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Shielding Ability of a Novel Iron Ceramic Material for Gamma-Rays

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Radiation shielding is one of the necessary procedures in radiation protection. The lead blocks are commonly used to shield against gamma- and X-rays. However, due to lead's biotoxicity, the development of alternative materials is required. We developed a novel ceramic product as a non-biotoxic shielding material composed mainly of iron (III) oxide. In this study, the radiation shielding performance against gamma-rays was evaluated and its potential as a radiation shielding material was investigated. We measured the gamma-ray amount transmitted through the ceramic specimens using a NaI scintillation counter with three different gamma sources (^{133}Ba, ^{137}Cs, and ^{60}Co). The order of shielding ability of the sample with the same volume was lead > iron > the ceramics. The effects of piling the blocks and the type of jointing agent used in the gaps on the shielding ability were also observed for considering actual use.

Key Words: gamma-rays, shielding, attenuation, half-value layer, ceramics

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1. Introduction

One of the most important aspects of radiation work is to avoid unnecessary external exposure. There are various ways to achieve this object, such as using tongs and remote control to keep distance from the source, rational experimental design, and skill training to reduce exposure time and shielding with appropriate materials.

The microscopic aspect of radiation-matter interaction is that between radiation and the atom or molecule, while the macroscopic aspect is the attenuation of radiation passing through the matter. The manner of attenuation depends largely on the type and energy of the radiation and material characteristics. In some cases, secondary radiation is generated, and activation occurs, in which the material becomes radioactive.

Shielding is one of the procedures necessary for work in radiation-controlled areas because it takes advantage of the attenuation of radiation. As mentioned above, the appropriate shielding material should be selected according to the type and energy of the radiation. For shielding against gamma- and X-rays, lead has been most used, and lead blocks are often piled together in front of any radiation source.1) Concrete and iron have been used for shielding walls and other large-area applications for cost reasons. However, concrete has a weaker shielding ability than lead, so it must be thicker for shielding use. Among these three materials, lead has the highest shielding ability, but lead has a biotoxicity as well known.2) For this reason, the use of lead is becoming contraindicated.3) The second highest shielding ability is iron. Iron is the most abundant element in nature. It is also easily processed and inexpensive and is often used as a shielding material. The weakness of iron is that it rusts. To avoid this, the surface may

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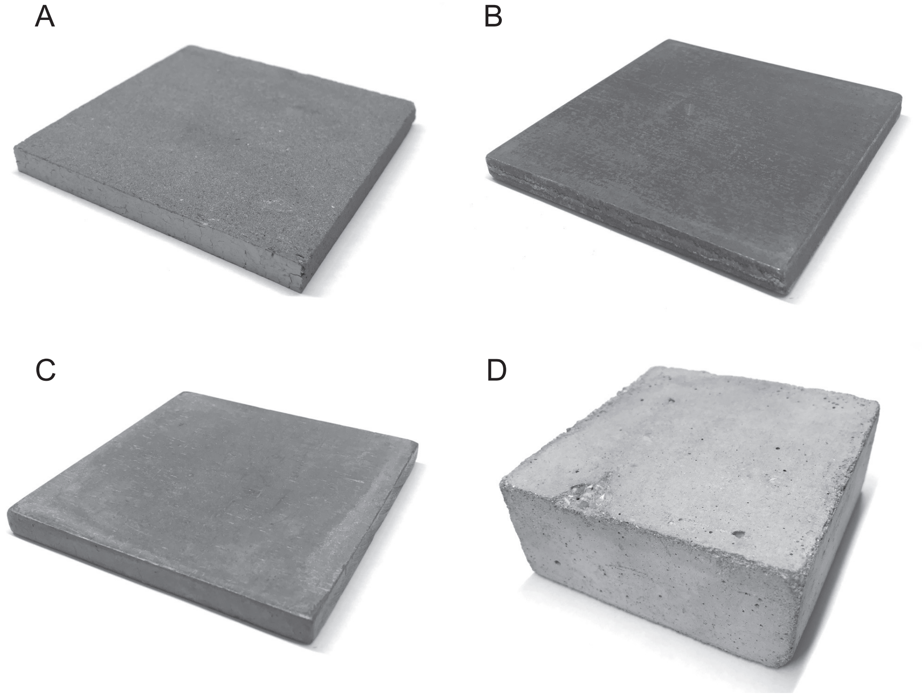

Fig. 1. The plate materials in this study. These are the ceramic (A), iron (B), lead (C), and concrete (D). These are squares with 10 cm on each side. The thicknesses are 1 cm for the ceramic, iron, and lead plates, and 5 cm for the concrete one.

be painted. However, it is difficult to use outdoors where it may get wet.

