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A SUSTAINABLE APPROACH FOR RADIATION PROTECTION APPLICATIONS: SYNTHESIS AND CHARACTERIZATION OF WASTE BRICKS BOTTOM ASH INVOLVING Bi_2O_3

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Abstract. *These days, the utilization of industrial solid waste substances for gaining added-value products has become of prime importance for securing a more sustainable future. With this in mind, the present study handles using waste bricks bottom ash (BBA) involving bismuth oxide (Bi_2O_3) dopant for understanding the potentiality as a radiation protection material. Four different material systems, 1 to 4, were designed using the batches of xBi_2O_3 - (100-x)BBA where x: 0, 5, 10, and 20 wt%. The intended pellets (D: 28 mm) were made ready after precisely weighing, mixing, and pressing steps. For sintering, the prepared bodies, a heat treatment process was initiated by applying 10 °C/min to reach 1100 °C, which was then dwelled 1h at the peak temperature. Afterward, the successfully produced waste-derived material systems were subjected to some material characterization analysis, as well as theoretical radiation shielding computations via Phy-X/PSD. According to the density measurements, we found out that the increasing doping rate from 0 to 20 wt% in Bi_2O_3 led to the improvement in bulk density from 1.3857 to 1.6177 g/cm^3 in the respective order. Additionally, the compressive strength showed an increasing trend from 7.28 to 8.01 MPa with the increasing Bi_2O_3 contribution. On the other hand, the essential radiation shielding parameters, linear attenuation coefficient (LAC), half-value layer (HVL), and effective atomic number (Z_{eff}) were figured out, and we found out that all parameters were enhanced owing to the higher Bi_2O_3 addition. As a result, the sample-4 can be preferred as an alternative material system where radiation protection is significant.*

Keywords: *waste utilization, Bi_2O_3, bricks bottom ash, radiation protection, sustainability*

1. Introduction

Medical diagnosis centers, radiotherapy facilities, nuclear medicine complexes, and nuclear power plants have necessarily required radiation protection materials [1]. This is because the radiations emitted from different radioisotope sources may cause serious health problems to onsite people [2]. In accordance with the design criteria in these application areas, heavyweight construction materials have been offered so as to achieve utmost protection [3]. To meet the demand in protection intentions, heavyweight concrete (*HWC*) materials have widely been preferred. Knowing that *HWC* materials can be prepared using standard cement and heavy aggregates, the researchers have canalized towards manipulating the technical properties to serve the need in radiation shielding applications [4]. Despite the benefits such as shape flexibility, ease of preparation, and the existence of diverse heavy aggregates, *HWC* materials have some critical drawbacks [5]. Since cement production consumes primary raw materials and fossil fuels, they cause multi-hazards to the environment. The fundamental damages can be regarded as the greenhouse effect, water pollution, and depletion of natural resources. From these perspectives, the scientific community has moved towards sustainable and green materials for the provision of high-performance radiation protection materials.

In the modern world, concerns for the future have keenly arisen as it has never been before. As it is clear that climate change has already begun, and therefore some must take action to prevent catastrophic conclusions. With these motivations, solid waste substances-based material systems can appear as an alternative solution for many applications including radiation shielding [6]. Instead of utilizing primary resources, one can use waste materials to obtain similar properties to those composed of primary raw materials provide. To our way of thinking, HWC materials can be partially or totally replaced with waste-derived material systems to secure a more sustainable future. As an alternative material system, waste bricks bottom ash (*BBA*) can possess great potential.

In Afyonkarahisar/ Turkey region, there are many companies producing tiles and bricks products. These producers use primary raw materials and annually cause tonnes of waste *BBA* at the end of the process. Typically, the waste *BBA* consists of aluminosilicate with a high amount of Fe_2O_3 and CaO. That means, their valorization for the way of alternative radiation protection materials seems highly possible. When the literature was widely reviewed in terms of waste *BBA*-based radiation shielding materials, almost no other investigations have been found according to the best of our knowledge. On the other hand, many literature studies have already confirmed the advantages of using bismuth oxide (Bi_2O_3) content to improve the photon

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attenuation characteristics owing to its high density [7], [8], [9]. Supposing one compares the density value of Bi_2O_3 (8.90 g/cm^3) to those available in the literature, for instance, barium oxide (BaO, 5.72 g/cm^3) or lanthanum oxide (La_2O_3, 6.51 g/cm^3). In that case, employing Bi_2O_3 to improve radiation shielding properties is beneficial [10], [11]. For these reasons, the authors were strongly motivated to prepare a radiation shielding block made of waste BBA involving varying amounts of Bi_2O_3.

