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Measurements and Monte-Carlo simulations of the particle self-shielding effect of B_4C grains in neutron shielding concrete

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ABSTRACT

A combined measurement and Monte-Carlo simulation study was carried out in order to characterize the particle self-shielding effect of B_4C grains in neutron shielding concrete. Several batches of a specialized neutron shielding concrete, with varying B_4C grain sizes, were exposed to a 2 Å neutron beam at the R2D2 test beamline at the Institute for Energy Technology located in Kjeller, Norway. The direct and scattered neutrons were detected with a neutron detector placed behind the concrete blocks and the results were compared to Geant4 simulations. The particle self-shielding effect was included in the Geant4 simulations by calculating effective neutron cross-sections during the Monte-Carlo simulation process. It is shown that this method well reproduces the measured results. Our results show that shielding calculations for low-energy neutrons using such materials would lead to an underestimate of the shielding required for a certain design scenario if the particle self-shielding effect is not included in the calculations.

1. Introduction

The use of concrete as a neutron shielding material is common practice at neutron research facilities, nuclear reactors, and hadron therapy treatment facilities. The choice of using concrete is a trade-off between the shielding characteristics, cost, and other engineering design requirements, such as stability and physical space for example. A common approach to enhance the shielding characteristics of concrete for low-energy neutrons is to add boron containing compounds to the mixture (Schmidt, 1970). This enhancement is due to the large low-energy neutron absorption cross-section for ^{10}B and additionally to the low-energy of the emitted secondary photon radiation after the absorption process (Database for Prompt Gamma-ray Neutron Activation Analysis). The latter property helps to limit the dose rate behind a shield from photons produced in low-energy neutron absorption processes in the concrete material itself. One example of such a concrete is the outer layers of the target monolith at the Swiss Spallation Neutron Source (SINQ - The Swiss Spallation Neutron Source; Wagner, 2001).

For energies up to 1 MeV, it has been suggested in addition to add polyethylene (PE) to improve the neutron slowing down properties of the concrete (Park et al., 2014). Such a concrete can be especially effective at spallation neutron sources, such as the European Spallation Source (ESS) (Peggs et al., 2013) currently under construction in Lund, Sweden, where a significant number of high-energy neutrons, keV and above, will escape the target into the bulk shielding of the facility (Bauer, 2001; Koprivnikar and Schachinger, 2002). For this reason, we have developed a new specialized neutron shielding concrete based on the addition of B_4C grains and PE beads and studied the performance of the concrete in the MeV energy range in a previous publication (DiJulio et al., 2017). This concrete is referred to as PE-B4C-concrete below. In the current work, we report on the low-energy neutron transport properties of the specialized concrete. The results have relevance for any type of shielding material containing a low amount of small neutron absorbing grains.

The effectiveness of a concrete containing a small amount of B_4C grains depends not only on the weight fraction of B_4C added to the mixture but also on the size of the grains. This effect is referred to as the particle self-shielding effect, which can lead to a reduced performance of the additive in the concrete. If the diameter of a grain is large enough, the interior region of the grain will be shielded from neutrons by the outer layers of the grain. Thus a fraction of the boron which was added to the concrete is rendered in-effective. Early studies of the reduced performance of absorbing grains due to this effect were carried out for neutron transmission in Boral (Burrus, 1960; Åkerhielm, 1960)

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and in samples containing Al and B_4C spherical particles (Doub, 1961). Later, an analytical model (Levermore et al., 1986) was used to show the limitations of assuming a homogeneous sample for the transmission of neutrons passing through a mixture of sulfur and tungsten grains (Becker et al., 2014). More recently, HDPE loaded with small B_4C grains was investigated in a combined simulation and experimental study and it was noted that smaller grain sizes led to improved neutron shielding properties (Soltani et al., 2016).

The design of neutron shielding components is frequently carried out using Monte-Carlo simulations. Typically, the material of a shield is assumed to be composed of a homogeneous random distribution of the elements within the shield and the particle-self shielding effect is not included. If this effect is completely neglected, the shielding calculations would lead to incorrect predictions of the required thicknesses of the materials needed for the design scenario. A possible way to include this effect is to adapt an effective density for the absorbing additive. However, as the particle-self shielding effect is energy dependent, such a method would have limited applicability especially over a broad energy spectrum. Alternatively, a study presented by Yamamoto (2014) proposed an effective cross-section calculation method for this application where effective cross-sections of the components in the material were calculated during a Monte-Carlo simulation. The effective cross-sections took into account the particle self-shielding effect of the absorber grains. This method has the added benefit that the user does not need to model each individual grain in the material, which would lead to an increased computational burden. While a Monte-Carlo benchmark of the method was shown in the previous study (Yamamoto, 2014), no experimental investigation of the method was presented.

In the following, we first describe an experimental investigation of the particle self-shielding effect in our developed concrete using low-energy neutrons. We then give a description of the concrete, followed by a discussion of the theoretical model and simulation methodology used to analyze the experimental data. Lastly, we present a comparison of the simulations and measured results.

