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INVESTIGATION OF THE ACTIVITY LEVEL AND RADIOLOGICAL IMPACTS OF NATURALLY OCCURRING RADIONUCLIDES IN BLAST FURNACE SLAG

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The activity level and possible radiological impacts of naturally occurring radionuclides on the health of workers and members of the public, as a result of utilisation of blast furnace slag (BFS) samples as a substitute for aggregate in road construction were investigated by using a gamma-ray spectrometer and potential exposure scenarios given in Radiation Protection 122. The mean activity concentrations of the ^{226}Ra, ^{232}Th and ^{40}K in BFS samples were found to be 152.4, 54.9 and 183.1 Bq kg^{-1}, respectively. These values are compared with typical values measured in BFS samples from the European Union countries, which are 270, 70 and 240 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively. The values of radium equivalent activity index calculated for BFS samples were within the recommended safety limits. The highest total annual effective doses evaluated as 0.9 and 0.4 mSv y^{-1} for members of the public and workers, respectively, were lower than the annual limit of 1 mSv y^{-1}.

INTRODUCTION

Turkey has been an important player in the international steel trade. Turkey produced ~32 million tonnes (Mt) crude steel in 2011[(1)], of which 23 Mt was from electric arc furnaces and 9 Mt from blast furnaces. The iron-steel industry uses raw material such as iron ore, coal and limestone in steel production. These raw materials contain low levels of naturally occurring radioactive materials (NORMs). However, blast furnace slag (BFS),which is a non-metallic by-product involved in the iron and steel-making process and forms when iron ore, coke ash and limestone are added to the blast furnace, includes enhanced concentrations of naturally occurring radionuclides relative to the raw materials used[(2)]. The US steel industry produces 13–15 Mt of BFS annually, while in Europe 26.2 Mt of BFS is produced every year[(3)]. Approximately, 300–350 kilograms of BFS is generated for each ton of steel production[(4)]. Every year millions of tons of BFS is normally stored in piles, dumped or deposited on the open land around the steel factories or plants. BFSs accumulated at iron-steel plants' open areas can lead to environmental and radiological problems through its dispersal into atmosphere and its handling or disposal. Therefore, reuse or recycling of BFS appears as a convenient alternative to dumping. Historically, BFSs have been used as a substitute for aggregate in road base, asphalt concrete, railroad ballast filling in road construction in road bases, fill and railroad ballast and cement additive. BFA piles or ponds are considered an ionising radiation source because BFS contains naturally occurring radionuclides emitting alpha particles, beta particles and gamma rays. The radionuclide contents of these materials may lead to the exposure of members of the general public and workers to ionising radiation via three pathways: firstly external exposure of people and local workers to gamma radiation emitted from the members of the ^{226}Ra and ^{232}Th series along with ^{40}K which is in all potassium required element for 'life'; secondly, internal exposure of the respiratory tract to alpha and beta particles due to inhalation of the radioactive inert radon gas and its short-lived decay products; lastly, internal exposure due to inhalation and/or ingestion of BFS particles.

It is very important to study in detail the radiological characteristics of BFSs for accurately assessing the radiation exposure of the members of the public and workers and developing standards and guidelines for the use and management of these materials. There have been many studies related to the mechanical properties (strength, durability, etc.) and radiation shielding of the building materials containing BFS collected from some iron-steel plants in the literature[(4–14)]. However, the radioactivity level of BFS and the radiological impacts of the utilisation of BFSs as a substitute for aggregate in road construction have not been reported in literature previously.

In this study, the radioactivity level of BFS was investigated by using a gamma-ray spectrometer

with a high-purity germanium (HPGe) detector. Radium equivalent activity (Ra_{eq}) index was calculated to assess the usability of BFS samples as a substitute for aggregate in road base, asphalt concrete and railroad ballast filling in road construction from a radiological point of view. Individual doses and risks to members of the public and workers from potential exposure scenarios (living in a house built with building material containing BFS and near the BFS pile/landfill for adults and outdoor storage, transportation and road construction for workers) given in Radiation Protection 122[15] were assessed as part of this study.

