New composite material based on heavy concrete reinforced by basalt-boron fiber for radioactive waste management

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Abstract. A new composite material with neutron radiation shielding properties is presented. This fiber reinforced concrete material incorporates basalt-boron fiber, with different concentrations of boron oxide in fiber, and is applicable to nuclear energy and nuclear waste management. The methodology for production of boron oxide (B_2O_3) infused basalt fiber has been developed. First experimental samples of basalt boron fiber containing 6% of B_2O_3 and 12% B_2O_3 have been produced in laboratory conditions. The concrete samples reinforced by two types of basalt-boron fiber with different dosages have been prepared for neutron experiment. The neutron experimental investigations on radiation shielding properties of concrete reinforced by basalt-boron fiber have been performed by means of Pu-Be neutron source. The prepared samples have been tested in the course of several series of tests. It is shown that basalt-boron fibers in concrete improve neutron radiation shielding properties for neutrons with different energies, but it appears to be most effective when it comes to thermal neutrons.

1 Introduction

For safe operation of various sources of radioactivity, it is necessary to have reliable radiation protection. To date, there are many different types of radiation sources in the world, such as conventional fission reactors, fusion neutron sources, D-D and D-T neutron generators, plasma focus devices used as neutron sources and many gamma sources [1,2]. These radiation sources are used for industrial, scientific and medical purposes.

At the moment, there are different types of radiation shielding. The most widespread is heavy concrete with various additives [3–12]. Such heavy concrete should have radiation shielding properties, both against neutron and gamma irradiation. For example, in order to protect against gamma radiation, we need to use materials with large values of the atomic number Z [13]. As a result, for protection against gamma radiation, fillers are used most widely, among them such natural minerals as barite containing a lot of barium, magnetite, which consists of titanium and iron, and serpentinite. For VVER reactors,

heavy concrete with serpentinite is used as biological shielding [14]. Serpentinite contains such heavy elements as iron and magnesium.

In addition to heavy minerals, concrete should contain elements that are well scattering and absorb neutrons. By default, the concrete contains a large amount of hydrogen, on the nuclei of which effective neutron scattering is observed.

In this paper, the authors suggest a new type of composite material based on heavy concrete reinforced by improved basalt-boron fiber (BBF), in which the boron oxide is added during the production process.

2 Basalt-boron fiber

The proposal to add a basalt fiber (BF) containing boron is based on the fact that there is enough hydrogen in the concrete to slow down fast neutrons, and if we add a material with a large neutron absorption cross section (for example, B-10), then it can become very effective material with neutron radiation shielding properties [14].

Basalt fiber is produced similarly to glass fiber. The BF production contains several stages: the preparation of the basalt rock, the melting, the formation of fiber, the drying of the fiber, cutting the fiber and obtaining final products [15].

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Fig. 1. Scheme of the process for BBF production. (1) Metering & mixing equipment (batch preparation). (2) Conveying equipment. (3) Batch charger. (4) Melting chamber. (5) Conditioning chamber. (6) Fiber forming chamber. (7) Fiber's strand. (8) Induction coil of melting chamber. (9) Induction coil of fiber forming chamber. (10) Sizing applicator. (11) Gathering shoe. (12) Direct chopper. (13) Fiber drawing plate [13].

Table 1. The chemical composition of BBF type BasBor6.

Main constituents	B ₂ O ₃	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	SO ₃	Cl
%	6.2	1.809	5.93	13.888	50.40	0.125	0.015	0.010
Main constituents	K ₂ O	CaO	TiO ₂	V ₂ O ₅	MnO	Fe ₂ O ₃	Co ₂ O ₃	NiO
%	1.439	8.040	1.134	0.08	0.164	10.590	0.0033	0.002
Main constituents	CuO	ZnO	Ga ₂ O ₃	Rb ₂ O	SrO	Y ₂ O ₃	ZrO ₂	BaO
%	0.003	0.014	0.002	0.0067	0.0349	0.006	0.0032	0.03

Table 2. The chemical composition of BBF type BasBor12.

