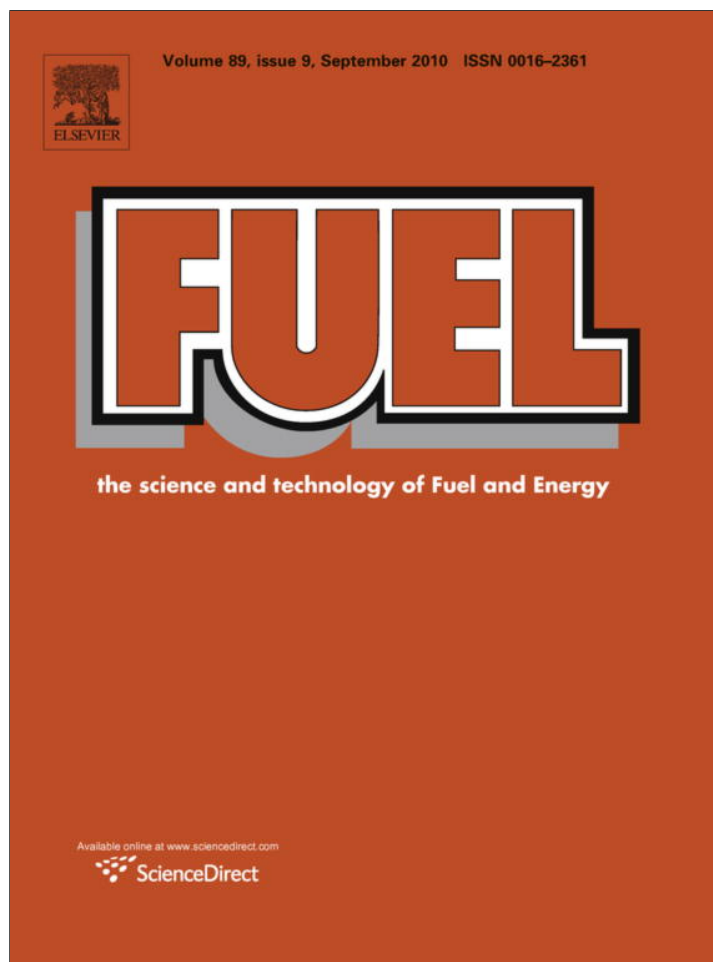


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## Evaluation of the radiological safety aspects of utilization of Turkish coal combustion fly ash in concrete production

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### ABSTRACT

The aim of this study is to evaluate radiological safety aspects of the utilization of fly ash in concrete manufacturing in the construction industry. The specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in one hundred 55 concrete mixture samples incorporating 10, 20 and 30 wt.% of fly ash collected from the 11 coal-fired thermal power plants were measured by means of gamma-ray spectrometry with HPGe detector. The results of the measurement were used to evaluate the radiological safety aspects of utilization of the fly ash as cement replacement in concrete by assessing the radium equivalent activity, the gamma index, the absorbed gamma dose rate and the corresponding annual effective dose due to the external exposure in indoor. The results of evaluation show that all concrete mixture samples are within the recommended safety limits except for concrete mixture samples incorporating 30 wt.% fly ash of Kangal coal-fired thermal power plant.

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### 1. Introduction

Building materials of terrestrial origin contain, to a greater or lesser extent, naturally occurring radionuclides such as uranium–radium ( $^{238}\text{U}$ – $^{226}\text{Ra}$ ) and thorium ( $^{232}\text{Th}$ ) and their decay products and the radioactive isotope of potassium ( $^{40}\text{K}$ ). These building materials are the major source of radiation exposure of the public. In the  $^{238}\text{U}$  series, the decay chain segment starting from radium ( $^{226}\text{Ra}$ ) is radiologically the most important and, therefore, reference is often made to  $^{226}\text{Ra}$  instead of  $^{238}\text{U}$ . The median values of the specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in the earth's crust are 35, 30 and 400  $\text{Bq kg}^{-1}$ , respectively [1]. When industrial raw materials containing naturally occurring radionuclides such as coals and phosphate rocks are processed, the industrial by-products from processing such as fly ash, bottom ash, slag, bauxite and phosphogypsum are likely to have higher specific activities than the raw materials. These industrial by-products are called technologically enhanced naturally occurring radioactive materials. Some of building materials in which industrial by-products were used as building raw materials or building material additives contain relatively high specific activities of  $^{238}\text{U}$ ,  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and other natural radionuclides. Radiation exposure due to these radionuclides in building materials can be classified into external and internal exposure. The external radiation exposure is caused by direct gamma radiation from radionuclides in the  $^{238}\text{U}$ – $^{226}\text{Ra}$  and

$^{232}\text{Th}$  series and from the  $^{40}\text{K}$  while the internal exposure, mainly affecting the respiratory tract, is due to the radioactive inert gas radon ( $^{222}\text{Rn}$ , a daughter product of  $^{226}\text{Ra}$ ) and its short-lived decay products which are exhaled from building materials into room air. Besides many other factors, it is known that the rate at which radon is created is directly proportional to the  $^{226}\text{Ra}$  content. The extent of radon release by building material is characterized by its exhalation rate. Therefore, knowledge of the level of natural radioactivity in building materials and the radon emissions from these materials are very important for accurately assessing the external and the internal radiation exposure and developing standards and guidelines for the use and management of these materials.

Coal (lignite and bituminous coal) is the most important natural energy source available in abundance in Turkey and used widely as fuel for thermal power plants (TPPs) producing electricity. Lignite coal is the largest energy source produced in Turkey. The lignite coal deposits are distributed throughout the country more fairly on the contrary to bituminous coal reserves. Lignite recoverable reserves are estimated to be about 8300 million tons (Mt) while bituminous coal reserves are about 1330 Mt [2]. The majority of lignite coal production (about 82%) was consumed by the electricity sector in 2008 while the bituminous coal was used intensively in industry and heating. At the end of the year 2008, the electrical energy installed capacity of Turkey has become 42,000 megawatt (MW) with an increase of 1151 megawatt (MW), an equivalent increase of about 3% from the previous year. Turkey produced 198,400 gigawatt hours (GWh) of electricity, of which 48% is from

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natural gas, 29% is from coal and 17% is from hydraulic in 2008 [3]. At present, the total installed electricity generation capacity of the fifteen coal-fired TPPs in operation in Turkey is about 9845 MW (Table 1) [4,5]. These coal-fired TPPs consume over 55 Mt of coal per year [6].