2. Experimental procedure

The low-energy neutron measurements were carried out at the R2D2 test beamline at the JEEP II reactor at the Institute for Energy Technology located in Kjeller, Norway (Institute for Energy Technology). Neutrons from the reactor core were incident on a Ge wafer monochromator, of total crystal height 108 mm and width 54 mm, which reflected and focused neutrons of a given wavelength at a 90° take-off angle into a borated PE collimator. The 400 reflection of the Ge wafers was used to provide neutrons of 2 Å. Outside of the collimator, a neutron beam monitor provided an indication of the number of reflected neutrons exiting the collimator and two borated aluminum slits from JJ-XRAY (JJ X-RAY) were used to define the divergence of the beam. The first slit had a opening width of 11.7 mm and a height of 43 mm while the second slit had an opening width of 7.6 mm and a height of 26 mm. This allowed a maximum beam divergence of ~ 3.6° in the vertical direction and ~ 2.3° in the horizontal direction to pass through the slits. The concrete samples were placed after the slits and a ^{3}He proportional counter (GE Digital Solutions) was placed some distance behind the position of the samples. The counter was placed in a borated PE housing, with an opening of width 5 mm and height 65 mm. Furthermore, a 2 cm thick B_4C slit with an opening width of 5 mm and height 25 mm was used to define the beam at the counter position. An overview of the experimental setup outside of the collimator is shown in Fig. 1 and a photo is shown in Fig. 2.

A detailed description of the PE-B4C-concrete is given previously in DiJulio et al. (2017), however a brief overview is given here. The concrete was created by adding 10 wt% of PE in the form of a 50–50 mix of 2.5 mm and 5.0 mm diameter beads and a total of 0.76 wt% of B_4C grains to a standard concrete mixture. This is equivalent to 20 vol% PE and 0.6 vol% B_4C, where the PE replaced the same volume of granite in the concrete and the B_4C replaced the same volume of SiO_2. Due to these modifications, the specialized concrete had a lower density and lower compression strength than a standard concrete (DiJulio et al., 2017). The exact contents of the mixture are given in DiJulio et al. (2017) and the calculated elemental content from this mixture is given in Table 1.

Five different batches of the concrete were produced with different B_4C grain sizes, however the total weight fraction of B_4C was kept the same. The grain size diameter groupings ranged from: less than

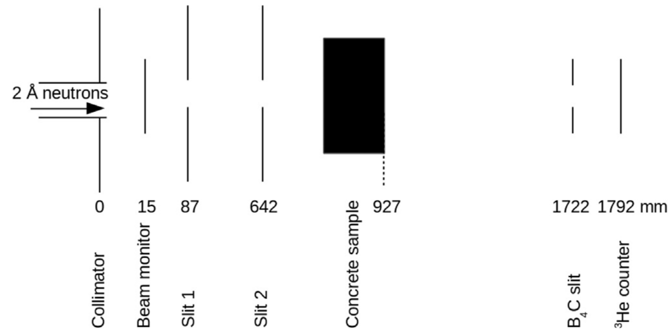

Fig. 1. A schematic of the setup used for the concrete measurements at the R2D2 test beamline.

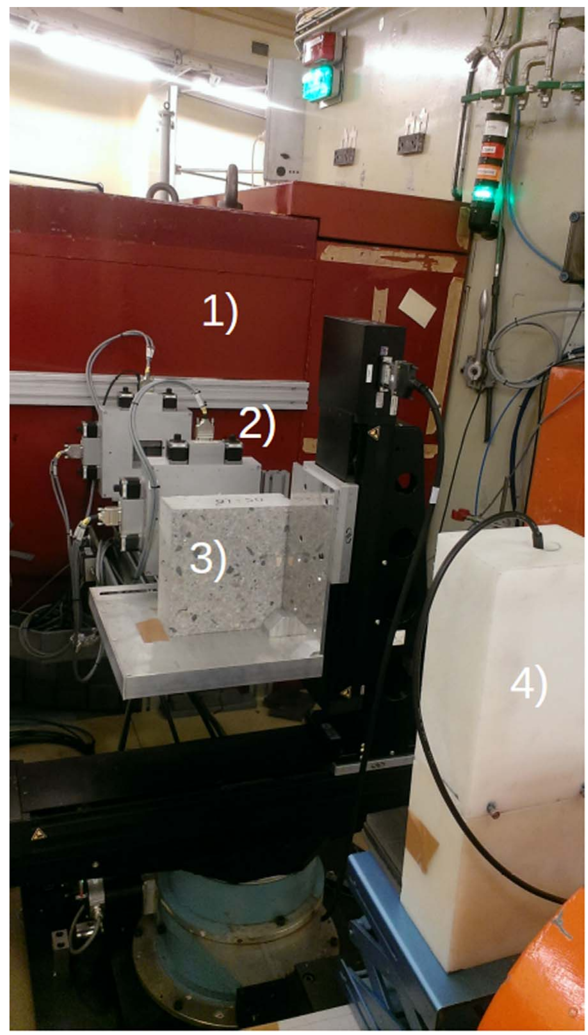

Fig. 2. A photo of the setup used for the concrete measurements at the R2D2 test beamline. The components indicated are 1) the monochromator shielding, 2) the slit system, 3) a concrete sample, and 4) the proportional counter and shielding.