Thermal neutron shielding performance and mechanism of a novel, low cost material: Boron-rich slag

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Abstract: In this paper, thermal shielding performance and mechanism of boron-rich slag was studied. Data of neutron scattering lengths and cross sections were used to analyze the shielding properties and mechanism. It was found that the macro-cross section of boron-rich slag is 5.02 cm^{-1}, higher than ordinary concrete, PE-B_4C concrete, FeCr slag and colemanite concentrator for neutron shielding. The maximum contribution of the elements contained in boron-rich slag for shielding thermal neutron was B, it was 92.85%, far more than the contribution of other elements. $2MgO \cdot B_2O_3$ was the main compound of boron-rich slag for shielding thermal neutron. Main shielding forms are elastic and absorption. However, the effect of absorption was far more than elastic. Besides, the effect of absorption emitted the gamma ray was the biggest. Boron-rich slag would be excellent shielding material or filler for neutron shielding. Besides, the investigation provides a method to analyze the shielding mechanism of complex shielding material for thermal neutron.

Key words: boron-rich slag; thermal neutron; shielding properties; mechanism

1 Introduction

Boron reserve of China ranks fourth in the world next to Turkey, USA and Russia. In China, the main boron-containing ores are szaibelyite, ludwigite and brine. However, Ludwigite resource is relatively abundant and account for 58.4% of the total Chinese boron reserve [1]. The main utilization method for Ludwigite is used to produce pig iron. Besides, iron slag would be emitted which is named as boron-rich slag, moreover, the slag is mainly used for the production of boron products [1-3]. It is well known that boron has excellent shielding property for neutron radiation protection. For example, B_4C/ Al composites were successfully fabricated by vacuum hot pressing followed by hot rolling in atmospheric environments for shielding thermal neutron, it was found the materials has good properties [4]; Khong *et al* [5] investigated some new alloys contained boron for neutron shielding. In addition, Li *et al* [6-8] had used the boron-rich slag to make composites with epoxy resin matrix for shielding thermal neutron, it was found the shielding properties were excellent. However, the shielding properties of boron-rich slag itself for thermal neutron have never been studied. Moreover, the shielding mechanism for thermal had not been studied.

Neutron scattering lengths and cross sections of the elements and their isotopes for thermal neutron (E= 25.3meV, V= 2200 m/s) was reported by Sears [9]. Besides, the data was widely used in many studies [10-21]. For example, Leguy *et al* [10] used the data to analyze scattering cross-section of H in their research. Hillborg et al [13] calculated the coherent scattering length of some polymers using the data. Özdemir *et al* [20, 21] investigated the shielding performance of some boron containing materials for shielding thermal neutron using the data. Besides, the past studies had not investigated the shielding mechanism for thermal neutron; this encourages us to do this investigation.

In this work, shielding properties and mechanism of boron-rich slag for thermal neutron shielding will be studied. The investigation will provide useful utilization information for boron-rich slag in the field of shielding material application and a method to analyze the shielding mechanism of complex shielding material for thermal neutron.

2 Material and methods

2.1 Material

The raw material used in the work was boron-rich slag (Density=2.97 g/cm^3, Fengcheng Iron and Steel Group Co. Ltd. of Dandong). Table 1 shows the chemical composition of boron-rich slag, besides, the content of B-10 and B-11 is calculated according to the abundance of B-10 and B-11 contained in

natural boron [5]. Fig.1 shows the SEM of boron-rich slag and distribution of boron element contained in the raw material. Fig.2 shows the XRD pattern of boron-rich slag, it is found that the main compounds of boron-rich slag are $2MgO•B_2O_3$, Mg_2SiO_4 and Ca_2SiO_4.

Table 1 Chemical composition of boron-rich slag (*wt%*)

Element	B	O	C	Mg	Al	Si	Ca	Fe
Boron-rich slag	3.65	42.097	7.364	21.068	3.727	10.763	10.541	0.79

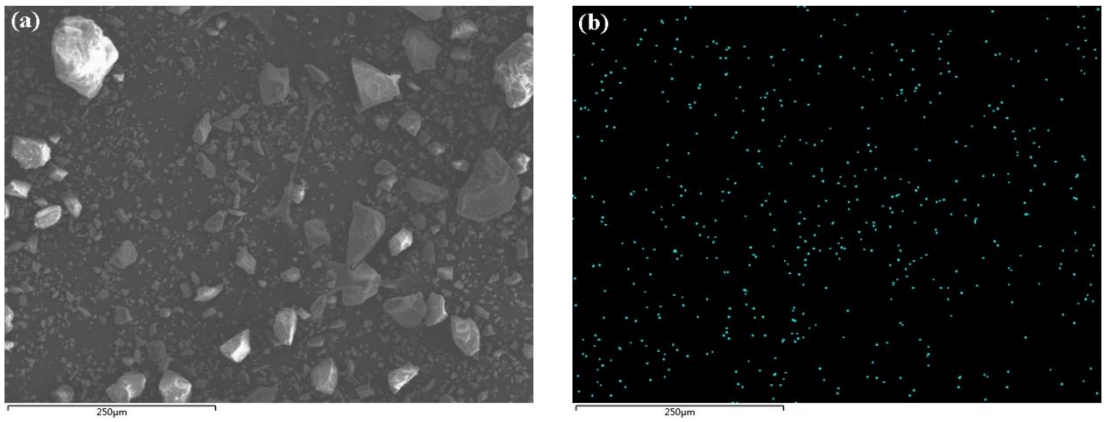

Fig.1. SEM of boron-rich slag (a) and distribution of boron element (b)