Fly ash (FA) is a by-product or combustion residue of pulverized coal blown into a fire furnace at a coal-fired TPP. The fifteen coal-fired TPPs listed in Table 1 produce a total of over 15 Mt of FA annually [6]. Depending on the emission control systems such as cyclone and bag filters or mechanical and electrostatic precipitators, the largest fraction of FA is collected and usually stored in piles, or dumped or deposited on the land in the vicinity of the TPP. Although the emission control systems have high efficiency rates (near 99.9%), considerable amounts of FA can be emitted into the surrounding environments because of high coal consumption rates of TPPs, the emissions being even greater if the ash content of coal is high [7]. The ash content of the Turkish coal ranges from 16% to 50% (Table 1). The growing production of FA has long caused an environmental problem with technological and economic effects in the world. Also, accumulation of FA stored in piles can contribute to environmental radiological problems through its dispersal into atmosphere and its handling or disposal [8]. These economic and environmental problems have led to the implementation of various alternative utilizations, in which FA is considered as value-added product. However, there are difficulties around the world to achieve effective utilization of FA.

FA has several advantages such as pozzolanic and cementitious property over conventional by-products. FA is an excellent potential raw material for the manufacture of construction materials such as cement production, concrete, ceramics and hollow blocks. It also can be used for geotechnical applications such as paving roads, building embankments and mine fills [9]. Most important use of FA is as cement replacing material in concrete industry because of its pozzolanic and cementitious properties. The utilization of FA in the concrete industry has economical and environmental advantages such as increasing the life of concrete roads and structures by improving concrete durability, the exploitation of non expensive by-products in civil engineering, the reduction of the amount of FA that must be disposed in landfills, greenhouse gas and other adverse air emissions. However, the large scale utilization of FA with enhanced levels of radioactivity as a cement replacement in concrete can considerably increase overall radiation exposure [10]. It is known that although there is significant linear relationship between  $^{226}\text{Ra}$  specific activity of FA and the radon exhalation rate of concrete, the addition of FA to concrete does not necessarily increase the amount of radon exhalation for that

concrete [11]. The understanding of the influence of FA on the radon exhalation rate of concrete is a critical issue. For example, it is known that FA is produced at high temperatures and has a glassy structure, which keeps most of the radon from escaping. In addition, the microstructure of the cementitious matrix, curing and age of the specimens, pozzolanic reactions occurring with time, geometry of the specimens, surface treatment, temperature, moisture of building materials, air pressure gradient and some other factors make the picture more complicated [12–15]. The problem of the radon exhalation rate of concrete mixture samples incorporating FA is not in the scope of the present study.

Approximately 33% of the total FA produced in Europe is used as cement raw materials, as constituent in blended cements and as addition for the production of concrete [16], while roughly 1% of the total FA produced in Turkey is being used in a variety of products such as cement, concrete, aggregate in stabilizing roadways, etc. [17]. Although several papers have been published concerning to the potential applications [5,6,18–23], characterization and mineralogy [9,24–28] and the radioactivity of Turkish FA [17,29–32], Turkey has few data published so far on the radiological safety aspects of the utilization of FA as cement replacement in concrete mixtures in the construction of buildings. In the present study, a total of 155 concrete mixture samples incorporating 10, 20 and 30 wt.% of FA collected from the 11 coal-fired TPPs were analyzed using gamma-ray spectrometry to determine the specific activity of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ . In order to evaluate radiological safety aspects of the utilization of FA as cement replacement in concrete, the radium equivalent activity, the gamma index, the absorbed gamma dose rate and the corresponding annual effective dose caused from the external exposure in indoor were evaluated for concrete mixture samples incorporating 10, 20 and 30 wt.% of FA.

## 2. Material and methods

### 2.1. Sample collection and preparation

As mentioned above, FA can be used for a variety of applications such as aggregate use in concrete construction, partial cement replacement, production of normal and lightweight concrete and structural fills depending on its chemistry. The major chemical components in FAs are  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$  and  $\text{MgO}$  [26]. According to ASTM C618 that classifies FA for use as a mineral admixture in Portland cement concrete, there are two classes of FA, Class F and Class C [33]. Class F FA (the total amount of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  is minimum 70%) is normally produced from burning anthracite or bituminous coal and contains small amounts of

**Table 1**  
Main characteristics of coal-fired thermal power plants in Turkey.

Power plant	Location	Unit number × installed power (MW)	Coal type	Fuel capacity (ton/y)	Ash ratio (%)
Afşin-Elbistan A	K.Maraş	4 × 340	Lignite	10,970,167	19–20
Afşin-Elbistan B	K.Maraş	4 × 360	Lignite	–	–
Çan	Çanakkale	2 × 160	Lignite	1,800,000	32
Çatalağzı	Zonguldak	2 × 150	Bituminous	1,658,630	41–48
Çayırhan	Ankara	2 × 150 + 2 × 160	Lignite	3,696,266	36–42
Çolakoğlu 2	Kocaeli	1 × 190	Bituminous	–	–
Kangal	Sivas	2 × 150 + 1 × 157	Lignite	5,194,456	48
Kemerköy	Muğla	3 × 210	Lignite	4,563,781	31–36
Orhaneli	Bursa	1 × 210	Lignite	1,413,436	25–31
Seyitömer	Kütahya	4 × 150	Lignite	5,384,720	32–37
Soma (A + B)	Manisa	2 × 22 + 6 × 165	Lignite	8,948,501	25–28 39–50
Sugözü	Adana	2 × 650	Bituminous	3,300,000	–
Tunçbilek (A+B)	Kütahya	2 × 32 + 1 × 65 2 × 150	Lignite	1,907,753	16–51
Yatağan	Muğla	3 × 210	Lignite	5,538,297	26–36
Yeniköy	Muğla	2 × 210	Lignite	3,412,505	32–40

lime and has pozzolanic properties, which by itself possesses little or no cementitious value, but in the presence of moisture, reacts chemically with lime at ordinary temperatures to form cementitious compounds. Class C FA (the total amount of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> is minimum 50%) is normally produced from burning lignite coal or subbituminous coal and usually contains a significant amount of lime along with pozzolanic materials. At the same time, if FA contains more than 10% CaO, it is defined as a high-calcium FA and less than 10% CaO it is a low calcium FA. It is known that low-calcium fly ash is pozzolanic with little or no cementing value alone and high-calcium FA has self cementing properties as well as pozzolanic properties [34].