Main constituents	B ₂ O ₃	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	SO ₃	Cl
%	11.7	1.715	5.66	13.120	47.64	0.117	0.010	0.008
Main constituents	K ₂ O	CaO	TiO ₂	V ₂ O ₅	MnO	Fe ₂ O ₃	Co ₂ O ₃	NiO
%	1.313	7.421	1.044	0.051	0.149	9.688	0.0028	0.003
Main constituents	CuO	ZnO	Ga ₂ O ₃	Rb ₂ O	SrO	Y ₂ O ₃	ZrO ₂	BaO
%	0.0028	0.012	0.003	0.0061	0.0313	0.005	0.0029	0.03

However, the process of BBF production is easier than the production of glass fiber: it does not require a complicated and expensive process of preparation of the charge, but requires only one supply line of crushed basalt rocks in the furnace for melting. The basalt breed is first crushed, then washed, dried and loaded into containers attached to the heater, which mixes the basalt to the melting bath in gas ovens (see Fig. 1).

A number of studies have shown that concrete reinforced with BF has high chemical and corrosion resistance, durability, resistance to abrasion, and frost resistance [1,13–17]. Since the specific density of the BF is approximately the same as that of the main components of the concrete, it is evenly distributed over the entire volume of concrete in the form of steel and other types of polymer fiber.

The first experimental samples of BBF were prepared in Institute for Problems in Materials Science in Ukraine for

two different types of basalt fibers infused with boron as reinforcing material. The first type of BBF, hereinafter referred to as BasBor6, contains 6% of B₂O₃, of which 19.8% B-10 and 80.2% B-11. The second type of BBF, represented in the text as BasBor12, contains 12% of B₂O₃, of which 19.8% B-10 and 80.2% B-11. The chemical composition of the BBF with the infusion of boron BasBor6 is displayed on Table 1. The chemical composition of the BBF with the infusion of boron BasBor12 is displayed in Table 2.

3 Radiation shielding properties experiment for Pu-Be neutron source

3.1 Description of experiment

For measurements a plutonium-beryllium neutron source, (ИБН-12) was used, creating a flux of fast neutrons with

Table 3. The main technical characteristics of neutron source.

Source type	Source dimensions (active part), mm		Neutron intensity, neutrons s ⁻¹	Maximum activity Pu-239 at source	
	Diameter, <i>D</i> (d)	Height (Length) <i>H</i> (<i>h</i>), (L)		Bq	Ci
ИБН-12	54 (46)	64 (46)	$(5.0 \pm 1.0) \times 10^7$	1.3×10^{12}	35

Fig. 2. Layout of the room and equipment placement during measurements.

isotropic distribution and intensity 5×10^7 neutrons s⁻¹. Table 3 shows its main technical characteristics.

Measurements of the neutron flux were carried out with a radiometer-dosimeter МКС-01Р with a detection unit БДКН-03Р. The apparatus measurement error of the МКС-01Р when measuring the neutron flux does not exceed 20 %. Measurements of neutron flux were carried out in two types of the neutron energy spectrum:

- for “thermal” neutrons;
- for intermediate and fast neutrons (with cadmium attachment to the detecting unit).

The measurements were carried out for two conditions of irradiation of the samples, in different geometries:

- concrete samples are placed in an isotropic neutron field from a Pu-Be neutron source (“simple” neutron experiment);

- measurements with geometry, allowing to take into account the reflected and scattered neutrons (“complex” neutron experiment).

During the measurements, the neutron source ИБН-12 was in the transport container. The transport container is a metal container with a central tube into which the source is installed. The inner space of the container is filled with paraffin. For personnel protection, a container with a source from three sides was surrounded by panels of “neutron stops” of type TP12-41-MMS 065/73 and metal tanks with water. “Neutron stops” are blocks of polyethylene with boron content and are effective neutron absorbers. The thickness of the neutron-stop panels is 70 mm. Water tank thickness 150 mm.

The floor plan and layout of equipment is shown in Figure 2, and Figure 3 shows a front view of the source and the overall dimensions of the equipment.

Fig. 3. Frontal view and overall dimensions of the container with a neutron source.

As mentioned above, this study investigates two different types of basalt fibers infused with boron as reinforcing material (**BasBor6** and **BasBor12**). There are 5 types of concrete mixtures in the neutron experiment conducted, all of them with same type of cement, CEM I 42.5R, same water-to-cement ratio and same river sand as fine aggregate. The density of concrete was 2.33 g/cm^3 . All in all, there are five main types of concrete mixtures in this study and they are noted throughout the paper as follows: **R** – plain concrete without BBF; **A** – concrete with **BasBor6** dosage: 5 kg/m^3 ; **B** – concrete with **BasBor6** dosage: 20 kg/m^3 ; **C** – concrete with **BasBor12** dosage: 5 kg/m^3 ; **D** – concrete with **BasBor12** dosage: 30 kg/m^3 . Concrete samples have dimensions: $10 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm}$.

