IRRADIATED AGGREGATES - FUZZY LOGIC MODEL

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ABSTRAKT

Bezpečnost a prodlužování životnosti jaderných zařízení je diskutovaným tématem posledních let. Díky tomu jsou po celém světě zkoumány dopady jaderného záření na betonové konstrukce, zejména na konstrukci biologického stínění.
Několik výzkumných institucí se zabývá vlivem záření na mikrostrukturu betonu a na mechanismy a změny v materiálu. Za tímto účelem testují betonové vzorky, ale i vzorky samotných minerálů.
Na základě materiálových změn v minerálech je možné modelovat chování kameniva složeného z těchto minerálů.
V tomto článku je představen model, který používá laboratorní výsledky z testů na minerálech a aplikuje je na model popisující změnu vlastností ozářeného kameniva.
Model je založen na fuzzy logickém přístupu ke zpracování dat.

KLÍČOVÁ SLOVA

Ozářené minerály • Ozářený beton • Dávka neutronů • Fuzzy logika • Biologické stínění

ABSTRACT

The nuclear power plant safety and lifetime extension is an important topic in recent years. Therefore the research of the irradiation impact on the concrete structures, especially biological shielding is studied, discussed and checked worldwide. In order to understand the material changes and mechanism in the concrete microstructure, several research institutes tests irradiated concrete samples but also mineral samples. When the effect of irradiation on minerals is well comprehended the impact on the aggregates composed of the minerals can be not just tested but also modelled.
In this paper such model is presented. Based on the data of mechanical tests on irradiated minerals the model of the aggregate mechanical changes due to irradiation is developed. The fuzzy logic modelling is used within the developed model.

KEYWORDS

Irradiated minerals • Irradiated concrete • Neutron fluence • Fuzzy logic • Biological shielding

1. INTRODUCTION

The bilogical shielding is the envelope of the nuclear reactor itself. Since the biological shielding has a shielding and in many instances also a load-bearing function, the material condition and soundness are the essential criteria for safe reactor operation. The worldwide need for license renewal of nuclear facilities has raised the question of what are the effects of radiation on concrete.
The collection of irradiated concrete data shows a large scatter which is thought to be due to different testing conditions and material composition (Hilsdorf 1978, Seeberger 1982). Therefore, deeper understanding of testing conditions as well as materials composition on concrete properties, is crucial for a comprehensive assessment of the condition of a biological shielding structure.

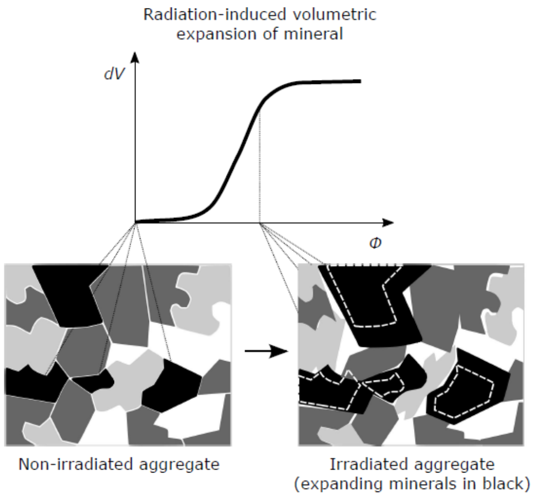

Figure 1: *Radiation induced volumetric expansion of minerals.*

Not only is concrete a composite or multiphase material, but the aggregates used in concrete are composed of minerals that exhibit radiation-induced volumetric expansion (RIVE) as shown in Fig. 1. That is why minerals deserve attention in order to understand the overall effects of radiation on concrete. Minerals determine the resulting behavior of irradiated aggregate, which in turn determines the behavior of the irradiated concrete. It seems that step-by-step upscaling of the

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material behavior is the proper method that leads to obtaining the concrete properties after years of irradiation.

Since the data used for the development of the model are limited, the fuzzy logic approach is utilized for the same reasons as in the previous work (Pokorná 2009).

The following paper describes a fuzzy logic model that uses the trends of mineral radiation-induced expansion for determining the expansion of irradiated aggregates. Also the preliminary results were presented in (Vaitová 2018).