FA samples used in this study were collected from Afşin-Elbistan, Çatalağzı, Çayırhan, Kangal, Kemerköy, Orhaneli, Seyitömer, Soma, Tunçbilek, Yatağan and Yeniköy coal-fired TPPs. The total amount of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> of FAs from Çatalağzı, Çayırhan, Orhaneli, Seyitömer, Soma, Tunçbilek and Yatağan exceeds 70%, while it is minimum 50% of FAs from Afşin-Elbistan and Kemerköy [24,25]. Also, FAs from Afşin-Elbistan, Kangal, Kemerköy and Yeniköy are high-calcium FA [24,25]. Concrete sample is a mixture of cement (CEM I Portland cement), sand (fine aggregate), gravel (coarse aggregate), FA and water. A total of 155 concrete mixture samples incorporating 10%, 20% and 30% of FA as replacement of the CEM I Portland cement in weight basis were prepared. The samples were ground into a fine powder and then dried in a temperature-controlled furnace at 110 °C for 24 h to remove moisture. After moisture removal, these samples were cooled in moisture-free atmosphere. Each sample was then filled into cylindrical plastic containers, weighed and hermetically sealed. The geometrical dimensions of the samples were kept identical to those of the reference materials. The sealed samples and the reference materials were stored for more than 30 days before counting to allow <sup>226</sup>Ra and its short-lived decay products to reach the secular equilibrium.

## 2.2. Radiometric measurement

A high-resolution gamma spectrometry system with p-type coaxial HPGe detector with an active volume of 62 cm<sup>3</sup> connected with standard fast electronics was used to measure the natural radioactivity in the concrete mixture samples. The detector has a relative efficiency of 12.4% relative to a 7.62 × 7.62 cm NaI(Tl) detector, an energy resolution of 1.8 keV at 1332.5 keV of <sup>60</sup>Co. The detectors were shielded to reduce gamma-ray background. Energy calibration of the detector was performed using point sources (<sup>60</sup>Co and <sup>137</sup>Cs). The absolute efficiency calibration of the gamma spectrometry systems was carried out using a solid nuclide mixture of Amersham gamma reference material containing known activities of <sup>109</sup>Cd, <sup>57</sup>Co, <sup>139</sup>Ce, <sup>113</sup>Sn, <sup>137</sup>Cs, <sup>88</sup>Y and <sup>60</sup>Co. The sample containers were placed on top of the detector for counting. The same geometry was used to determine peak area of samples and references. On average, the counting time was 20 and 24 h. Background measurements were taken under the same conditions of sample measurements and subtracted in order to get net counts for the sample.

The specific activities were averaged from gamma-ray photopeaks at several energies. The gamma-ray line of the 351.9 keV from <sup>214</sup>Pb and the 609.3 keV from <sup>214</sup>Bi were used to determine the specific activity of <sup>226</sup>Ra. The gamma-ray line of the 911.2 keV from <sup>228</sup>Ac and the 583.2 keV from <sup>208</sup>Tl were used to determine the specific activity of <sup>232</sup>Th. The specific activity of <sup>40</sup>K was measured directly by its own gamma-ray at 1460.8 keV.

The minimum detectable activity (MDA) of the present measurement system was calculated as follows [35]:

$$MDA = \frac{1.64\sigma_{N_B}}{\varepsilon \cdot P \cdot t \cdot w} \quad (1)$$

where MDA is in Bq kg<sup>-1</sup> (confidence level 95%),  $\sigma_{N_B}$  is the standard deviation of the background in the region of interest and equals square root of the number of counts for the background spectrum,  $\varepsilon$  is the absolute efficiency of the detector,  $P$  is the absolute emission probability of the gamma decay,  $t$  is the measurement time in seconds and  $w$  is the weight of the dried sample expressed in kg. The mean values of the MDA measured for <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K were 1.6 Bq kg<sup>-1</sup>, 2.7 Bq kg<sup>-1</sup> and 12.7 Bq kg<sup>-1</sup>, respectively.

## 3. Results and discussion

### 3.1. Specific activity

The range (maximum and minimum) and mean of the specific activity values of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K measured in the concrete mixture samples incorporating three different percentages of FA as replacement of the cement in weight basis together with the statistical uncertainty (1 $\sigma$ ) are shown in Table 2 (10 wt.% of FA), Table 3 (20 wt.% of FA) and Table 4 (30 wt.% of FA). The mean specific activities are compared with typical values of specific activity measured in concrete samples in the European Union (EU) countries, which are 40, 30 and 400 Bq kg<sup>-1</sup> for <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K, respectively [36] in Fig. 1.

As can be seen from Tables 2–4 the highest mean values of the specific activity of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K are 211.9 ± 4.9 (30 wt.% of Kangal FA), 17.0 ± 3.9 (30 wt.% of Çayırhan FA) and 319.8 ± 30.0 Bq kg<sup>-1</sup> (30 wt.% of Orhaneli FA), respectively, while the lowest mean values of the specific activity of the same radionuclides are 11.06 ± 0.9 (10 wt.% of Orhaneli FA) and 3.6 ± 0.3 (10 wt.% of Yeniköy FA) and 27.8 ± 1.9 Bq kg<sup>-1</sup> (10 wt.% of Yeniköy FA), respectively. It is clear from Fig. 1 the mean values of the specific activity of <sup>232</sup>Th and <sup>40</sup>K measured for all the concrete mixture samples are lower than typical values of specific activity in the EU concrete samples. The mean values of the specific activity of <sup>226</sup>Ra measured for the concrete mixture samples with three different percentages of FA from Çatalağzı, Çayırhan and Seyitömer are lower than typical value of specific activity in the EU concrete samples. The mean values of the specific activity of <sup>226</sup>Ra measured for the concrete mixture samples incorporating 10 and 20 wt.% of FA from TPPs, except Afşin-Elbistan, Kangal, Orhaneli, Soma and Yeniköy, are lower than typical value measured for EU concrete samples.