3.2 “Simple” experiment

The scheme of measurement of geometry in a “simple” experiment is shown in Figure 4. The detecting unit was located along the axis and at the height of the source in the containers. The distance between the detecting unit and the front wall of the container is $L = 500 \text{ mm}$.

Ten measurements were conducted without samples of concrete. The measurements were carried out for thermal (see Fig. 5) as well as intermediate and fast neutrons (using a detection unit with an installed cadmium packing (see Fig. 6)).

Between the detecting unit and the source, one to five concrete samples from each set were sequentially installed. Ten measurements were conducted for each configuration and set of samples. The measurements were carried out for thermal as well as intermediate and fast neutrons (a detection unit with an installed cadmium packing). All experimental and simulations results will be presented in next journal paper which is currently being prepared.

3.3 “Complex” experiment

A diagram of the measurement geometry in a “complex” experiment is shown in Figure 7.

Fig. 4. Schematic representation of measurement geometry in a “simple” experiment.

Fig. 5. The measurements for thermal neutrons.

For measurements, a container was assembled from “neutron stops”. The container is a box with dimensions of $580 \times 500 \times 300 \text{ mm}$ closed on all sides, with wall thickness

Fig. 6. The measurements for intermediate and fast neutrons.

Fig. 7. Schematic representation of the measurement geometry in a “complex” experiment.

70 mm. In one of the walls of the container, a rectangular opening with a section equal to the section of the samples is made. A detection unit was installed inside the container opposite the opening. This measurement geometry allows

shielding from neutrons reflected from the walls of the room and equipment, and taking into account their contribution to the measurement results of neutron flux.

The hole in the container was closed with a stopper made of neutron stops and 10 measurements of φ_ϕ – background neutron flux were performed. The measurements were carried out for thermal as well as intermediate and fast neutrons (a detection unit with an installed cadmium packing).

Ten measurements of neutron flux φ_0 were conducted without samples of concrete. The measurements were carried out for thermal as well as intermediate and fast neutrons (a detection unit with an installed cadmium packing).

Opposite the opening between the detection unit and the source, one to five concrete samples from each set were sequentially installed. Ten measurements of neutron flux were then conducted for each configuration and set of samples. The measurements were carried out for thermal as well as intermediate and fast neutrons (a detection unit with an installed cadmium packing).

Based on the results obtained of neutron flux density measurements, the mean values, the standard deviation and the relative statistical error of each measurement by formulas (1)–(3) were calculated.

$$\bar{\varphi} = \frac{\sum_{i=1}^{i=n} \varphi_i}{n}, \quad (1)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{i=n} \varphi_i - \bar{\varphi}}{n-1}}, \quad (2)$$

$$\delta = 2 \times \frac{\sigma}{\bar{\varphi}} \times \sqrt{n} \times 100\%, \quad (3)$$

where, φ_i – measured values of neutron flux, neutron/(cm² sec); $\bar{\varphi}$ – the average value of neutron flux, neutron/(cm² sec); $n=10$ is the number of measurements; σ – standard deviation, neutron/(cm² sec); δ is the limit of the relative statistical error, percentage.

The results of measurements and calculations in the “complex” experiment for all series of measurements are given in Tables 4 and 5. The numbers 1–5 mean that: 1 – one concrete sample between source and detector; 2 – two concrete samples between source and detector; 3 – three concrete samples between source and detector; 4 – four concrete samples between source and detector; 5 – five concrete samples between source and detector.

It can be seen from Table 4 that there is a slight increase of neutron radiation shielding properties (up to 5%) in the case of low concentrations of BBF in concrete (A and C types of concrete samples), but considerable increase of neutron radiation shielding properties (up to 13%) with the addition of higher concentration of BBF in concrete (B and D types of concrete samples) for intermediate and fast neutrons. It can also be noted from Table 5 that a similar trend can be observed for thermal neutrons, which is a direct result of the increased fraction of neutrons with high absorption cross-section for Boron-10 in the thermal

Table 4. The neutron-physical characteristics on radiation shielding experiment for intermediate and fast neutrons.