2. MINERAL DATABASE

In order to use mineral expansion data, the sigmoid curves for different temperature ranges are fitted to the data points based on the coefficient of determination R^2. Each experimental data point was obtained within a known temperature range, therefore, each expansion curve is also given for a range of temperatures. The general formula of the sigmoid curve is

$$dV(\Phi) = dVmax/(1 + e - p(\Phi - q)) - r \qquad (1)$$

where dV is volumetric expansion, dV_{max} is the maximum overall expansion of the mineral, Φ is neutron fluence, and p and q are parameters describing the shape of the sigmoid curve, specifically, the slope and its position in the coordinate system. The parameter r shifts the function vertically so that it goes through the origin. It should be noted that all of the sigmoidal function parameters are strongly dependent on the temperature during irradiation.

These sigmoid curves for quartz in different temperature ranges are shown in Fig. 2. Moreover the curves are developed for each constituent mineral used in the model. The minerals used in the model are described below.

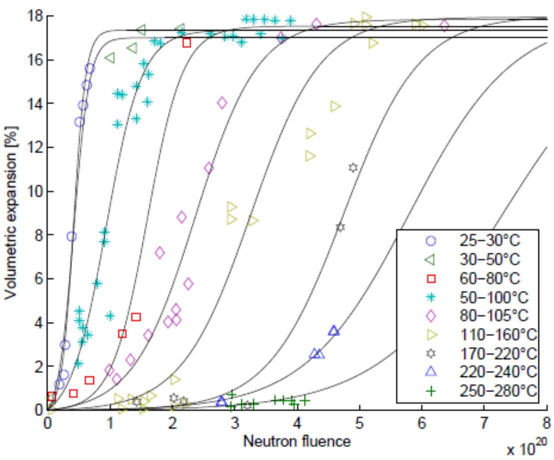

Figure 2: *Sigmoid curves of quartz RIVE.*

3. FUZZY LOGIC APPROACH

Since the use of statistics would be dubious for the available experimental data, which were obtained under poorly defined temperature conditions, it was decided to use the fuzzy logic to propagate the uncertainty contained in the experimental data for the minerals into estimates of RIVE of various aggregate types.

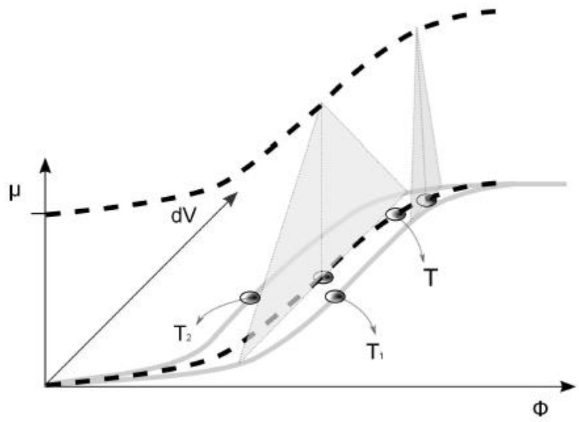

Figure 3: *Fuzzy number of RIVE under certain temperature.*

The fuzzy logic helped to define the validity of the scatter of the experimental data of RIVE with respect to the temperaturerange. The concept of definition of a fuzzy set, or a fuzzy number, which expresses the uncertainty of the RIVE estimate with respect to temperature is shown in Fig. 3, where μ is the degree of membership, Φ is the neutron fluence and dV is volumetric expansion.

The general strategy is to define a measure of validity of a RIVE estimate, using the shape of a fuzzy set, which is based on the definition of the lower and the upper bound of the RIVE over the temperature range. The lower and the upper bound are then evaluated using the coefficient of determination in order to take into account the effect of temperature on the validity of the experimentally obtained RIVE of each mineral at a given fluence. The coefficient of determination R^2 is then used to define the shape of the fuzzy set. For example, when $R^2 = 1$ the resulting RIVE is valid for the entire range of temperatures and when $R^2 = 0$ the resulting RIVE is only an estimate valid for the average temperature; however, it has some limited validity over the range of the temperature, Fig. 4.

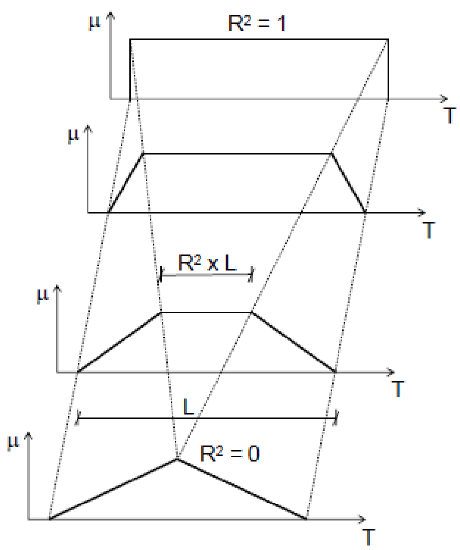

Figure 4: *Definition of shape of fuzzy set.*

These fuzzy sets are then used when the combined effect of temperature on the individual minerals is evaluated for a given aggregate type. In Fig. 4, *L* in is the difference between the highest and the lowest temperature for given irradiation data.