### 3.2. Evaluation of radiological safety aspects of concrete mixture samples

#### 3.2.1. Radium equivalent activity

A common radiological index, called the radium equivalent activity (Ra<sub>eq</sub>), has been used to compare the specific activities of materials containing different amounts of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K and evaluate the radiation hazards associated with these radionuclides. This index is defined based on the fact that 10 Bq kg<sup>-1</sup> of <sup>226</sup>Ra, 7 Bq kg<sup>-1</sup> of <sup>232</sup>Th and 130 Bq kg<sup>-1</sup> of <sup>40</sup>K produce the same gamma dose rate and calculated from the following equation [37]:

$$Ra_{eq} = A_{Ra} + \frac{10}{7} \cdot A_{Th} + \frac{10}{130} \cdot A_K \quad (2)$$

where  $A_{Ra}$ ,  $A_{Th}$  and  $A_K$  are the specific activities of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K, respectively in Bq kg<sup>-1</sup>. The maximum value of the Ra<sub>eq</sub> in building raw materials and products must be less than 370 Bq kg<sup>-1</sup> for the safe use, i.e., to keep to external dose below 1.5 mSv y<sup>-1</sup> [38]. The range and mean values of the calculated Ra<sub>eq</sub> for all the studied concrete mixture samples are shown in the last columns of Tables 2–4. The mean values of the calculated Ra<sub>eq</sub> for all concrete mixture samples studied are lower than the value of 370 Bq kg<sup>-1</sup>.

**Table 2**  
Specific activities of <sup>226</sup>Ra, <sup>232</sup>Th, <sup>40</sup>K and Ra<sub>eq</sub> for the concrete mixture samples incorporating 10 wt.% of FA.

Power plant	N		Specific activity (Bq kg <sup>-1</sup> ± 1σ)			Ra <sub>eq</sub> (Bq kg <sup>-1</sup> ± 1σ)
			A <sub>Ra</sub>	A <sub>Th</sub>	A <sub>K</sub>	
Afşin-Elbistan	4	Range	22.2 ± 2.6–34.8 ± 8.0	3.0 ± 2.0–4.9 ± 1.6	33.5 ± 2.7–55.0 ± 8.0	29.6 ± 3.18–44.8 ± 10.3
		Mean ± SE*	29.2 ± 2.6	3.6 ± 0.4	40.7 ± 4.9	37.5 ± 3.1
Çatalağzı	3	Range	16.0 ± 5.0–18.2 ± 2.5	5.0 ± 1.0–12.0 ± 3.0	52.0 ± 3.5–73.0 ± 7.0	30.5 ± 4.4–37.2 ± 5.9
		Mean ± SE	17.2 ± 0.6	7.8 ± 2.1	59.4 ± 6.8	32.9 ± 2.2
Çayırhan	8	Range	13.0 ± 4.0–18.0 ± 2.6	4.2 ± 2.0–13.0 ± 3.0	27.0 ± 2.0–114.0 ± 5.2	23.4 ± 2.3–40.6 ± 5.1
		Mean ± SE	15.6 ± 0.8	7.4 ± 1.2	64.8 ± 11.8	31.1 ± 1.9
Kangal	4	Range	57.0 ± 3.9–121.0 ± 9.0	4.7 ± 0.8–7.1 ± 1.3	33.0 ± 4.0–50.0 ± 5.0	66.3 ± 5.0–132.8 ± 9.9
		Mean ± SE	96.8 ± 13.8	5.7 ± 0.5	42.5 ± 3.6	108.2 ± 14.5
Kemerköy	4	Range	21.0 ± 3.0–25.2 ± 7.5	3.0 ± 2.0–5.0 ± 1.0	38.4 ± 3.2–60.0 ± 5.4	31.2 ± 3.2–35.8 ± 3.4
		Mean ± SE	22.8 ± 1.1	4.2 ± 0.4	51.8 ± 4.9	32.7 ± 1.1
Orhaneli	5	Range	9.0 ± 1.0–14.0 ± 3.0	3.2 ± 0.6–12.0 ± 2.0	82.0 ± 8.0–132.0 ± 5.0	23.9 ± 2.8–35.6 ± 5.1
		Mean ± SE	11.6 ± 0.9	7.2 ± 1.6	103.4 ± 8.4	29.9 ± 2.4
Seyitömer	4	Range	10.0 ± 2.0–16.6 ± 4.5	7.0 ± 1.3–13.0 ± 1.0	40.4 ± 5.2–289.0 ± 8.0	26.6 ± 2.3–53.8 ± 8.6
		Mean ± SE	13.9 ± 1.5	10.3 ± 1.4	105.8 ± 61.1	36.7 ± 6.2
Soma	5	Range	19.6 ± 2.5–36.5 ± 3.3	4.0 ± 0.9–7.3 ± 2.1	34.5 ± 7.2–40.0 ± 3.2	31.1 ± 4.9–49.6 ± 4.2
		Mean ± SE	28.2 ± 3.3	6.0 ± 0.6	37.8 ± 1.0	39.8 ± 3.5
Tunçbilek	7	Range	18.0 ± 3.2–30.0 ± 6.0	5.0 ± 0.6–9.0 ± 3.0	31.3 ± 6.2–45.0 ± 6.0	30.7 ± 3.2–46.3 ± 4.0
		Mean ± SE	22.6 ± 1.6	6.8 ± 0.5	38.1 ± 1.9	35.2 ± 2.0
Yatağan	7	Range	10.0 ± 2.0–25.0 ± 4.0	4.0 ± 1.0–10.0 ± 1.0	31.4 ± 2.3–93.0 ± 1.0	18.5 ± 2.5–45.0 ± 3.1
		Mean ± SE	16.8 ± 2.4	6.6 ± 1.0	46.1 ± 8.1	29.9 ± 3.7
Yeniköy	3	Range	27.6 ± 2.9–48.3 ± 3.3	3.0 ± 1.3–4.0 ± 1.0	24.4 ± 3.0–31.0 ± 3.0	35.6 ± 3.2–55.6 ± 4.8
		Mean ± SE	41.3 ± 6.9	3.6 ± 0.3	27.8 ± 1.9	48.6 ± 6.5

\* SE: Standard error.