Based on the above, various efforts are being made regarding radiation shielding materials. For example, in various concrete, heavy concrete is used as shielding material.4) Ceramics is also tested to find more optimal materials.5) We developed a ceramic made with iron (III) oxide (Fe_2O_3) expected to be a novel toxic-free shielding material named RASHIX.6) This material is already in practical use, though chemical analysis of its properties is still needed. In this study, the radiation shielding performance of this material against gamma-rays was evaluated in detail, and its potential as a radiation shielding material was examined. As a result, this ceramic was found to be useful as an alternative shielding material to lead.

The shielding material is often used by piling up blocks of shielding material near the source of radiation. There is a risk of radiation leakage through gaps between the blocks. In this study, two approaches were taken to address this issue. One is to change the shape of the blocks. The contact surface between blocks is flat in general blocks (straight gap). Here we created blocks with a mountain-shaped concave-convex contact surface (offset gap) and evaluated the radiation leakage. Gaps between blocks are often covered with a jointing agent in common blocks. Therefore, the jointing agent that fills the contact surface of the block was also examined, and the difference in shielding ability between the different types of jointing agents was also studied.

2. Materials and Methods

The ceramic products used in this study were produced by the previously reported procedure, whose main ingredient is iron (III) oxide.6) A brief description of how to make it is given below. A powder containing 99% iron oxide was fabricated into specimens by pressing gently into an iron mold, and then it was pushed and hardened with 3 MPa/cm^2. The specimen was subjected to a firing process up to 1,320°C and then cooled at room temperature for 10 days. Other details related to sample preparation are referred to our previous report.6)

To investigate the shielding ability, plate-like samples of 1 cm in thickness and 10 cm in height and width were prepared, and the required number of plates were piled on top of each other. Controls for the shielding ability evaluation experiments were lead and iron plates of the same shape and a piece of concrete of 5 cm in thickness, 10 cm in height and width (Fig.

1). To evaluate the effect of block piling, the ceramic blocks with 5 cm thick, 10 cm height, and 20 cm width were used. For comparison of radiation leakage during the piling gap, 5 cm in length was prepared and used for piling. The blocks were piled in three differently shaped blocks without a gap, with a straight gap, and an offset gap (Fig. 2). The offset between the center and both ends of the block is 5 mm.

The jointing agents used were prepared by mixing the materials listed below. Epoxy resin was purchased from Konishi Co., Ltd., Japan. Super3000SW was from Nippon Crucible Co., Ltd., Japan. Fuji Light#10 and Sealex were made by Fujikawa Kenzai Co., Ltd., Japan. The sticky rice was from Okayama Pearl Rice Co., Ltd., Japan. Iron sand was from Kato Hikinzoku Kogyo Co., Ltd., Japan. Borax sand and Boric acid were from Borax Tech, United States, and Ohara & Co., Ltd., Japan, respectively.

Three different gamma-ray sources including ^{133}Ba, ^{137}Cs, and ^{60}Co were used to determine the radiation penetration ability. The radio activities of these gamma sources were 1,028.7 kBq, 3,598.0 kBq, and 154.3 kBq, respectively. The attenuation calculation obtained these radio-activities values on September 1st, 2019. These gamma sources were obtained from Japan Radioisotope Association, Japan. The energies of the gamma-rays from ^{133}Ba and ^{137}Cs are 356 keV and 662 keV, respectively. ^{60}Co releases two gamma-rays with 1,173 and 1,333 keV. Therefore, the average of these two gamma-rays, 1,253 keV, is used in the discussion. The radiation beam from the radiation source was guided to the sample through a square aperture with a side length of 2 cm using a lead block, and the radiation dose was measured. The distance between the radiation source and the detector was 20 cm. The detector used for the measurements was a NaI (Tl) detector (Universal Scaler TPC-501, Aloka, Japan) with a diameter of 5 cm. The measurement time was 30 seconds, and measurements were taken 10 times for the same sample.

The sample was 1 cm-thick ceramic plates as mentioned above, and the amount of the radiation that passed through them was measured when the thickness was increased from 1 cm to 10 cm. Similarly, the shielding ability of 1 cm-thick steel, lead, and 5 cm-thick concrete plates were compared by measuring the amount of radiation that passed through them at similar thicknesses. Ten measurements were taken at a time, and the mean value and standard deviation were calculated. The obtained values were statistically processed and examined for their certainty.