4. AGGREGATE COMPOSITION

The common aggregates used for concrete production are igneous rocks containing silica dioxide. Moreover the mineral expansion referenced in the literature, specifically (Denisov 2012), is mostly related to silicate minerals. Therefore, the experimental data on silicate minerals assembled by Denisov, (Denisov 2012), are used to create a model of radiation expansion of silicate igneous rocks such as granite, diorite and gabbro.

According to the petrographic composition of these rocks, see Fig. 5, the behaviour of minerals namely quartz, plagioclase feldspar, orthoclase feldspar, augite(pyroxene), hornblende(amphibole), olivine, and mica, should be known. However, since the experimental data are limited the proper data set should be chosen for the model.

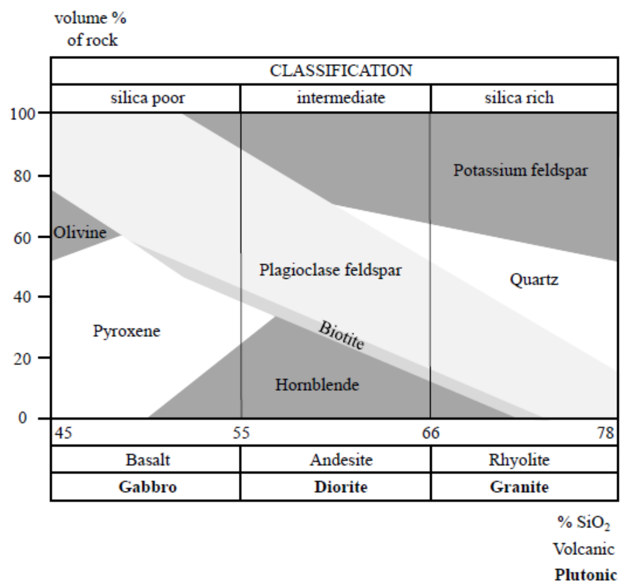

Figure 5: *Igneous rock composition.*

5. MODEL OF AGGREGATE EXPANSION

The aggregates, as a multiphase material, are composed of different minerals, therefore, each mineral affects the aggregate behavior to a different degree. Specifically, the aggregate radiation-induced expansion is derived from the expansion of the component minerals.

Each aggregate has a specific mineral composition. For the aggregate behavior prediction, the content of minerals is the determining factor. Based on the similar shapes of the aggregate and mineral expansion curves, it is assumed that the function used to describe radiation-induced expansion of minerals, Eq. (1), can also be utilized to describe the shape of the aggregate expansion curve and, thereby, provide the same parameters of the aggregate expansion curves.

The proposed model intends to utilize the trends of the mineral behavior described by the parameters in Eq. (1) to predict the aggregate expansion. Specifically, the parameters dV_{max}, p, and q are calculated as linear interpolations of parameters used for the minerals in aggregates based on the volume fraction of minerals, see Fig. 6 showing the algorithm flow.

Table 1: *Mineral mixing algorithm.*

Algorithm 1 Mixing of minerals algorithm.

Define: irradiation temperature T, maximum aggregate expansion $dV_{\max_a}$, fraction of each mineral f_{m_i} and neutron fluence ϕ.
for i **do**
  if f_{m_i}>0 **then**
    Evaluate one input (T) — three output fuzzy logic model
    Store output data (p_{m_i}, q_{m_i} and dV_{m_i})
  else
    Continue
  end if
end for
Determine dV_{cr}
Determine $p_a(f_{m_i})$, $q_a(f_{m_i})$ and $dV_a(f_{m_i})$
Determine $dV(\phi)$ {Eq. (1)}