**Table 3**  
Specific activities of <sup>226</sup>Ra, <sup>232</sup>Th, <sup>40</sup>K and Ra<sub>eq</sub> for the concrete mixture samples incorporating 20 wt.% of FA.

Power plant	N		Specific activity (Bq kg <sup>-1</sup> ± 1σ)			Ra <sub>eq</sub> (Bq kg <sup>-1</sup> ± 1σ)
			A <sub>Ra</sub>	A <sub>Th</sub>	A <sub>K</sub>	
Afşin-Elbistan	4	Range	35.5 ± 6.7–46.0 ± 4.0	5.0 ± 2.4–7.0 ± 1.0	58.0 ± 14.0–65.0 ± 7.0	47.1 ± 5.7–60.7 ± 6.9
		Mean ± SE*	40.6 ± 2.2	5.8 ± 0.5	60.8 ± 1.5	53.5 ± 2.8
Çatalağzı	2	Range	18.7 ± 2.6–19.7 ± 2.8	9.6 ± 1.3–14.8 ± 1.5	76.4 ± 4.4–97.0 ± 3.8	39.9 ± 4.8–46.7 ± 5.4
		Mean ± SE	19.2 ± 0.5	12.2 ± 2.6	86.7 ± 10.3	43.3 ± 3.4
Çayırhan	7	Range	20.1 ± 5.0–27.5 ± 5.6	5.0 ± 1.0–17.0 ± 1.5	58.0 ± 6.0–297.0 ± 6.0	39.5 ± 3.5–73.2 ± 6.2
		Mean ± SE	23.3 ± 1.1	9.9 ± 2.0	158.9 ± 34.9	49.7 ± 4.5
Kangal	4	Range	77.6 ± 9.5–206.0 ± 11.0	5.0 ± 1.0–7.4 ± 1.3	31.9 ± 3.4–50.0 ± 4.0	89.6 ± 5.4–219.6 ± 12.4
		Mean ± SE	163.9 ± 29.2	6.6 ± 0.5	40.2 ± 3.7	176.4 ± 29.4
Kemerköy	4	Range	27.0 ± 5.0–38.1 ± 7.5	3.0 ± 1.5–7.0 ± 2.0	63.0 ± 13.0–134.0 ± 14.0	41.8 ± 3.4–48.0 ± 3.9
		Mean ± SE	31.8 ± 2.4	5.2 ± 0.8	92.3 ± 16.3	46.3 ± 1.5
Orhaneli	4	Range	15.0 ± 3.0–27.0 ± 2.0	4.3 ± 0.3–21.0 ± 2.0	148.0 ± 5.0–245.0 ± 10.0	34.1 ± 2.8–68.8 ± 5.6
		Mean ± SE	19.3 ± 2.8	11.6 ± 3.5	191.9 ± 21.5	50.5 ± 7.5
Seyitömer	5	Range	18.0 ± 5.0–22.8 ± 8.2	5.4 ± 1.7–15.0 ± 4.0	56.2 ± 4.0–193.0 ± 15.0	39.4 ± 4.1–57.3 ± 5.5
		Mean ± SE	20.4 ± 0.9	11.4 ± 2.0	109.4 ± 25.3	45.2 ± 3.2
Soma	6	Range	37.5 ± 6.9–64.0 ± 13.0	7.0 ± 1.0–10.0 ± 1.5	42.9 ± 3.4–73.0 ± 8.0	52.7 ± 4.7–82.3 ± 8.7
		Mean ± SE	48.5 ± 3.8	8.3 ± 0.4	62.3 ± 4.8	65.1 ± 4.3
Tunçbilek	7	Range	29.5 ± 2.9–41.0 ± 2.0	4.2 ± 1.9–15.0 ± 3.0	50.0 ± 2.0–111.0 ± 14.0	42.8 ± 4.0–61.0 ± 4.7
		Mean ± SE	34.1 ± 1.6	10.1 ± 1.3	78.3 ± 8.7	54.5 ± 2.3
Yatağan	5	Range	26.0 ± 4.0–41.0 ± 8.0	6.0 ± 1.0–9.0 ± 3.0	45.0 ± 5.0–68.0 ± 8.0	40.9 ± 4.3–59.1 ± 5.2
		Mean ± SE	34.8 ± 3.0	8.0 ± 0.5	55.0 ± 4.7	50.5 ± 3.7
Yeniköy	3	Range	49.9 ± 9.0–56.0 ± 12.0	4.0 ± 2.0–7.7 ± 3.0	34.6 ± 5.0–42.0 ± 5.0	58.8 ± 5.1–66.7 ± 5.6
		Mean ± SE	52.3 ± 1.9	5.7 ± 1.1	37.9 ± 2.2	63.4 ± 2.4

\* SE: Standard error.