Measurement	Neutron flux for intermediate and fast neutrons, neutron/(cm ² sec)										Average flux, neutron / (cm ² sec)	Standard deviation	δ , %
	1	2	3	4	5	6	7	8	9	10			
ϕ_0	633.7	659.3	644.8	651.5	646.6	638.2	645.9	620.8	653.5	650.5	644.5	11.1	1.1
ϕ_Φ	289.4	294.1	300.4	282	306.1	297.6	302.2	289.4	297.3	298.3	295.7	7.1	1.5
R1	411.5	413.8	397.6	392.5	400.8	396.3	409.2	385.2	405.7	391.7	400.4	9.4	1.5
R2	337	355	352	314	333	331	390	302	321	371	340.6	26.8	5.0
R3	294	310	311	305	310	315	289	311	306	337	308.8	12.8	2.6
R4	263	300	309	318	324	316	313	309	311	334	309.7	18.8	3.8
R5	325	326	301	327	300	288	296	305	303	283	305.4	15.7	3.3
A1	421	393	370	425	407	398	401	434	394	404	404.7	18.4	2.9
A2	314	351	329	382	327	360	334	332	315	326	337.0	21.3	4.0
A3	318	322	329	314	325	299	259	351	317	296	313.0	24.4	4.9
A4	292	324	351	316	301	326	319	362	313	304	320.8	21.7	4.3
A5	313	308	315	305	332	301	277	303	308	306	306.8	13.7	2.8
B1	412	364	423	400	384	431	360	399	415	395	398.3	23.6	3.7
B2	322	325	333	317	318	297	342	331	315	342	324.2	13.7	2.7
B3	280	304	306	275	307	295	302	286	319	303	297.7	13.6	2.9
B4	270	298	282	286	282	295	279	296	272	297	285.7	10.4	2.3
B5	290	271	259	279	281	265	257	259	287	264	271.2	12.2	2.9
C1	426	394	357	395	396	388	456	382	449	409	405.2	30.6	4.8
C2	344	350	336	349	332	326	337	302	347	346	336.9	14.6	2.7
C3	295	328	348	312	300	331	317	312	305	321	316.9	15.8	3.2
C4	304	309	294	297	302	334	294	293	304	331	306.2	14.8	3.1
C5	321	258	302	278	309	295	280	332	333	297	300.5	24.3	5.1
D1	373	389.5	388.7	384.5	376.9	368.8	369.7	401.6	400.8	388.2	384.2	11.9	2.0
D2	327	324	336	306	309	330	321	304	308	335	320.0	12.3	2.4
D3	277	285	316	302	295	282	331	292	329	297	300.6	19.0	4.0
D4	248	289	280	293	289	298	297	287	274	293	284.8	14.9	3.3
D5	296	282	280	274	269	254	273	288	261	279	275.6	12.4	2.8

neutron spectrum. Therefore, it could be argued that the use BBF could decrease the thickness of radiation shielding protection at nuclear energy applications.

4 Conclusions

In present work, the radiation shielding properties of basalt-boron fiber reinforced concrete are investigated. The samples of basalt fibers infused with boron oxide are prepared for neutron experiment. Two types of basalt-boron fiber referred to as BasBor6 (contains 6% of B₂O₃) and BasBor12 (contains 12% of B₂O₃) are used for preparation of four types of fiber concrete samples. The neutron radiation shielding experiment for concrete samples with different dosages of basalt-boron fiber are conducted with help of Pu-Be neutron source. The experiment includes Pu-Be neutron source (ИБН-12), a radiometer-dosimeter MKC-01P with a detection unit БДКН-03P and panels of “neutron stops” of type TP12-41-MMS 065/73.

It is found that the addition of basalt-boron fiber in concrete has effects for fiber dosages 20 kg/m³ and 30 kg/m³ in case of thermal and fast neutrons. Obviously, a low dosage of basalt-boron fiber (5 kg/m³) does not produce a noticeable effect in neutron radiation shielding properties.

The presented experimental results indicate that basalt-boron fiber reinforced concrete has a good potential for use in nuclear energy application and in nuclear waste management. Also, the basalt-boron fiber reinforced concrete is expected to have good mechanical properties including enhanced tensile strength and strong durability, based on its fiber content.

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Table 5. The neutron-physical characteristics on radiation shielding experiment for thermal neutrons.