Besides the mineral content, another important parameter which influences the aggregate expansion in the proposed model is temperature. Since the curves for mineral expansion are given within a temperature range, the temperature as an input parameter in the model is fuzzified using triangular membership functions where the temperature range gives the lower and upper limit of the fuzzy number. Nevertheless, for the sake of more general applicability of the model, non-linear membership functions can also be assumed in the proposed model. However, because of the limited available data, the triangular membership functions are adopted. Moreover, the parameters dV_{max}, p, and q describing the mineral radiation-induced expansion within a specific temperature range are fuzzified, because the temperature itself is a fuzzy number. Generally, the parameter p governing the slope of the sigmoid curve as well as the parameter q, which shifts the kick-off point of the sigmoid curve, are dependent on the temperature at irradiation. The parameter p decreases with increasing temperature while the parameter q increases with increasing temperature. Therefore, the lower temperature of irradiation is more detrimental to aggregates and thus the concrete mechanical performance.

Since the cracks constitute a significant portion of the overall expansion of aggregates, the parameter dV, which describes the expansion of minerals, needs to be corrected after the calculation, which is based on the volumetric fraction of minerals. Since the experimental data of rocks show the peak of the radiation-induced expansion within just a few temperature ranges, the estimate of the volumetric fraction of cracks in the total expansion can be determined based on the data in [5], which provides a plot that describes the dependence of the increase of the volume due to cracking on the increase of the volume of the rock in total for different rocks. Based on that plot, the correcting coefficient K_{cr} can be determined from

$$K_{cr} = I / (I - C) \tag{2}$$

where I is the total increase of the volume of the rock and C is the increase in volume due to cracking.

Moreover, the estimate of the crack volume is used in the calculation for the same aggregate but within the temperature range where the peak expansion has not yet been measured. The volumetric fraction of cracks in a particular rock is designated as dV_{cr}.

6. MODEL VALIDATION

In order to evaluate the model accuracy compared to experimental data, a method to evaluate such a model is developed. Since the fuzzy logic model of radiation-induced expansion of aggregates gives the boundary curves of each temperature range, the data between the curves are assumed to be results with no errors. However, the data outside the boundary curves do contain errors. Each data point error is evaluated twice to get errors for both boundary curves. The minimum error is then used in the calculation of the mean model error *ME* using equation (3):

$$ME = 1 - \frac{\sum_{i=1}^{n}\left|\frac{f_i - y_i}{y_i}\right|}{n} \tag{3}$$

where n is the number of data points, f_i is the output of the aggregate radiation-induced expansion model function (corresponding to the curve nearest the data point), and y_i is the experimentally obtained radiation-induced expansion of aggregate. The mean error evaluation of the proposed model gives a sense as to how the model is able to capture experimental data and also provides the ability to compare how the model works for different types of rocks.

7. READY-TO-USE RIVE ESTIMATES

The proposed model was tested on three different aggregates: granite, gabbro, and diorite as shown in Fig. 7 and Fig. 8.

Table 2: *Mineral composition of studied aggregates.*

Silica minerals	Gabbro	Granite	Diorite
quartz	0.00	0.25	0.00
potassium feldspars	0.60	0.50	0.75
plagioclase feldspars	0.00	0.24	0.05
pyroxenes	0.40	0.00	0.15
biotite	0.00	0.01	0.05

In the case of granite (Fig. 9), the model captured experimental data for temperatures above 70 °C. For the temperatures between 40-65 °C, the model captured the data only partially, which was caused by the small R^2 of potassium feldspars at 45 °C due to the limited data points at that temperature. The results of the gabbro model (Fig. 10) are worse than for granite, which is caused by the very limited input dataset of pyroxene minerals. The last aggregate tested with the model is diorite (Fig. 11). Since the data on diorite expansion are only for high temperatures, labradorite with the similar content of SiO_2 was used for estimation of diorite expansion at lower temperatures. Then, with very high R^2 (with the only exception being potassium feldspars at 45 °C), the model in the case of diorite/labradorite has very good correlation with the experimental data.