### 3.2.2. Gamma index

In this study, in order to evaluate the radiological hazards of the potential use of concrete mixture samples containing FA as building materials, the gamma index was assessed by converting the specific activity of a building material (Bq kg<sup>-1</sup>) into a measure of radiation dose (mSv) that may be received by an individual occupying a model room constructed from a building material with a specific activity of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K. Gamma index (*I<sub>γ</sub>*) is expressed in terms of the specific activities of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K as proposed by the European Commission (EC) [36]:

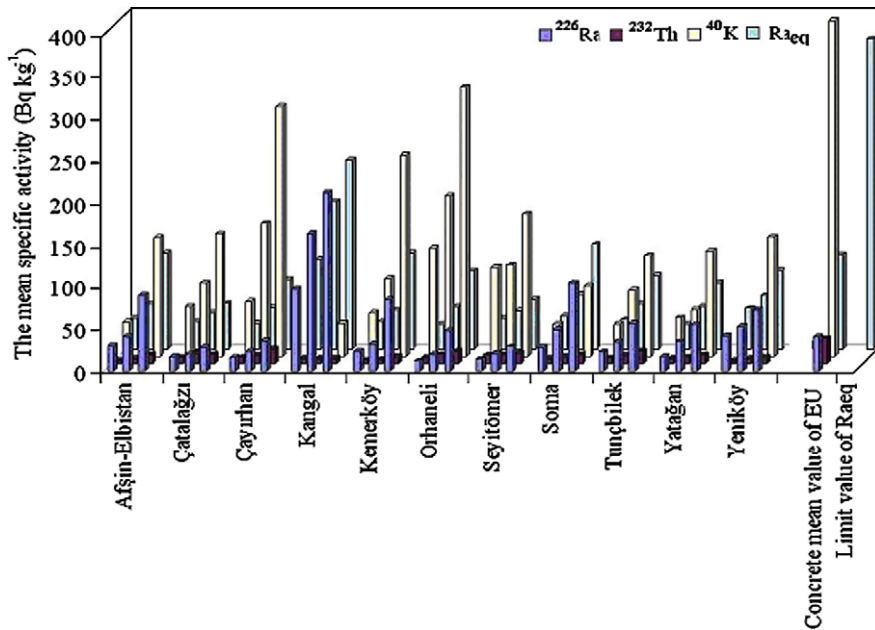
$$I_{\gamma} = \frac{A_{Ra}}{300 \text{ Bq kg}^{-1}} + \frac{A_{Th}}{200 \text{ Bq kg}^{-1}} + \frac{A_K}{3000 \text{ Bq kg}^{-1}} \quad (3)$$

where *A<sub>Ra</sub>*, *A<sub>Th</sub>* and *A<sub>K</sub>* are the specific activities of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K, respectively in Bq kg<sup>-1</sup>. The *I<sub>γ</sub>* should be used only as a screening tool for identifying materials which might be of concern. For materials used in bulk amounts, e.g. concrete *I<sub>γ</sub>* ≤ 1 corresponds to an annual effective dose less than or equal 1 mSv, while *I<sub>γ</sub>* ≤ 0.5 corresponds to an annual effective dose less than or equal to 0.3 mSv. When industrial by-products such as fly ash, bauxite and phosphogypsum are incorporated in building materials and there is reason to suspect that these contain enhanced levels of natural radionuclides, the specific activities of these nuclides in the final product should be measured or assessed reliably from the activities of all component materials [36]. The range and mean values of the calculated *I<sub>γ</sub>* for the concrete mixture samples

**Table 4**  
Specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  and  $\text{Ra}_{\text{eq}}$  for the concrete mixture samples incorporating 30 wt.% of FA.

Power plant	N		Specific activity ( $\text{Bq kg}^{-1} \pm 1\sigma$ )			$\text{Ra}_{\text{eq}}$ ( $\text{Bq kg}^{-1} \pm 1\sigma$ )
			$A_{\text{Ra}}$	$A_{\text{Th}}$	$A_{\text{K}}$	
Afşin-Elbistan	4	Range	$70.0 \pm 9.0$ – $110.0 \pm 8.0$	$7.0 \pm 1.0$ – $20.3 \pm 1.0$	$75.0 \pm 8.0$ – $286.0 \pm 5.0$	$88.1 \pm 8.3$ – $127.0 \pm 9.5$
		Mean $\pm$ SE*	$89.5 \pm 9.7$	$10.6 \pm 3.3$	$142.5 \pm 48.3$	$115.6 \pm 9.2$
Çatalağzı	3	Range	$25.0 \pm 6.0$ – $32.0 \pm 6.0$	$8.0 \pm 1.0$ – $14.0 \pm 1.0$	$82.0 \pm 7.0$ – $256.0 \pm 6.0$	$47.1 \pm 4.3$ – $67.7 \pm 5.6$
		Mean $\pm$ SE	$28.3 \pm 2.0$	$10.7 \pm 1.8$	$146.7 \pm 55.0$	$54.9 \pm 6.5$
Çayırhan	5	Range	$29.0 \pm 3.0$ – $41.4 \pm 5.8$	$5.0 \pm 1.0$ – $25.8 \pm 1.7$	$108.0 \pm 6.0$ – $436.0 \pm 7.0$	$53.5 \pm 6.0$ – $103.7 \pm 7.2$
		Mean $\pm$ SE	$35.3 \pm 2.1$	$17.0 \pm 3.9$	$297.4 \pm 53.9$	$82.4 \pm 9.0$
Kangal	4	Range	$84.4 \pm 4.3$ – $258.0 \pm 13.0$	$5.1 \pm 1.5$ – $7.4 \pm 1.4$	$34.0 \pm 2.6$ – $45.0 \pm 3.5$	$97.0 \pm 5.7$ – $271.4 \pm 10.5$
		Mean $\pm$ SE	$211.9 \pm 42.5$	$6.6 \pm 0.5$	$39.6 \pm 2.9$	$224.3 \pm 42.5$
Kemerköy	3	Range	$53.2 \pm 9.9$ – $117.0 \pm 6.0$	$6.0 \pm 1.0$ – $14.0 \pm 2.3$	$190.0 \pm 5.0$ – $333.0 \pm 9.8$	$98.8 \pm 9.4$ – $140.6 \pm 7.3$
		Mean $\pm$ SE	$84.4 \pm 18.4$	$8.7 \pm 2.7$	$239.7 \pm 46.7$	$115.2 \pm 12.9$
Orhaneli	5	Range	$29.0 \pm 2.0$ – $64.7 \pm 4.9$	$5.3 \pm 1.0$ – $26.7 \pm 1.3$	$265.0 \pm 5.0$ – $424.0 \pm 7.0$	$62.2 \pm 4.5$ – $124.8 \pm 8.6$
		Mean $\pm$ SE	$47.8 \pm 7.2$	$14.4 \pm 3.5$	$319.8 \pm 30.0$	$93.0 \pm 10.6$
Seyitömer	4	Range	$22.0 \pm 2.0$ – $40.0 \pm 4.0$	$5.0 \pm 1.0$ – $18.0 \pm 3.0$	$63.0 \pm 4.0$ – $281.0 \pm 3.0$	$35.0 \pm 4.6$ – $70.6 \pm 7.8$
		Mean $\pm$ SE	$28.8 \pm 4.2$	$12.3 \pm 2.7$	$170.0 \pm 61.8$	$59.3 \pm 8.2$
Soma	6	Range	$67.0 \pm 8.0$ – $153.0 \pm 12.0$	$9.0 \pm 2.0$ – $14.1 \pm 2.0$	$70.0 \pm 6.0$ – $106.0 \pm 3.7$	$88.8 \pm 6.8$ – $174.2 \pm 10.7$
		Mean $\pm$ SE	$103.6 \pm 12.7$	$11.2 \pm 0.8$	$83.6 \pm 5.5$	$126.1 \pm 12.0$
Tunçbilek	6	Range	$43.0 \pm 14.0$ – $84.0 \pm 6.0$	$10.1 \pm 1.3$ – $26.0 \pm 2.0$	$74.0 \pm 4.0$ – $206.0 \pm 6.2$	$75.6 \pm 8.7$ – $111.1 \pm 7.3$
		Mean $\pm$ SE	$56.5 \pm 5.9$	$15.3 \pm 2.3$	$121.0 \pm 19.2$	$87.6 \pm 5.0$
Yatağan	6	Range	$42.5 \pm 2.9$ – $71.0 \pm 14.0$	$3.0 \pm 0.8$ – $20.0 \pm 2.0$	$35.0 \pm 7.0$ – $414.0 \pm 10.0$	$59.4 \pm 5.1$ – $90.6 \pm 7.8$
		Mean $\pm$ SE	$54.6 \pm 4.7$	$10.3 \pm 2.6$	$126.9 \pm 59.9$	$79.0 \pm 4.8$
Yeniköy	4	Range	$57.0 \pm 10.0$ – $96.0 \pm 5.0$	$6.0 \pm 1.3$ – $9.0 \pm 1.0$	$66.0 \pm 7.0$ – $364.0 \pm 2.5$	$75.0 \pm 7.2$ – $111.1 \pm 8.2$
		Mean $\pm$ SE	$71.9 \pm 9.3$	$7.3 \pm 0.6$	$142.9 \pm 73.7$	$93.2 \pm 7.4$