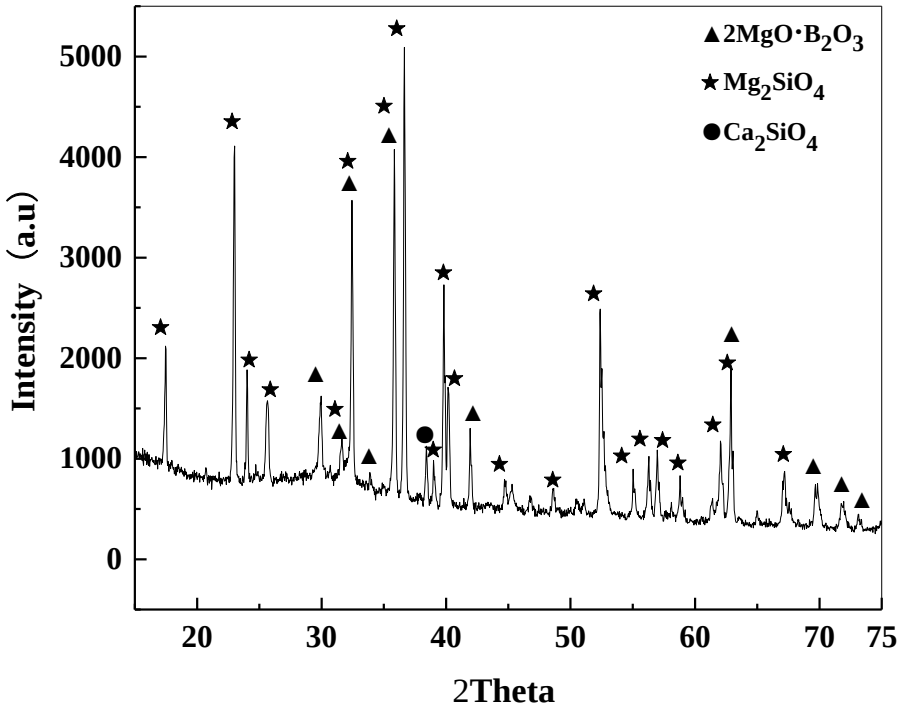

Fig.2. XRD pattern of boron-rich slag

2.2 Methods

It is well known that Sears reported the neutron scattering lengths and cross sections which provided the bound coherent scattering cross section, bound incoherent scattering cross section and

absorption cross section of the elements and their isotopes for thermal neutron [9], while the energy of thermal neutron was 25.30meV [9, 20, 21]. Besides, the total micro cross section could be calculated as follows:

$$\sigma=\sigma 1+\sigma 2+\sigma 3 \tag{1}$$

Where σ is total micro cross section, σ1 is the bound coherent scattering cross section, σ1 is the bound incoherent scattering cross section and σ3 is absorption cross section. Table 2 shows the total micro cross section of the elements contained in boron-rich slag from the data reported by Sears [9].

Table 2 Micro cross section of elements contained in boron-rich slag for thermal neutron

Element	B	O	C	Mg	Al	Si	Ca	Fe
Micro-cross section (barn)	772.24	4.23219	5.5545	3.773	1.734	2.338	3.26	14.18

While the macro cross section of boron-rich slag ($\sum E$, cm^{-1}) could be calculated as follows [8, 22]:

$$\sum E=N_{\mathrm{A}}\rho\sum_i\frac{\omega_i}{M_i}(\sigma)_i \tag{2}$$

$$\sum E=\sum_i\omega_i(\sum E)_i \tag{3}$$

Where $\sum E$ (cm^{-1}) is the macro-cross section of boron-rich slag, ω_i is the mass fraction of *i*th element, N_A is the Avogadro Constant, ρ (g/cm^3) is the density of boron-rich slag, M_i is the molar mass of *i*th element, $(\sigma)_i$ (measured in barn) is micro-cross section of *i*th element.

Thus the contribution of each element contained for the macro cross section of boron-rich slag could be calculated as follows:

$$C=\frac{N_{\mathrm{A}}\rho\frac{\omega_i}{M_i}(\sigma)_i}{\sum E}\times 100\% \tag{3}$$

3 Results and discussion

3.1 Shielding properties of boron-rich slag for thermal neutron

It can be seen from the Table 2 that the maximum micro-cross section is B, next is Fe, and other elements are nearly the same. Besides, the value of micro-cross section of B is far more than other elements. The result of the macro-cross section of boron-rich slag is 5.02 cm^{-1}. Fig. 3 shows the comparative of boron-rich slag and some concretes and fillers for neutron shielding, it is found that the macro cross section of boron-rich slag is higher than ordinary concrete, PE-B4C concrete, FeCr slag and colemanite concentrator for neutron shielding. It can be that the boron-rich slag would be excellent

shielding material or filler for neutron shielding.