This investigation addresses fabricating waste *BBA* blocks involving Bi_2O_3 for radiation shielding applications. Four different material systems, 1 to 4, were designed using the batches of xBi_2O_3 - $(100-x)BBA$ where x: 0, 5, 10, and 20 wt%. The traditionally-known experimental procedure, weighing-mixing-pressing-sintering, was followed to produce the sample blocks. After that, the samples were analyzed using density, compressive strength, and Phy-X/PSD software to understand the physical, mechanical, and radiation shielding properties, respectively. The results were found to be promising, and the highest Bi_2O_3 insertion ratio provided high performance for the properties.

2. Materials and Methods

For producing the samples, we followed the flowchart given in Figure 1. First, the starting materials, waste *BBA* (Uysallar Inc., Afyonkarahisar/ Turkey) and Bi_2O_3 (Riedel-de Haen, 99.5% purity) were prepared. Afterward, the weighing of the corresponding substances was done according to the batch designs. The final compositions for the samples are given in Table 1.

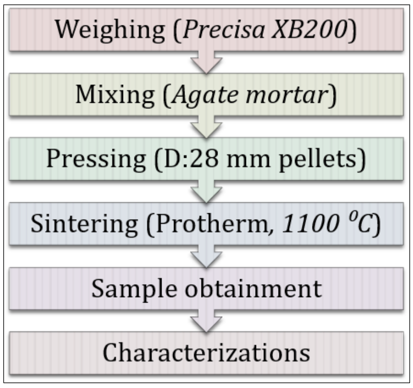

Figure 1. Flowchart for the experimental procedure

Table 1. Chemical compositions of the prepared samples

	1	2	3	4
SiO_2	55.8	53.06	50.31	44.82
Al_2O_3	18.35	17.33	16.31	14.28
Fe_2O_3	7.42	7.00	6.59	5.77
CaO	7.97	7.53	7.08	6.20
MgO	2.39	2.26	2.13	1.86
K_2O	3.46	3.27	3.08	2.70
Na_2O	4.60	4.54	4.49	4.37
Bi_2O_3	0	5.00	10.00	20.00

An agate mortar was used to mix each material system, and then the mixtures were separately pressed using uniaxial hydraulic pressing at 5 MPa. The pellets with a diameter of 28 mm were placed into the furnace (Protherm) for sintering at 1100 C with a heating rate of 10 C/min. Once the samples were kept at the peak temperature for 1h, the furnace was shut down and let the samples cool to the ambient temperature. After cooling, the samples were successfully obtained as revealed in Figure 2. The obtained samples were subjected to some characterization analysis including bulk density, compressive strength, and theoretical radiation shielding calculations (Phy-X/PSD) [12].

For bulk density measurements, Equation 1 was applied with respect to the Archimedes' principle. Here, m_{air} and m_{liquid} represent the weight in air and water medium (ρ_{water}: 0.99 g/cm^3).

$$\rho_{glass} = \frac{m_{air}}{m_{air} - m_{liquid}} \tag{1}$$

Compressive strength (CS) analysis was carried out using a universal mechanical test using a Shimadzu AG IS 100 kN (Afyonkarahisar, Turkey) in order to comprehend the mechanical characteristics of the manufactured samples.

Finally, Phy-X/PSD software was employed using the sample compositions given in Table 1 and the measured bulk density values. We simply entered the data and let the software compute them accordingly.