MATERIALS AND METHODS

Sample preparation

A total of 40 BFS samples were collected from slag heaps in the Iskenderun Iron and Steel Plant (Isdemir). Isdemir is an integrated plant with a production capacity of 2.2 Mt/year and it is the second largest integrated iron and steel works of Turkey. It is located at ~17 km north of Iskenderun city. The BFS samples were hard, dense and non-crystalline. The BFS samples were ground into a fine powder with a particle size of <1 mm. The BFS samples were then dried in a temperature-controlled furnace at 110°C for 8 h to remove moisture. After moisture removal, these samples were cooled in a moisture-free atmosphere. Each sample was then filled into cylindrical plastic containers (ϕ=5 cm, h=6 cm), weighed and hermetically sealed. The geometrical dimensions of the samples were kept identical to those of the reference materials, which were used for the efficiency calibration of the gamma spectrometry system. The sealed samples and the reference materials were stored for >30 d before counting to allow ^{226}Ra and its short-lived decay products to reach secular equilibrium[16].

Experimental set-up

The high-resolution gamma ray spectrometer was used to determine the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the BFS samples. The spectrometer consisted of a coaxial p-type HPGe detector (GX5020) with an relative efficiency of 50 % relative to a 7.62 cm (diam.)×7.62 cm cylindrical NaI(Tl) detector, an energy resolution of 2.0 keV at 1332.5 keV and a peak-to-Compton ratio of 60:1. For gamma-ray shielding, a front opening split-top shield (Canberra Model 767) was used to reduce the background. It features 100-mm-lead thickness, which is jacketed by a 9.5-mm steel outer housing. The graded liner comprises a 1-mm-thick tin layer and a 1.5-mm-thick copper layer to prevent interference by lead X-rays. To minimise scattered radiation from the shield, the detector was centred in it. The detector was interfaced to the digital spectrum analyzer (DSA-1000), which was a full-featured 16-K channel multichannel analyzer on advanced digital signal processing (DSP) techniques. DSA-1000 operates through the Genie-2000 gamma spectroscopy software including tasks such as peak searching, peak evaluation, energy/efficiency calculation and nuclide identification.

Radioactivity analysis

The sample containers were placed on top of the detector for counting (close geometry). The same geometry was used to determine the peak area of samples and references. The measurement time for each was sufficiently long such that the uncertainty in the counting rates was <10 % at the 95 % confidence level. Prior to sample measurement, gamma-ray background at the laboratory was determined with an empty container under the same conditions of sample measurements and subtracted in order to get net counts for the sample.

The absolute efficiency calibration of the gamma spectrometry systems was carried out using the radionuclide-specific efficiency method in which the efficiency values of gamma-ray lines belonging to the specific radionuclide existing only in the reference material and sample were used. Thus, the uncertainty in gamma-ray intensities, the influence of coincidence summation and self-absorption effects of the emitting gamma photons were avoided for the close geometry conditions. The reference materials RGU-1, RGTh-1, RGK-1 and soil 375 were employed for radionuclide-specific efficiency calibration of the counting system. RGU-1 and RGTh-1 reference materials were prepared on behalf of the International Atomic Energy Agency (IAEA) by the Canada Centre for Mineral and Energy Technology by dilution of a uranium ore BL-5 (7.09 % U) and a thorium ore OKA-2 (2.89 % Th, 219 μg U per gram) with floated silica powder of a similar grain size distribution, respectively[17]. GK-1 is produced from high-purity (99.8 %) K_2SO_4 supplied by the Merck Company. The potassium property value and its uncertainty were obtained from repeated measurements performed at the IAEA[17].

The activity concentrations (A) (Bq kg^{-1}) of the aforementioned radionuclides were calculated from the following equation:

$$A = \frac{N}{\varepsilon(E_\gamma) \cdot I_\gamma \cdot t \cdot M} \quad (1)$$

where N is the net peak area, subtracted from background, of gamma-ray at energy E_γ, $\varepsilon(E_\gamma)$ is the

absolute efficiency of gamma rays at a particular energy, I_γ is the gamma-ray yield per decay, t is the counting live time mass in terms of seconds and M is the dried sample mass in kilograms.

The activity concentrations were averaged from gamma-ray peaks at several energies assuming secular equilibrium in the ^{238}U and ^{232}Th decay series. Gamma-ray peaks of 351.9 keV from ^{214}Pb and 609.3 keV from ^{214}Bi were used to determine the activity concentration of ^{226}Ra. Gamma-ray peaks of 911.2 keV from ^{228}Ac and 583.2 keV from ^{208}Tl were used to determine the activity concentration of ^{232}Th. The activity concentration of ^{40}K was measured directly by its own gamma-ray peak at 1460.8 keV.