Table 3: *Example of resulting parameters of studied aggregates.*

Aggregate	T[°C]	K_{cr}	dV_{max}	p	q
Gabbro	70 − 140	2.8	13.7 − 14.1	$1.6-5.5\times10^{-20}$	$1.4-3.7\times10^{20}$
Granite	45 − 160	2.5	24.6 − 25.7	$1.4-7.5\times10^{-20}$	$0.8-4.4\times10^{20}$
Diorite (Labradorite)	90 − 160 (65−85)	3.4	21.0 − 22.6	$2.5-4.8\times10^{-20}$	$1.3-2.31\times10^{20}$

The proposed model captures trends in aggregate expansion behavior upon irradiation. Firstly, the model is based on individual mineral expansion so the lower R^2 of the mineral expansion curve affects the *ME* of the resulting aggregate expansion curve. The low R^2 is due to the limited data for that particular mineral or the specific temperature range of mineral expansion. This is especially apparent in the case of pyroxenes and potassium feldspars at 45 °C. The R^2 is low which results in a low *ME* for aggregates containing these minerals. Secondly, the aggregate structure that is given by the aggregate origin (how it is formed in nature) affects defect formation. For example, sedimentary rocks (cementitious) contain more pores than granite or other plutonic magmatic rocks (compaction). Therefore, the interconnection between the minerals contained in the rock should be incorporated into the model in order to obtain more realistic data. For this reason, the model clearly works better for compacted and well-crystallized aggregates than it would work for cementitious aggregates. For cementitious rocks, the kinetics of RIVE of minerals with respect to the neutron fluence should be assumed.

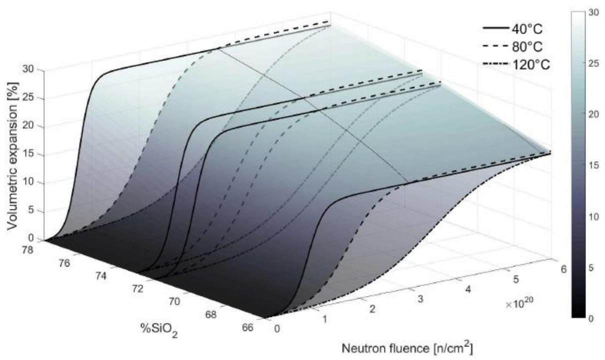

Figure 6: *Granite RIVE.*

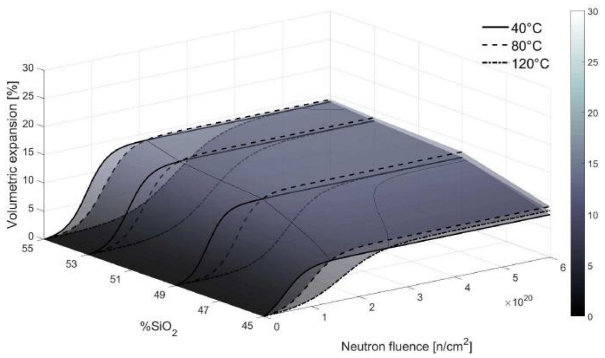

Figure 7: *Gabbro RIVE.*

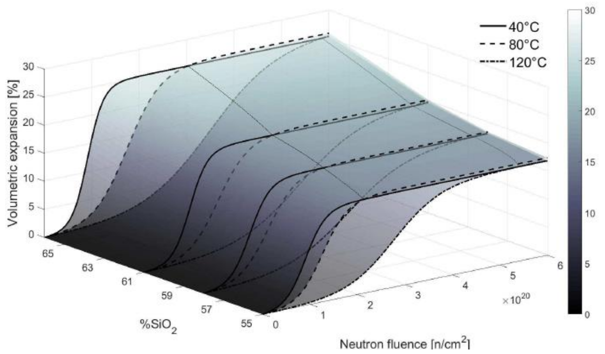

Figure 8: *Diorite RIVE.*

8. CONCLUSIONS

The model of irradiated aggregate expansion based on the mineral content of the aggregate is presented in this paper. The results obtained with this model provide an estimate of the aggregate radiation-induced volumetric expansion considering the mineral content, the temperature during irradiation and the neutron fluence, which is the actual dose of neutrons causing damage to the biological shield structure. The aggregate expansion estimates may be used in the meso-scale modeling of concrete for determination of the reduction of concrete mechanical properties. Based on that information, the irradiated concrete structure performance can be assessed.

The trends in the material behavior and the uncertain descriptions of the experimental data provided an opportunity to use the fuzzy logic to evaluate the available information on irradiated minerals. Because of the limited experimental data, the model should not use the classical homogenization approaches usually used for heterogeneous materials.

The results presented in this paper show good correlation between the proposed model and the experimental data mainly for compact and well-crystallized aggregates that are typically found in the NPP structures. Therefore, the results of this paper can be also used for assessment of concrete structure conditions during the license renewal process.

ACKNOWLEDGEMENTS

This work was financially supported by the Czech Technical University in Prague, project no. SGS19/038/OHK1/1T/11, which is gratefully acknowledged.

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