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Original Article

Potential of biochar reinforced concrete as neutron shielding material

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ABSTRACT

Biochar is a novel carbon based material derived from waste that shows promising properties for several applications. In this paper we investigate its potential use as a low cost, greener alternative to commonly used aggregates employed to enhance the neutron shielding performance of concrete. Monte Carlo simulations are performed with the PHITS code to estimate the neutron attenuation of blank and biochar-reinforced concrete exposed to high energy neutrons. We find that the shielding performance of concrete with 15% biochar is comparable with commonly used materials such as Boron Carbide at 20% and exceeds that of Basalt fibers with the same concentration, making these composites an interesting greener alternative to current solutions. A combination of biochar and heavier fillers also show extremely promising performance.

1. Introduction

Energy production from nuclear fusion reactors is one of the greatest hopes for achieving the green transition. However, the nuclear reaction between Deuterium and Tritium produces high energy neutrons that need to be contained [1]. For this reason, together with other nuclear technologies such as fission plants [2] and medical applications, radiation shielding technology and materials are increasingly important aspects.

The most commonly employed radiation shielding material is concrete, reinforced with various aggregates. The advantage of concrete comes from its composition, rich of both light and heavy nuclei, suitable to attenuate at some degree both neutron and gamma radiation; and from its pervasive use in construction and its low cost [3].

The search for efficient reinforcing materials for concrete should also take into account the environmental sustainability of the proposed fillers, therefore biochar - a waste-derived carbon material [4] - might be an interesting candidate. It has a low cost [5], an increasingly wide employment [6], highly tunable properties [7,8] and is mainly composed of light atoms. Moreover, promising results in terms of mechanical, thermal and acoustic properties were reported in concrete-biochar composites [9–11].

In this paper, we computationally investigate the neutron shielding performance of biochar reinforced concrete, analyzing the relevance of composite density and filler concentration and comparing this novel material with commonly employed fillers.

2. Materials

Concrete reinforced with aggregates is the most common choice regarding the material used for radiation shielding in the construction industry [12]. Concrete has many advantages like cheapness, high tensile strength and the presence of light nuclei, which have a large neutron scattering cross section, and it is a material pervasively used regardless of the need of shielding the environment from energetic particles [13]. Although the basic elements are always similar, the stoichiometry of concrete has a strong variability, due to the fact that it is, in fact, a mixture of many aggregates. Therefore, it is important to carefully define the one used in this study: we consider the exact composition from Ref. [14], also shown in Table 1, with density (ρ) of 2.40 g/cm^3.

We investigate the enhancement of the shielding properties of concrete when Biochar is added. Biochar is a solid recovery material derived from the pyrolysis of biomass with strong presence of carbon [15]. Its chemical composition depends on many factors, such as temperature of pyrolysis, initial biomass and residence time [16]. All these parameters influence its stoichiometry (mainly composed of Carbon, Hydrogen, Oxygen, Nitrogen and Sulphur), as well as the level of disorder and the macrostructure [16]. This flexibility makes biochar a multi-purpose material with very

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Table 1
Chemical composition of the concrete considered in this study as experimentally determined in Ref. [14].

Element	Weight[%]
H	0.561
C	4.377
O	48.204
Na	0.446
Mg	1.512
Al	2.113
Si	16.175
S	0.414
K	0.833
Ca	23.929
Ti	0.173
Fe	1.263

tunable properties. For what concerns radiation shielding applications, it is convenient to have a maximal presence of hydrogen, due to its large neutron scattering cross section. Table 2 shows the stoichiometry of the biochar considered for this study, taken from that experimentally determined in Ref. [17] from biochar from corn stalk at 300 °C of pyrolisis. Moreover, as a reference, we also studied the shielding of concrete reinforced with Basalt fibers [3], Boron Carbide [18] and Iron–Boron [18]: technological fillers already successfully employed and well characterized in literature.

For the shielding performance, a key point of the new composite material is the density, which can strongly depend on the preparation process. In fact, both concrete and biochar are porous materials, and the preparation of each component and of the final composite strongly affects density. Porosity has an impact on density because it potentially allows one to obtain a wide range of values, therefore we investigated the effects of different densities, considering them as a free parameter within a reasonable range [19].

3. Methods

Neutron shielding simulations were performed with the Monte Carlo code PHITS [20] that allows simulating the transport of charged and neutral particles and the interactions with target materials defined by their stoichiometry and density.