The minimum detectable activity concentrations (MDCs) (Bq kg^{-1}) of the gamma-ray measurements were calculated as follows[16]:

$$\mathrm{MDC} = \frac{F_C \cdot \sigma_B}{\varepsilon(E_\gamma) \cdot I_\gamma \cdot t \cdot M} \quad (2)$$

where F_C is the statistical coverage factor equal to 1.64 (confidence level 95%), $\sigma_{N_B}$is the standard deviation of the background in the region of interest and equals the square root of the number of counts for the background spectrum, $\varepsilon(E_\gamma)$ is the absolute efficiency of the detector, I_γ is the gamma-ray yield per decay, t is the counting live time in seconds and M is the dried sample mass. The mean values of MDC for ^{226}Ra, ^{232}Th and ^{40}K were estimated to be 0.2, 0.2 and 2.1 Bq kg^{-1} for BFS samples.

The uncertainty of the activity concentration (ΔA) is calculated by the following formula:

$$\frac{\Delta A}{A} = \sqrt{\frac{\Delta N_R}{N_R} + \frac{\Delta I_\gamma}{I_\gamma} + \frac{\Delta \varepsilon}{\varepsilon} + \frac{\Delta M}{M}} \quad (3)$$

where ΔN_R is the count rate uncertainty, ΔI_γ the emission probability uncertainty found in the nuclear data tables, $\Delta\epsilon$ the efficiency uncertainty and ΔM the weighing uncertainty.

RESULTS AND DISCUSSION

Radioactivity level of the BFS samples

The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K measured in the BFS samples together with the statistical uncertainty (1σ) are given in Table 1. As can be seen from Table 1, there is a wide range of the measured concentrations of NORM in the various samples of BFS. It appears that most of the NORM came from the coke slag. The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the BFS samples examined ranged from 8.0 to 310.1 Bq kg^{-1} with a mean of 152.4 ± 10.8 Bq kg^{-1}, 3.0–330.0 Bq kg^{-1} with a mean of 54.9 ± 13.1 Bq kg^{-1} and 18.1–385.6 Bq kg^{-1} with a mean of 183.1 ± 12.2 Bq kg^{-1}, respectively. The mean values are given with standard error. The typical values measured in the BFS samples from the European Union (EU) countries are 270, 70 and 240 Bq kg^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively[18]. It can be seen that the mean activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the BFS samples are lower than the corresponding typical values of EU.

Radium equivalent activity index

Radium equivalent (Ra_{eq}) activity index has been used to compare the activity concentrations of materials containing different amounts of ^{226}Ra, ^{232}Th and ^{40}K and assess the radiation hazards associated with these radionuclides. This activity index is defined on the basis of the fact that 10 Bq kg^{-1} of ^{226}Ra, 7 Bq kg^{-1} of ^{232}Th and 130 Bq kg^{-1} of ^{40}K produce the same gamma dose rate and calculated from the following equation[19]:

$$Ra_{eq} = A_{Ra} + \frac{10}{7} \cdot A_{Th} + \frac{10}{130} \cdot A_K \quad (4)$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations (Bq kg^{-1}) of ^{226}Ra, ^{232}Th and ^{40}K, respectively. The recommended limits of the Ra_{eq} index for earthwork applications are as follows: Ra_{eq} must be $<$2220 Bq kg^{-1} for highway, road, railway and bridge constructions (roadbeds, road pavement, road stabilization, etc.) and $<$3700 Bq kg^{-1} for utilisation in foundation of non-residential buildings (structural fill, landfill, embankments, etc.)[20]. The values of the calculated Ra_{eq} activity index for the BFS samples examined are shown in the last column of Table 1. It can be easily seen from Table 1 that the values of the Ra_{eq} activity index are significantly lower than the recommended limits of 2220 and 3700 for Bq kg^{-1}.

Annual effective doses

The total annual effective doses (H_{total}) received by members of the general public and workers were estimated using methods recommended in Radiation Protection 122[15]. In general, the total annual effective dose is determined by means of the following equation:

$$H_{total} = H_{ext} + H_{inh} + H_{ing} \quad (5)$$

where H_{ext}, H_{inh} and H_{ing} are the annual effective doses (in μSv y^{-1}) due to external gamma radiation,

Table 1. The values of the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K measured in the Turkish BFS samples and the radium equivalent activity (Ra_{eq}) index.