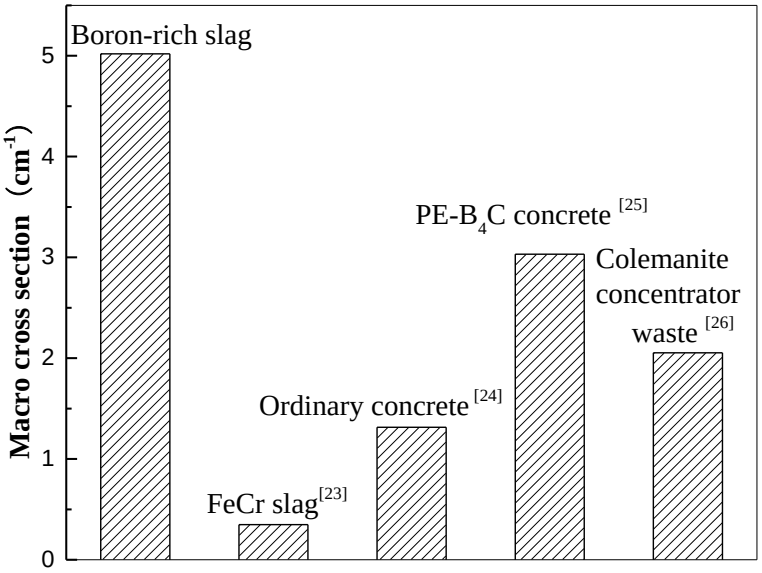

Fig.3. Macro cross section of some concretes and fillers for neutron shielding

3.2 Shielding mechanism of boron-rich slag for thermal neutron

Table 3 Contribution of each element contained in boron-rich slag for thermal neutron shielding

Element	B	O	C	Mg	Al	Si	Ca	Fe
Contribution(%)	92.85	3.97	1.26	1.15	0.09	0.32	0.31	0.07

The contribution of each element contained in boron-rich slag for thermal neutron shielding is shown in Table 3. From Table3, it can be seen that the maximum contribution of the elements contained in boron-rich slag is B, it is 92.85%, far more than the contribution of other elements. Next is O (3.97%), C(1.26%), Mg(1.15%), however, the contribution of Al, Si, Ca and Fe is relatively samll. Combined with XRD pattern of boron-rich slag (Fig.2), it is found that the main compounds of boron-rich slag are $2MgO{\bullet}B_2O_3$, Mg_2SiO_4 and Ca_2SiO_4, besides, the $2MgO{\bullet}B_2O_3$ is the only compound contains the boron element in the slag. Nevertheless, Mg_2SiO_4 contains little Mg and O. Thus $2MgO{\bullet}B_2O_3$ is the main compound for shielding thermal neutron and far more than other compounds. Thus, the shielding mechanism of boron-rich slag for thermal neutron can be concluded as shown in Fig.4. It can be seen that the main shielding forms are elastic and absorption. However, the effect of absorption is far more than elastic. Besides, the effect of absorption emitted the gamma ray is the biggest [27-29].

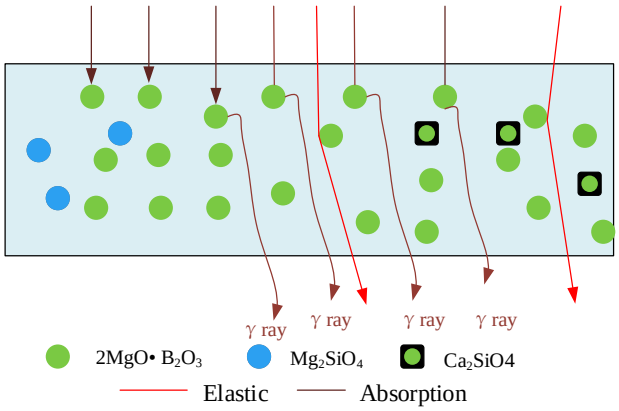

Fig.4. Shielding mechanism of boron-rich slag for shielding thermal neutron

4 Conclusions

The result of the macro-cross section of boron-rich slag is 5.02 cm^{-1}, higher than ordinary concrete, PE-B_4C concrete, FeCr slag and colemanite concentrator for neutron shielding.

The maximum contribution of the elements contained in boron-rich slag for shielding thermal neutron is B, it is 92.85%, far more than the contribution of other elements. $2MgO•B_2O_3$ is the main compound of boron-rich slag for shielding thermal neutron. Main shielding forms are elastic and absorption. However, the effect of absorption is far more than elastic. Besides, the effect of absorption emitted the gamma ray is the biggest.

Boron-rich slag would be excellent shielding material or filler for neutron shielding. Besides, the investigation provides a method to analyze the shielding mechanism of complex shielding material for thermal neutron.

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