The amount of radiation passing through the gap between the blocks was measured when the 5 cm-thick ceramic blocks were piled. The blocks were piled in three differently shaped blocks without or with different gaps as mentioned above (Fig. 2). The offset between the center and both ends of the block is 5 mm. For using those shaped blocks, the amount of radiation leaking through the gaps between the blocks was compared. We also measured the amount of radiation that passed through the gaps between the blocks when they were filled with jointing agents. The jointing agents used were (1) epoxy resin, (2) Super3000SW, (3) Fuji Light #10, (4) sticky rice, (5) epoxy

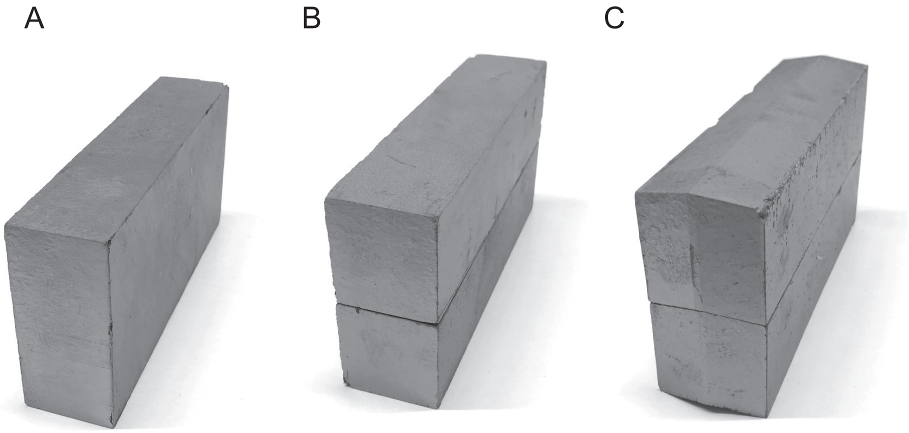

Fig. 2. The block-shaped ceramic used in this study. The size of each block is 18 cm (width)×10 cm (height)×5 cm (depth). We used three types of blocks without a gap (A), with a straight gap (B), and an offset gap (C). The offset between the center and both ends of the block is 5 mm.

resin (90%) + iron sand (10%), (6) Super3000SW (80%) + iron sand (20%), (7) Fuji Light #10 / Sealex, (8) Fuji Light #10 / Sealex (60%) + iron sand (40%), and (9) sticky rice / borax / boric acid.

3. Results and Discussion

The shielding ability of the novel ceramic material was examined using three different sources emitting gamma-rays with different energies. To compare the shielding ability of the ceramic, we used iron, lead, and concrete for references. We set 1 cm thick plates (Fig. 1) made of them between the gamma source and detector, and the shielding ability was evaluated by measuring the dose of gamma-rays that passed through the plates and reached the detector. As more and more plates were piled, the dose of gamma-rays reaching the detector from the source decreased (Fig. 3). This phenomenon was similar for all radiation types and all shielding materials. From these plots, we calculated the half-value layers and used them to compare the shielding ability of respective materials. The half-value layers of each material for each gamma-ray show that lead has the highest shielding ability for all three different gamma-rays, followed by iron, then the ceramic, and finally concrete (Table 1). The gamma-rays emitted from ^{133}Ba and ^{137}Cs are 356 keV and 662 keV, respectively, while ^{60}Co emits gamma-rays of 1,173 keV and 1,333 keV. The half-value layer was naturally proportional to the strength of the gamma-rays. From the shielding material's point of view, the trend of the strength of the shielding ability was proportional to the respective density. The measured densities of lead, iron, the ceramic, and concrete are 1104.8, 798.6, 493.4, and 228.9 kg/m^3, respectively. The iron oxide ceramic whose density is 62% that of iron. It is also 45% that of lead and 2.2 times that of concrete. The linear attenuation coefficient (μ) for ^{60}Co gamma-rays is 0.162 and 0.254 for the ceramic and iron, respectively. Dividing these by their respective densities to obtain the mass attenuation coefficients (μ/ρ), the results are 0.033 and 0.032 for the ceramic and iron, respectively, which are in close agreement. This means that the ceramic consists of pure iron (III) oxide (Fe_2O_3) and that the shielding ability is almost the same for the same mass. The above suggests use of the ceramic as a substitute for other shielding materials.