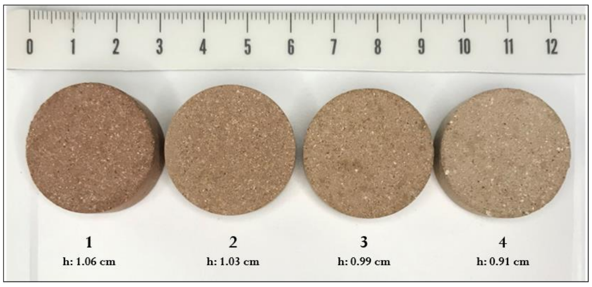

Figure 2. Photographs of the prepared samples (h: height of the sample)

3. Results and Discussion

The density parameter is a critical factor for radiation shielding applications. This is because the higher density values lead to higher attenuation characteristics [13]. For the synthesized waste *BBA* samples, we found the bulk density values as 1.39, 1.43, 1.49, and 1.62 g/cm^3 for samples 1 to 4, respectively. That means bulk density shows an increasing behavior with the insertion of the Bi_2O_3 ratio. The reason behind this increment can be attributed to the higher molecular weight of Bi_2O_3 (465.96 g.mol^{-1}) compared to other constituents in the waste bricks bottom ash system. On the other hand, mechanical resistance against failure is an essential property of radiation protection material. This is the fact that the protector block may carry loads under operational conditions, eg. wall element [14]. From this perspective, the performed universal mechanical testing results indicated that the increasing

Bi_2O_3 content ensured the obtainment of the increased compressive strength values.

The compressive strength (*CS*) of the fabricated samples was evaluated for understanding the resistance to mechanical failure. According to the findings, the *CS* values were found to be 7.28, 7.55, 7.89, and 8.01 MPa for the samples 1 to 4, respectively. This means that the increasing Bi_2O_3 content aided *CS* to increase. The results may seem reasonable, however, they show a promising aspect for the products made of waste substances. Therefore, Bi_2O_3 can be a good option for improving the mechanical properties in the waste-derived bricks system.

After presenting the findings for the physical and mechanical properties of the prepared waste *BBA* blocks, radiation shielding characteristics will be given. In this sense, one of the most essential parameters, linear attenuation coefficient (*LAC*), was calculated via Phy-X/PSD software. In Figure 3, the variations in the *LAC* parameter against increasing photon energy levels are graphed for the synthesized blocks. In the lower photon energies (*eg*. 0.05 MeV), the *LAC* values are relatively high, however, these values show a sharp decrease through intermediate (*eg*. 0.1 MeV) and high (*eg*. 0.5 MeV) photon energies. Further, the increasing Bi_2O_3 contribution (sample 1 to sample 4) leads to the increasing *LAC* values at lower and intermediate photon energies. In the high photon energy levels, the difference among samples becomes lower in terms of *LAC* values. From the findings, it is evident that Bi_2O_3 in replacement for waste bricks bottom ash system results in enhancing photon shielding abilities.

To meet the demand by design criteria, one should figure out the thickness values. For achieving the required thickness values, the half-value layer (*HVL*) parameter is a good choice, this is because it is described as the thickness at which half of the incoming photon energy is attenuated [15]. To understand the variations in *HVL* thicknesses, Figure 4 is plotted. It can be seen that the *HVL* behaves similarly to each other (~ 0.025 cm) in the lower photon energies (*i.e.* <0.05 MeV). In the intermediate photon energies (*i.e.* 0.2 MeV), the *HVL* reveals a decreasing trend from 3.95 to 1.48 cm with the increasing Bi_2O_3 addition. In the higher photon energy levels (*i.e.* 1 MeV), the *HVL* increases more (~ 8 cm), however, the existence of Bi_2O_3 provides lower *HVL* thickness. That means the insertion of Bi_2O_3 leads to the improvement in *HVL* at all photon energies. This advancement can be attributed to the higher molecular mass of Bi_2O_3 (465.96 g/mol) compared to the waste bricks' bottom ash. Therefore, one can report that the increasing doping rate is an effective solution for decreasing the required *HVL* thickness.

Since Bi element has a high atomic number, it is worth comprehending the effective atomic number changes for the synthesized waste *BBA* blocks [16]. Figure 5 displays the changes in Zeff versus increasing photon energy levels for the prepared samples. That is to say, Z_{eff} is found to be high at lower photon energies (photoelectric effect) whereas a decreasing behavior is observable at intermediate photon energies (Compton scattering), however, an increasing trend is apparent at higher energy levels (pair production process). The contribution of Bi_2O_3 provides a visible enhancement in Z_{eff} at all photon energies. This improvement can be associated with the higher atomic number of Bi element (Z: 83) compared to waste bricks bottom ash elements (i.e. Z for Si: 14).