The source neutron energy was set to 14 MeV, the reference value for the nuclear fusion reaction between deuterium and tritium. A monochromatic point-like directional source, pointing to a target in the shape of a thick slab is the most practical way to study the shielding performance. The model in question is shown in Fig. 1. The lateral extension of the slab is taken large enough that no lateral escape of scattered neutron happens.

The composition of the target is defined by mixtures of concrete (with the stoichiometry defined in Table 1) and biochar (with the stoichiometry defined in Table 2) or of the other technological fillers previously mentioned.

Table 2
Chemical composition of the biochar considered in this study, as experimentally determined in Ref. [17] from biochar from corn stalk at 300 °C of pyrolisis.

Element	Weight[%]
C	48.35
H	5.07
O	45.79
N	0.63
S	0.16

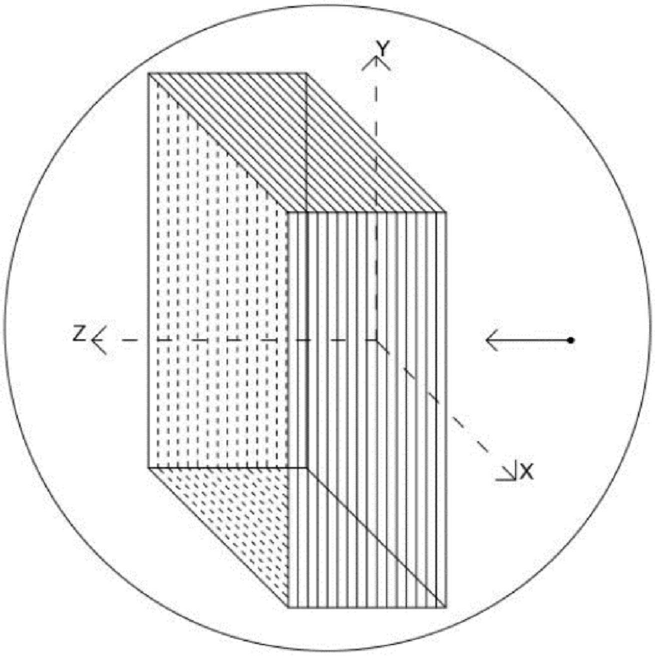

Fig. 1. Model of geometry.

Biochar was integrated in variable percentages as filler of the concrete in order to find out how biochar could improve shielding power of this material, as shown in Fig. 3. For a fixed biochar concentration, it is relevant to investigate the effect of composite density. As specified above, biochar is a porous material so its density ranges between values that could change the density of the composite and because the linear attenuation coefficient, which is defined as the probability of a neutron to interact with a material [21], depends on density [12]. In this way it was simulated the impact of the density on the shielding, results shown in Fig. 2.

The shielding performance is estimated in terms of the fraction of neutron (of any energy) that are transmitted through the

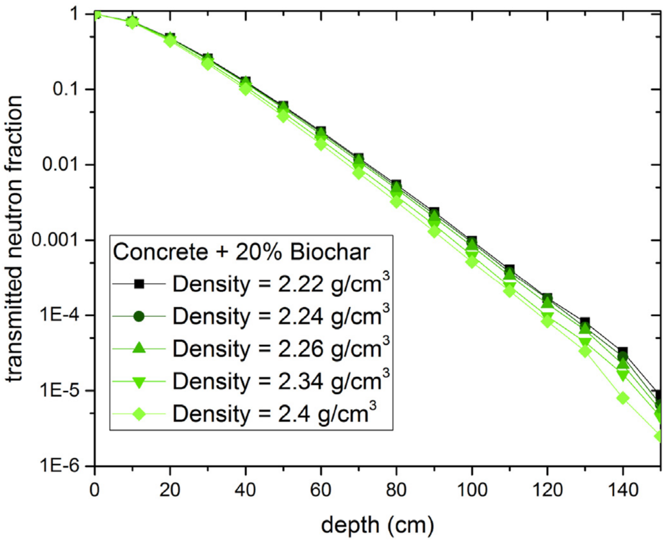

Fig. 2. Shielding performance for biochar-concrete composites with the same composition but different densities.