Lead and concrete blocks used for shielding are usually piled on top of each other. In such cases, radiation leakage from gaps between the blocks becomes a problem. We here compared and quantified the leakage of radiation from two

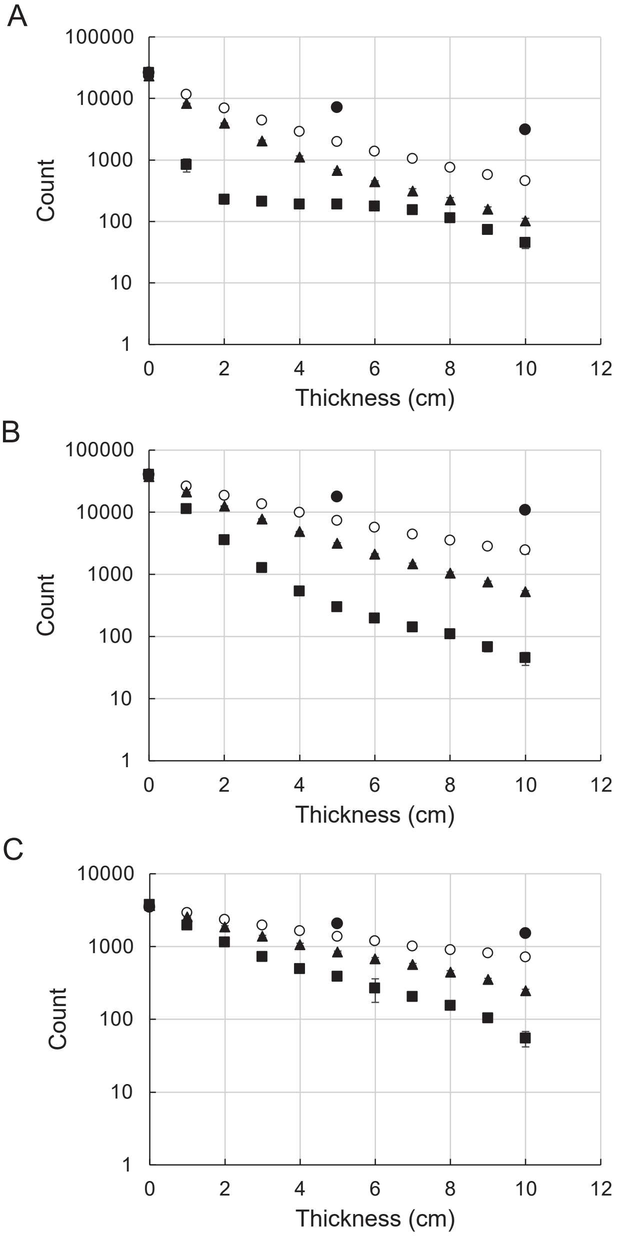

Fig. 3. Shielding capacities of plate samples for gamma-rays from ^{133}Ba (A), ^{137}Cs (B), and ^{60}Co (C). The plots are the ceramic (open circle), iron (closed triangle), lead (closed rectangle), and concrete (closed circle), respectively. Each count is the mean of 10 independent experiments, with standard deviations shown as bars, although some of the standard deviations are small and hidden by markers. The counts were obtained from 30-second measurements. Each value is from ten independent experiments, and the representation consists of the average ± standard deviation.

Table 1 Half-value layers of plate materials.

Shield material	Ba-133	Cs-137	Co-60
The ceramic	0.935 ± 0.018	2.066 ± 0.017	4.038 ± 0.033
Iron	0.282 ± 0.011	1.176 ± 0.021	2.496 ± 0.082
Lead	0.199 ± 0.003	0.533 ± 0.006	1.272 ± 0.078
Concrete	2.964 ± 0.028	4.868 ± 0.044	8.729 ± 0.298

Footnote: The half-value layers are expressed in terms of length (cm) in this table. The respective values are from the ten independent experiments, and the representation consists of the average ± standard deviation.

different types of gaps with the piled ceramic blocks and examined the effect of radiation leakage on the shielding. We compared two types of piling, one with a straight gap and the other with an offset gap (Fig. 2). We also used one without a gap as a control. The results of the experiment showed that the shape with no gaps had the lowest radiation leakage for all three types of gamma-rays, followed by the mountainous shape, and the straight shape had the highest radiation leakage (Fig. 4). The shielding capacities for ^{133}Ba gamma-rays were 88.7% and 51.2%, respectively, with no gaps as 100%. The capacity for ^{137}Cs gamma-rays was 89.0% and 67.2%, respectively. And the capacity for ^{60}Co gamma-rays, 85.8%, and 78.7%, respectively. Although the offset gap had a higher shielding capacity compared to the straight shape, it still showed an increase in leakage of more than 10% compared to the no-gap shape. This will be discussed later in the jointing agent experiments.