Measurement	Neutron flux for thermal neutrons, neutron/(cm ² sec)										Average flux, neutron/(cm ² sec)	Standard deviation	δ , %
	1	2	3	4	5	6	7	8	9	10			
φ_0	129.7	133	132.6	134.6	126.3	133.4	132.8	129.9	129.8	128.9	131.1	2.6	1.2
$\varphi\Phi$	21.6	20.8	18.5	18.6	22.7	18.1	19.1	19.3	22.6	20.2	20.2	1.7	5.4
R1	52	49	46	48	50	56	49	45	46	50	49.1	3.2	4.2
R2	45	52	48	41	58	51	50	47	52	47	49.1	4.6	6.0
R3	47	45	53	47	48	49	44	53	50	51	48.7	3.1	4.0
R4	55	41	43	46	40	46	52	44	54	52	47.3	5.5	7.4
R5	49	54	47	43	48	42	47	48	52	50	48.0	3.7	4.8
A1	48.8	49.3	51.3	51.8	56.8	51.5	51.6	49.9	51.3	54.1	51.6	2.3	2.9
A2	45.6	49.7	47	49.1	46.1	46.2	44.8	48.5	50	45.7	47.3	1.9	2.5
A3	46.5	45.8	45.7	47.1	41.5	45.6	46.3	46.9	49.3	50.2	46.5	2.3	3.2
A4	49.5	46.5	48.5	48.8	45.3	47.7	46.6	45.3	45.5	44.9	46.9	1.7	2.2
A5	44.6	44.7	45.7	46.9	50.7	42.7	46.9	44.8	45.5	42.6	45.5	2.3	3.2
B1	47.6	50.3	47.9	49.8	46.8	47.1	45.7	50.6	48.2	42.4	47.6	2.4	3.2
B2	42.9	41.7	44.1	42.8	46	44.9	46.5	44.2	46.9	45.4	44.5	1.7	2.4
B3	42	39.7	42.7	42.6	44	40.1	41.8	40.7	44.2	43.4	42.1	1.6	2.4
B4	42.7	41.9	42.2	41.1	41.4	40.7	40.3	43.9	39.5	41.3	41.5	1.3	1.9
B5	40.9	40.2	42.5	44.3	41	43.5	43.8	40.9	42.9	44.8	42.5	1.6	2.4
C1	45	52	48	50	44	45	41	49	45	41	46.0	3.7	5.1
C2	44	47	48	39	48	43	35	40	35	38	41.7	5.0	7.6
C3	34	37	40	37	40	33	45	42	46	32	38.6	4.9	8.0
C4	43	35	39	44	32	44	42	32	44	45	40.0	5.2	8.2
C5	39	41	37	36	31	34	36	39	37	45	37.5	3.8	6.5
D1	44.2	50.9	48.3	45.8	46.1	43.1	46.9	44.4	46	47.8	46.4	2.3	3.1
D2	43.7	39.8	41.3	42.4	41	41.1	44.1	41.5	41.2	41.7	41.8	1.3	2.0
D3	42.3	41.3	39.1	42.3	42.2	41.9	41.7	39.2	42.6	42.2	41.5	1.3	2.0
D4	42	39.5	40.1	40.7	39	37.5	41.5	40.5	40.1	37.5	39.8	1.5	2.4
D5	40	38.1	40.7	38.4	40.4	36.2	39.2	40.1	39.3	39.5	39.2	1.3	2.2

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Author contribution statement

I. Romanenko prepared the samples of fiberconcrete reinforced by basalt-boron fiber and analyzed the obtained experimental results. M. Holiuk analyzed the obtained experimental results and prepared manuscript. P. Kutsyn analyzed the obtained experimental results and prepared manuscript. I. Kutsyna analyzed the obtained experimental results and prepared manuscript. G. Odinokin conducted the neutron experiment on Pu-Be neutron source. A. Nosovskyi analyzed the obtained experimental results. V. Pastuk prepared the samples of fiberconcrete reinforced by basalt-boron fiber and conducted

the neutron experiment on Pu-Be neutron source. M. Kiisk analyzed the obtained experimental results and prepared manuscript. A. Biland analyzed the obtained experimental results and prepared manuscript. Y. Chuvashov prepared the samples of basalt-boron fiber for neutron experiment. V. Gulik conducted the neutron experiment on Pu-Be neutron source, analyzed the obtained experimental results and prepared manuscript.

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