Sample	Activity concentration (Bq kg^{-1})			Ra_{eq} (Bq kg^{-1})
	^{226}Ra	^{232}Th	^{40}K	
BFS1	198.4 ± 5.4	13.9 ± 3.1	145.1 ± 6.4	229.4
BFS2	159.3 ± 4.5	15.4 ± 2.5	199.7 ± 6.9	196.7
BFS3	143.4 ± 4.2	12.1 ± 2.4	171.4 ± 5.9	173.8
BFS4	124.4 ± 4.4	10.2 ± 5.8	142.7 ± 7.2	149.9
BFS5	107.5 ± 3.8	3.8 ± 1.7	109.0 ± 5.1	121.4
BFS6	139.3 ± 4.6	3.0 ± 1.9	102.2 ± 5.7	151.5
BFS7	151.2 ± 4.9	6.9 ± 4.7	206.4 ± 7.9	177.0
BFS8	158.4 ± 4.7	9.6 ± 3.5	186.2 ± 7.1	186.4
BFS9	174.2 ± 5.2	9.1 ± 4.6	189.1 ± 8.3	201.8
BFS10	136.4 ± 4.7	5.1 ± 1.9	104.6 ± 6.6	151.7
BFS11	80.8 ± 3.5	4.7 ± 2.0	43.6 ± 3.9	90.9
BFS12	150.0 ± 4.7	7.6 ± 3.4	148.7 ± 7.1	172.4
BFS13	172.4 ± 4.9	9.0 ± 2.4	173.0 ± 6.9	198.5
BFS14	199.8 ± 5.4	15.5 ± 3.2	276.3 ± 8.2	243.2
BFS15	221.1 ± 5.8	8.3 ± 3.2	201.9 ± 7.4	248.5
BFS16	184.9 ± 5.5	7.1 ± 3.6	215.9 ± 9.6	211.7
BFS17	98.4 ± 4.0	5.9 ± 1.2	82.2 ± 5.7	113.1
BFS18	112.9 ± 4.4	7.5 ± 1.4	105.0 ± 6.8	131.7
BFS19	220.2 ± 7.1	5.6 ± 4.9	244.7 ± 11.2	247.0
BFS20	130.3 ± 4.6	4.2 ± 1.2	141.9 ± 7.2	147.1
BFS21	49.1 ± 3.6	3.8 ± 0.4	24.9 ± 3.1	56.4
BFS22	310.1 ± 10.3	175.4 ± 20.5	385.6 ± 18.9	590.4
BFS23	270.0 ± 8.0	76.6 ± 5.6	274.4 ± 11.8	400.5
BFS24	179.3 ± 7.3	330.0 ± 15.4	251.5 ± 13.8	670.1
BFS25	276.3 ± 9.4	83.5 ± 7.5	280.9 ± 15.2	417.3
BFS26	187.3 ± 7.5	227.1 ± 12.1	290.1 ± 15.2	534.1
BFS27	177.7 ± 6.8	208.3 ± 11.1	266.7 ± 13.5	495.9
BFS28	183.5 ± 5.9	193.3 ± 8.9	217.7 ± 9.4	476.3
BFS29	193.7 ± 7.2	180.3 ± 10.0	270.5 ± 13.3	472.1
BFS30	172.4 ± 5.9	235.8 ± 10.6	252.7 ± 10.7	528.7
BFS31	8.0 ± 1.1	6.5 ± 1.8	18.1 ± 1.9	18.7
BFS32	181.6 ± 5.0	53.8 ± 4.5	188.7 ± 7.3	273.0
BFS33	181.1 ± 5.0	50.6 ± 4.2	216.3 ± 7.7	270.0
BFS34	180.1 ± 4.2	52.6 ± 3.4	208.2 ± 5.0	271.3
BFS35	115.7 ± 4.4	29.8 ± 7.0	138.5 ± 8.5	169.0
BFS36	15.5 ± 1.9	12 ± 3.4	153.3 ± 6.7	43.9
BFS37	181.6 ± 4.2	55 ± 3.5	203.8 ± 4.9	275.4
BFS38	134.8 ± 2.9	36 ± 2.1	200.2 ± 3.1	201.8
BFS39	20.0 ± 2.1	11 ± 3.0	155.0 ± 5.6	47.7
BFS40	13.7 ± 2.3	10 ± 0.7	137.0 ± 6.7	38.7
Mean ± SE	152.4 ± 10.8	54.9 ± 13.1	183.1 ± 12.2	244.9 ± 25.8

inhalation and ingestion exposure and calculated using the following equations:

$$H_{ext} = t_e \cdot f_d \cdot (D_{extRa} \cdot A_{Ra} + D_{extTh} \cdot A_{Th} + D_{extK} \cdot A_K) \quad (6)$$