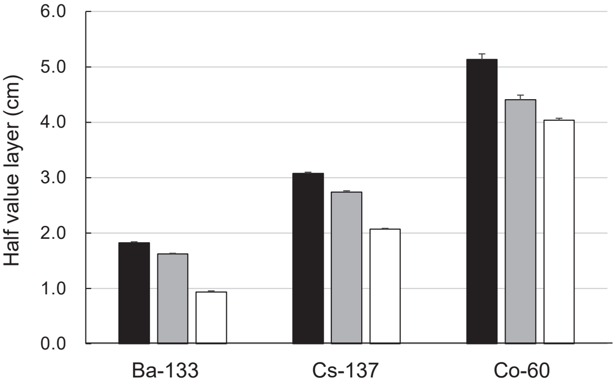

Fig. 4. The half-value layers of piled block samples were compared for the respective type of gamma radiations, ^{133}Ba, ^{137}Cs, and ^{60}Co. The shape of the piling are straight gap (closed bar), offset gap (gray bar), and no gap (open bar). The exact shape is in Fig. 2. Each value is from ten independent experiments, and the representation consists of the average ± standard deviation.

When the effect of piling blocks on shielding was examined in the last experiment (Fig. 4), an increase in leakage dose of more than 10% was observed regardless of the shape of the gap. Although it cannot be used for various experiments in irradiation chambers, it was considered that the leakage dose reduction could be achieved by filling the gaps with a jointing agent when used in a fixed condition, such as an internal shielding material in a wall. Therefore, we observed the effect of jointing agents on shielding by filling the gaps in the straight shape of the ceramic blocks with various jointing agents. The jointing agents were epoxy resins and other commercially available products, either alone or mixed (Table 2). Experimental results showed that the jointing agents could improve shielding capacity, although the effectiveness varied among the different types of jointing agents. The jointing agents that most improved the shielding ability were Fuji Light #10 for ^{133}Ba and ^{137}Cs gamma-rays and sticky rice for ^{60}Co gamma-rays. The improvement ratio was 1.1 to 1.3 times, which was almost the same as that of the straight-to-offset forming in this study. This means that offset molding and the use of jointing agents have almost the same effect, suggesting that there is little need for the former, which is more cost and time-consuming in process and storage.

In the above, we measured the gamma shielding ability of a new iron oxide ceramic material and discussed its ability as a shielding material. This new material is already in use in the field,[6)] and the fact that we were able to confirm its accurate shielding capability in this study may provide important suggestions for the rationalization of shielding in the future. On

Table 2 Effect of jointing agents for half-value layers of block materials.

Jointing agents	Ba-133	Cs-137	Co-60
Control (no filling)	1.825 ± 0.015	3.074 ± 0.023	5.133 ± 0.101
Epoxy resin	1.662 ± 0.014	2.890 ± 0.022	4.742 ± 0.087
Super3000SW	1.793 ± 0.020	3.075 ± 0.020	5.029 ± 0.141
Fuji Light ♯10	1.356 ± 0.012	2.745 ± 0.013	4.592 ± 0.082
Sticky rice	1.669 ± 0.013	2.792 ± 0.013	4.590 ± 0.070
Epoxy resin + iron sand (9:1)	1.799 ± 0.016	3.068 ± 0.025	5.065 ± 0.112
Super3000SW + iron sand (8:2)	1.837 ± 0.016	3.106 ± 0.030	5.142 ± 0.139
Fuji Light ♯10/Sealex	1.767 ± 0.017	2.966 ± 0.050	4.801 ± 0.134
Fuji Light ♯10/Sealex + iron sand (6:4)	1.808 ± 0.023	3.042 ± 0.014	5.049 ± 0.087
Sticky rice/Borax/Boric acid	1.412 ± 0.032	2.908 ± 0.014	4.733 ± 0.097

Footnote: The half-value layers are expressed in terms of length (cm) in this table. The respective values are from the ten independent experiments, and the representation consists of the average ± standard deviation.

the other hand, further study is needed to safely put this material to practical use. For example, studies on the generation of secondary radiation when high-energy beta-rays pass through it and on its activation when neutron-rays pass through it. Despite the remaining issues, the ceramic material examined in this study can be used as one of the new non-toxic and useful shielding materials.

4. Acknowledgments

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