed 3D model which can be used to predict behavior of concrete. An example of simulated damage under various irradiation sources is shown in Figure 3(d–f). While promising, the results suggest the model may overestimate irradiation damage, which can be addressed by further characterization of the smaller aggregates and features that were not captured by the XCT, and integrating them into the modeling process.

In summary, an innovative approach was developed using AI and deep-learning (a method that teaches computers to process data in a way that is inspired by the human brain) for developing accurate predictive models for irradiation-induced damage in concrete, particularly within the context of major concrete structures in most plants. By enhancing the segmentation of XCT images and developing detailed 3D models, this research contributes significantly to the understanding of concrete behavior under irradiation, paving the way for more reliable evaluations of structural integrity in nuclear applications.

References

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2. Amani Cheniour, Amir Koushyar Ziabari, and Yann Le Pape. "A mesoscale 3D model of irradiated concrete informed via a 2.5 U-Net semantic segmentation." Construction and Building Materials 412 (2024): 134392. https://www.sciencedirect.com/science/article/abs/pii/S0950061823041107.