\* SE: Standard error.



**Fig. 1.** Comparison of the mean specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  and  $\text{Ra}_{\text{eq}}$  of the concrete mixture samples incorporating 10, 20 and 30 wt.% of FA from the 11 TPPs with the mean of values of European Union (EU) concrete and the limit value of  $\text{Ra}_{\text{eq}}$ .

incorporating three different percentages of FA are shown in the fourth columns of Tables 5–7. The mean values of  $I_\gamma$  are compared with the recommended upper level in Fig 2. It is observed in Tables 5–7 and Fig. 2 that the all mean values of  $I_\gamma$ , except for concrete mixture samples with 20 and 30 wt.% of Kangal FA, are lower than the value of 0.5 corresponding to an effective dose 0.3 mSv while the all values of  $I_\gamma$  are below the value of the unity corresponding to an effective dose 1 mSv.

**3.2.3. Indoor absorbed gamma dose rate and the annual effective dose**

The absorbed dose rate in indoor air, due to gamma-ray emission from the radionuclides ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ ) in the building material, were evaluated using data and formula provided by the

EC report [36]. In the EC report, the dose conversion coefficients were calculated for the model room centre. Dimensions of the model room are  $4 \times 5 \times 2.8$  m. Thickness of walls, floor and ceiling and are 20 cm. The density of the concrete is  $2350 \text{ kg m}^{-3}$ . The indoor absorbed gamma dose rate ( $D_R$ ) was estimated from the following equation:

$$D_R(\text{nGy h}^{-1}) = C_{\text{Ra}} \cdot A_{\text{Ra}} + C_{\text{Th}} \cdot A_{\text{Th}} + C_{\text{K}} \cdot A_{\text{K}} \quad (4)$$

where  $C_{\text{Ra}}$ ,  $C_{\text{Th}}$  and  $C_{\text{K}}$  coefficients correspond to  $0.92 \text{ nGy h}^{-1}$  per  $\text{Bq kg}^{-1}$  for  $^{226}\text{Ra}$ ,  $1.1 \text{ nGy h}^{-1}$  per  $\text{Bq kg}^{-1}$  for  $^{232}\text{Th}$  and  $0.080 \text{ nGy h}^{-1}$  per  $\text{Bq kg}^{-1}$  for  $^{40}\text{K}$  and  $A_{\text{Ra}}$ ,  $A_{\text{Th}}$  and  $A_{\text{K}}$  are the specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ , respectively in  $\text{Bq kg}^{-1}$ .

**Table 5**

The gamma index ( $I_\gamma$ ), the indoor absorbed gamma dose rate ( $D_R$ ) and the corresponding effective dose ( $E_{\text{eff}}$ ) values for the concrete mixture samples incorporating 10 wt.% of FA.