$$H_{inh} = t_e \cdot f_d \cdot B_r \cdot C_{dust}(D_{inhRa} \cdot A_{Ra} + D_{inhTh} \times A_{Th} + D_{inhK} \cdot A_K) \quad (7)$$

$$H_{ing} = t_e \cdot f_d \cdot R_{ing}(D_{ingRa} \cdot A_{Ra} + D_{ingTh} \cdot A_{Th} + D_{ingK} \cdot A_K) \quad (8)$$

where D_{extRa}, D_{extTh} and D_{extK}; D_{inhRa}, D_{inhTh} and D_{inhK} and D_{ingRa}, D_{ingTh} and D_{ingK} are the dose coefficients (in μSv h^{-1} per Bq kg^{-1}) for external gamma radiation, inhalation and ingestion exposure for ^{226}Ra series, ^{232}Th series and ^{40}K, respectively; A_{Ra}, A_{Th} and A_K are the activity concentrations (in Bq kg^{-1}) of ^{226}Ra, ^{232}Th and ^{40}K measured in BFS samples, respectively; t_e is the exposure time (h y^{-1}); f_d is the dilution factor; B_r is the breathing rate (m^3 h^{-1}); C_{dust} is the dust concentrations (kg m^{-3}) and R_{ing} is the ingestion rate (kg h^{-1}).

Table 2. Parameters (exposure time, dilution factor, breathing rate, dust concentration, ingestion rate and dose coefficient) and exposure pathways in each scenario for members of the public (adults).

Parameters	Scenario for members of the public								
	Residence in a house (indoors, pile-25 m)			Staying in a garden (outdoor, pile-20 m)			Living in a house built with building material containing BFS		
	Exposure pathways			Exposure pathways			Exposure pathways		
	External	Inhalation	Ingestion	External	Inhalation	Ingestion	External	Inhalation	Ingestion
t_e (h y^{-1})	6000	6000	6000	1000	1000	1000	7000	—	—
f_d	1	1	1	1	1	1	0.3	—	—
B_r (m^3 h^{-1})		0.93			0.93			—	—
C_{dust} (kg m^{-3})		2×10^{-8}			5×10^{-8}			—	—
R_{ing} (kg h^{-1})			5×10^{-6}			5×10^{-6}			—
D_{ext} (μSv h^{-1} Bq kg^{-1}), D_{inh} (μSv Bq^{-1}) and D_{ing} (μSv Bq^{-1}) for ^{226}Ra	4.43×10^{-6}	9.53	0.28	5.37×10^{-5}	9.53	0.28	5.55×10^{-4}	—	—
D_{ext} (μSv h^{-1}/ Bq kg^{-1}), D_{inh} (μSv Bq^{-1}) and D_{ing} (μSv Bq^{-1}) for ^{232}Th	8.85×10^{-6}	84.6	1.06	8.19×10^{-5}	84.6	1.06	8.18×10^{-4}	—	—
D_{ext} (μSv h^{-1} Bq kg^{-1}), D_{inh} (μSv Bq^{-1}) and D_{ing} (μSv Bq^{-1}) for ^{40}K	4.90×10^{-7}	0	0	4.95×10^{-6}	0	0	5.13×10^{-5}	—	—

Exposure of members of the public

The scenario given in Radiation Protection 122 was considered a possible significant exposure route for an adult person to assess the radiological impact of the iron-steel plant on members of the public. This scenario includes three exposure situations: (i) living in a house built with building material containing BFS; (ii) living in a house located at a distance of 25 m from the edge of the pile/landfill and (iii) staying in the garden at a distance of 20 m from the edge of the pile/landfill belonging to the house. The annual effective doses of each exposure situation were estimated using the exposure pathways and parameters given in Table 2.

Exposure of workers

The annual effective doses received by workers handling BFSs were estimated using the storage scenario, the transport scenario and the road construction scenario given in Radiation Protection 122[15]. The storage scenario describes the storage of the BFSs in large quantities outdoors. In the transport scenario, a truck driver transports the BFSs from the iron-steel plant to its destination, which can be a landfill, a road construction site or a mill where the material is processed for the preparation of concrete or other building material. The road construction scenario contains the recycling of BFSs as a substitute for aggregate in road base, asphalt concrete and railroad ballast filling. The annual effective doses in each scenario were calculated using exposure pathways and parameters given in Table 3.