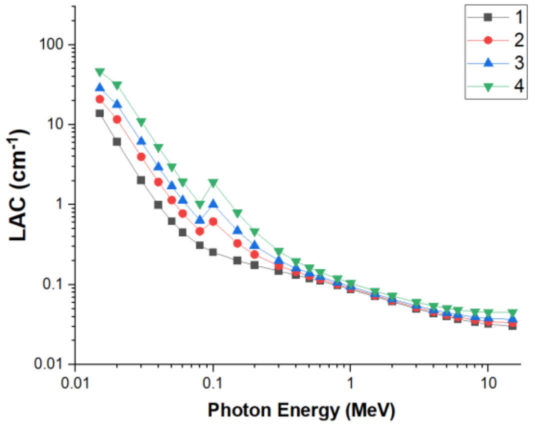

Figure 3. The variations in the *LAC* parameter against increasing photon energy levels.

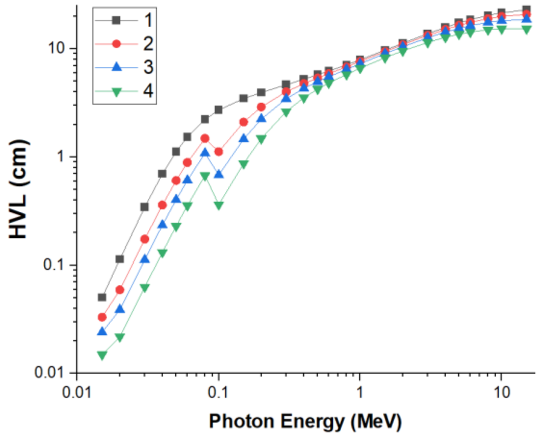

Figure 4.The alterations in the *HVL* parameter against increasing photon energy levels.

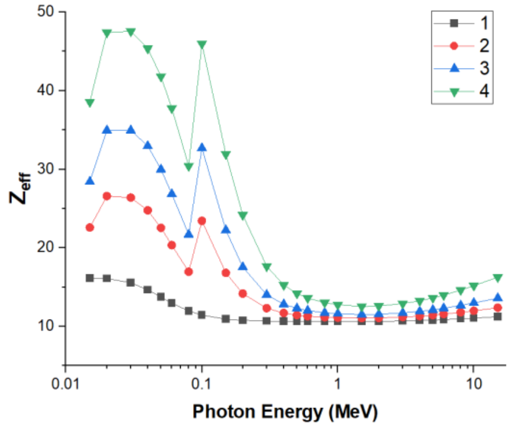

Figure 5.The changes in the Z_{eff} parameter against increasing photon energy levels.

4. CONCLUSION

The below-listed points can be given as a consequence of the present study:

i. It was revealed that a waste-derived material system could be used for radiation shielding.
ii. The gap in the literature regarding the use of waste brick bottom ash (BBA) for photon shielding was filled, particularly with the manufacture of sample series.
iii. Bulk density increased with the increasing content of Bi_2O_3 in BBA, namely from 1.39 to 1.62 g.cm^{-3}.
iv. Compressive strength displayed an increasing trend from 7.28 to 8.01 MPa with the addition of Bi_2O_3.
v. With increasing Bi2O3 contribution, the significant indicator of photon shielding competences, linear attenuation coefficient (LAC), increased. With the addition of 20 mol% Bi_2O_3, sample-4, the greatest LAC value was attained.
vi. Another important characteristic, the half-value layer (HVL), decreased as the Bi_2O_3 content increased. With the addition of 20 mol% Bi_2O_3, the lowest HVL value was obtained.
vii. The contribution of Bi_2O_3 provides a visible enhancement in Z_{eff} at all photon energies.
viii. In conclusion, the authors reported that the increasing Bi_2O_3 doping rate in the *BBA* system is beneficial for attenuating more photons, which in turn paves the way for being preferable for photon shielding applications.

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