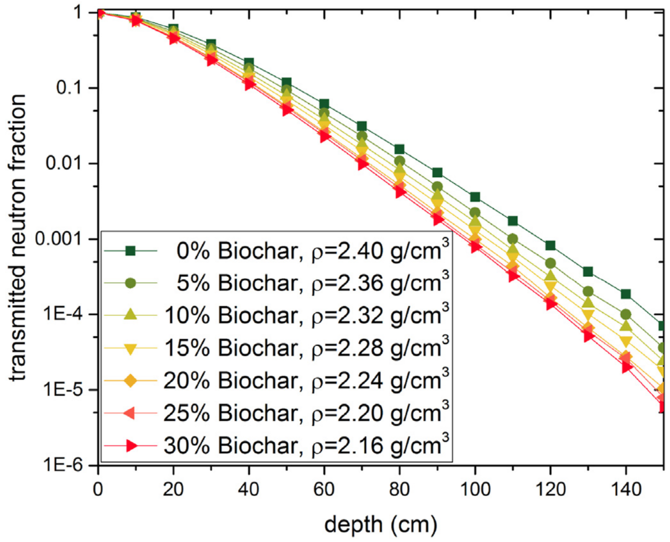

Fig. 3. Shielding performance for concrete composites with increasing biochar concentration.

reinforced concrete as a function of distance, estimated within PHITS with the so-called ”T-Cross” tally. Clearly, the transmitted neutron fraction at the front face of the concrete slab is always equal to one. The simulations are run with a high enough statistics so that all the quantities of interest have an associated statistical uncertainty smaller than 5%.

4. Results

4.1. Density

At first we focus on the strong impact of the composite density on the shielding performance. We keep the composition fixed and vary the density of the biochar in a reasonable range, resulting in different overall composite densities. The results are shown in Fig. 2: higher values of density enhance the capacity to shield neutron radiation.

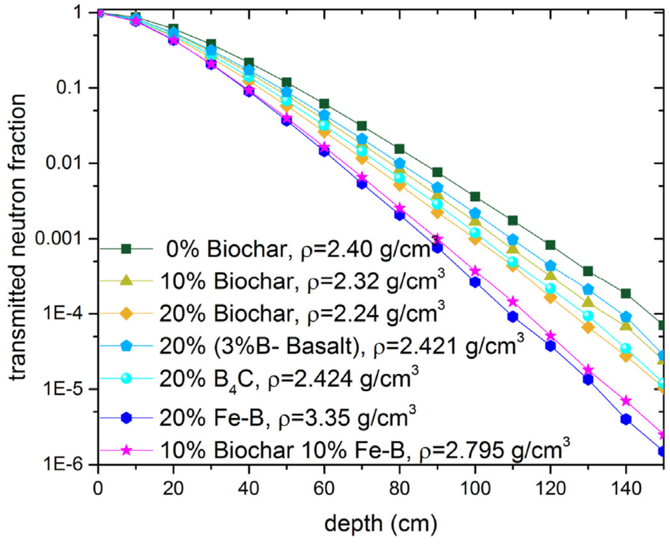

Fig. 4. Shielding enhancement for concrete composites with biochar and commercially employed fillers.

This result therefore gives directly an important indication for experiments and applications of biochar as a filler for radiation shielding: maximizing the packing of biochar inside concrete means to maximize density and so the shielding capacity of the entire material.

4.2. Biochar concentration

After having studied the effect of varying the density parameter, we focused on the filler concentration, i.e. the percentage of biochar within the concrete. This is done by keeping the concrete and biochar densities fixed to their reference values (taken to 2.40 g/cm^3 and 1.60 g/cm^3, respectively) and changing only their relative weight in the mixture. Fig. 3 clearly shows the correlation between a higher value of biochar percentage and an increased shielding capacity, despite the decreasing overall density. This nontrivial result is a consequence of the greater presence of elements with better scattering with neutrons. Depending on the specific application (e.g. structural or not), and therefore on the mechanical requirements of the concrete, the most appropriate biochar concentration can be chosen [9].

4.3. Comparisons

Finally, we focus on a comparison of the biochar performance with fillers already studied and used in applications. This is shown in Fig. 4, where concrete reinforced with representative concentrations of biochar are compared to 20% of Iron–Boron, 20% of Boron Carbide (B_4C) and 3% Boron-enriched 20% Basalt fibers fillers. At last, a mixture of 10% biochar and 10% of Iron–Boron reinforced concrete is proposed as high-performance composite.

5. Conclusions

In summary, we performed Monte Carlo simulations to investigate the neutron shielding performance of biochar reinforced concrete. We showed that biochar strongly enhances the shielding capacity due to its high light-nuclei content. Moreover, for better performances it is suggested to optimize the density of biochar by maximizing it. Finally, we directly show that, with the same filler percentage, the neutron shielding performance of biochar is comparable to that of Boron Carbide and exceeds that of Boron-enriched Basalt fibers. A combination of biochar and heavier fillers, such as Iron–Boron, can be extremely performing while enhancing the sustainability of the material.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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