The values of the annual effective doses of the total (H_{total}), external gamma radiation (H_{ext}), inhalation (H_{inh}) and ingestion (H_{ing}) estimated for members of the public and workers using the parameters shown in Tables 2 and 3 and Equations (5)–(8) are given in Tables 4 and 5, respectively. From Tables 4 and 5, the highest total annual effective dose (892 μSv y^{-1}) estimated for the members of the public is about two times higher than the highest

Table 3. Parameters (exposure time, dilution factor, breathing rate, dust concentration, ingestion rate and dose coefficient) and exposure pathways in each scenario for workers.

Parameters	Scenarios for workers								
	Outdoor storage (large quantities) exposure pathways			Transport (long distances) exposure pathways			Road construction (earthwork application) exposure pathways		
	External	Inhalation	Ingestion	External	Inhalation	Ingestion	External	Inhalation	Ingestion
t_e (h y^{-1})	1800	1800	1800	850	100	100	1800	1800	1800
f_d	1	1	1	1			1	1	1
B_r (m^3 h^{-1})		1.2			1.2			1.2	
C_{dust} (kg m^{-3})		2×10^{-7}			1×10^{-6}			1×10^{-6}	
R_{ing} (kg h^{-1})			1×10^{-5}			1×10^{-5}			1×10^{-5}
D_{ext} (μSv h^{-1} Bq kg^{-1}), D_{inh} (μSv Bq^{-1}) and D_{ing} (μSv Bq^{-1}) for ^{226}Ra	3.14×10^{-5}	2.23	0.28	7.61×10^{-5}	2.23	0.28	3.01×10^{-4}	2.23	0.28
D_{ext} (μSv h^{-1} Bq kg^{-1}), D_{inh} (μSv Bq^{-1}) and D_{ing} (μSv Bq^{-1}) for ^{232}Th	4.77×10^{-5}	48.2	1.06	1.18×10^{-4}	48.2	1.06	4.59×10^{-4}	48.2	1.06
D_{ext} (μSv h^{-1} Bq kg^{-1}), D_{inh} (μSv Bq^{-1}) and D_{ing} (μSv Bq^{-1}) for ^{40}K	2.86×10^{-6}	0	0	7.61×10^{-6}	0	0	2.89×10^{-5}	0	0

Table 4. The values of the annual effective dose of the total (H_{total}), external gamma radiation (H_{ext}), inhalation (H_{inh}) and ingestion (H_{ing}) estimated for members of public (adults).

	For members of the public									
	Residence in a house built with building material containing BFS			Residence in a house (Indoor, pile-25 m)			Staying in a garden (Outdoor, pile-20 m)			H_{total}
	H_{ext}	H_{inh}	H_{ing}	H_{ext}	H_{inh}	H_{ing}	H_{ext}	H_{inh}	H_{ing}	
Min	22.4	—	—	0.6	0.1	0.3	1.0	0.3	0.05	24.8
Max	801.1	—	—	23.0	3.3	12.0	36.7	13.8	2.0	891.9
Mean	290.0	—	—	7.5	0.7	3.0	12.7	2.8	0.5	317.2

Table 5. The values of the annual effective dose of the total (H_{total}), external gamma radiation (H_{ext}), inhalation (H_{inh}) and ingestion (H_{ing}) estimated for workers.

	For workers											
	Outdoor storage (large quantities)				Transport (long distances)				Road construction			
	H_{ext}	H_{inh}	H_{ing}	H_{total}	H_{ext}	H_{inh}	H_{ing}	H_{total}	H_{ext}	H_{inh}	H_{ing}	H_{total}
Min	1.1	0.1	0.2	1.4	1.3	0.03	0.01	1.3	10.7	0.1	0.03	11.6
Max	39.8	7.0	7.2	54.4	46.3	2.0	0.4	48.7	382.9	25.6	5.4	387.1
Mean	14.3	1.3	1.8	17.4	16.5	0.4	0.1	17.0	137.4	3.0	0.8	141.2

total annual effective dose (387 μSv y^{-1}) estimated for the workers.

CONCLUSION

The handling and disposal of BFSs may give rise to human health and environmental hazards because BFSs contain radiotoxic and heavy metals. For this reason, the reuse or recycling of BFS in building construction and road construction can bring economic and environmental advantages such as increasing the life of concrete roads and structures by improving the durability of concrete, the exploitation of non-expensive by-products in civil engineering and the reduction in the amount of BFS. The results of this study indicate that the utilisation of the examined BFS samples in the construction of roads, streets, roadbeds and road pavements and also landfill, landscaping and embankments is unlikely to pose any significant adverse health impacts, according to the cited national and international legislation and guidance used for comparison.

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