Power plant	N		$I_\gamma$	$D_R$ (nGy h <sup>-1</sup> )	$E_{\text{eff}}$ (mSv)
Afşin-Elbistan	4	Range	0.10–1.15	26.8–40.5	0.13–0.20
		Mean ± SD*	0.13 ± 0.02	34.1 ± 5.6	0.17 ± 0.03
Çatalağzı	3	Range	0.11–0.13	27.2–32.2	0.13–0.16
		Mean ± SD	0.12 ± 0.01	29.2 ± 2.7	0.14 ± 0.01
Çayırhan	8	Range	0.08–0.14	21.1–35.0	0.10–0.17
		Mean ± SD	0.11 ± 0.02	27.7 ± 4.5	0.14 ± 0.02
Kangal	4	Range	0.22–0.45	60.3–121.3	0.30–0.60
		Mean ± SD	0.37 ± 0.10	98.7 ± 26.6	0.48 ± 0.13
Kemerköy	4	Range	0.11–0.12	28.4–32.4	0.14–0.16
		Mean ± SD	0.11 ± 0.01	29.7 ± 1.9	0.15 ± 0.01
Orhaneli	5	Range	0.09–0.13	22.3–32.2	0.11–0.16
		Mean ± SD	0.11 ± 0.02	26.9 ± 4.3	0.13 ± 0.02
Seyitömer	4	Range	0.09–0.20	23.0–49.4	0.11–0.24
		Mean ± SD	0.13 ± 0.05	32.5 ± 11.9	0.16 ± 0.06
Soma	5	Range	0.11–0.17	27.7–44.5	0.14–0.22
		Mean ± SD	0.14 ± 0.03	35.6 ± 7.1	0.17 ± 0.03
Tunçbilek	7	Range	0.11–0.16	27.0–41.1	0.13–0.20
		Mean ± SD	0.12 ± 0.02	31.3 ± 4.8	0.15 ± 0.02
Yatağan	7	Range	0.07–0.16	16.5–40.3	0.08–0.20
		Mean ± SD	0.10 ± 0.03	26.5 ± 8.6	0.13 ± 0.04
Yeniköy	3	Range	0.12–0.19	32.2–50.5	0.16–0.25
		Mean ± SD	0.17 ± 0.04	44.2 ± 10.4	0.22 ± 0.05

\* SD: Standard deviation.

**Table 6**

The gamma index ( $I_\gamma$ ), the indoor absorbed gamma dose rate ( $D_R$ ) and the corresponding effective dose ( $E_{\text{eff}}$ ) values for the concrete mixture samples incorporating 20 wt.% of FA.

Power plant	N		$I_\gamma$	$D_R$ (nGy h <sup>-1</sup> )	$E_{\text{eff}}$ (mSv)
Afşin-Elbistan	4	Range	0.16–0.21	42.8–54.9	0.21–0.27
		Mean ± SD*	0.18 ± 0.02	48.6 ± 5.0	0.24 ± 0.02
Çatalağzı	3	Range	0.14–0.17	35.5–40.5	0.17–0.20
		Mean ± SD	0.15 ± 0.02	38.0 ± 3.5	0.19 ± 0.02
Çayırhan	8	Range	0.14–0.27	36.3–66.3	0.18–0.33
		Mean ± SD	0.18 ± 0.05	45.0 ± 11.0	0.22 ± 0.05
Kangal	4	Range	0.30–0.74	81.3–200.9	0.40–0.99
		Mean ± SD	0.59 ± 0.20	161.7 ± 54.2	0.79 ± 0.27
Kemerköy	4	Range	0.15–0.17	37.6–44.0	0.18–0.22
		Mean ± SD	0.16 ± 0.01	42.3 ± 3.2	0.21 ± 0.02
Orhaneli	5	Range	0.13–0.25	32.0–61.1	0.16–0.30
		Mean ± SD	0.19 ± 0.05	45.8 ± 13.0	0.22 ± 0.06
Seyitömer	4	Range	0.14–0.21	35.7–51.3	0.18–0.25
		Mean ± SD	0.16 ± 0.03	40.1 ± 6.4	0.20 ± 0.03
Soma	5	Range	0.18–0.28	47.3–74.5	0.23–0.37
		Mean ± SD	0.22 ± 0.04	58.7 ± 9.6	0.29 ± 0.05
Tunçbilek	7	Range	0.15–0.22	39.1–53.9	0.19–0.26
		Mean ± SD	0.19 ± 0.02	48.7 ± 5.1	0.24 ± 0.02
Yatağan	7	Range	0.14–0.20	36.3–53.1	0.18–0.26
		Mean ± SD	0.17 ± 0.03	45.2 ± 7.4	0.22 ± 0.04
Yeniköy	3	Range	0.20–0.23	53.7–60.5	0.26–0.30
		Mean ± SD	0.22 ± 0.01	57.5 ± 3.5	0.28 ± 0.02

\* SD: Standard deviation.

To estimate the annual effective dose, one has to take into account the conversion factor from absorbed dose in air to effective dose and the indoor occupancy factor. In UNSCEAR 2000 report [1], a value of 0.7 Sv Gy<sup>-1</sup> was used for the conversion factor from absorbed dose in air to effective dose received by adults, and 0.8 for the indoor occupancy factor, implying that 80% of time is spent indoors, on average, around the world. The annual effective dose ( $E_{\text{eff}}$ ) in units of mSv was estimated using the following formula:

$$E_{\text{eff}} = D_R (\text{nGy h}^{-1}) \cdot 8766 \text{ h y}^{-1} \cdot 0.8 \cdot 0.7 \text{ Sv Gy}^{-1} \cdot 10^{-6} \quad (5)$$

where  $D_R$  (nGy h<sup>-1</sup>) is given by Eq. (4).

**Table 7**

The gamma index ( $I_\gamma$ ), the indoor absorbed gamma dose rate ( $D_R$ ) and the corresponding effective dose ( $E_{\text{eff}}$ ) values for the concrete mixture samples incorporating 30 wt.% of FA.

Power plant	N		$I_\gamma$	$D_R$ (nGy h <sup>-1</sup> )	$E_{\text{eff}}$ (mSv)
Afşin-Elbistan	4	Range	0.30–0.45	80.5–115.1	0.40–0.57
		Mean ± SD*	0.40 ± 0.07	105.4 ± 16.7	0.52 ± 0.08
Çatalağzı	3	Range	0.17–0.25	42.2–61.6	0.21–0.30
		Mean ± SD	0.20 ± 0.05	49.5 ± 10.6	0.24 ± 0.05
Çayırhan	8	Range	0.19–0.38	49.1–92.9	0.24–0.46
		Mean ± SD	0.30 ± 0.08	74.9 ± 17.7	0.37 ± 0.09
Kangal	4	Range	0.33–0.91	88.1–248.6	0.43–1.22
		Mean ± SD	0.75 ± 0.28	205.3 ± 78.3	1.01 ± 0.38
Kemerköy	4	Range	0.36–0.49	91.0–129.9	0.45–0.64
		Mean ± SD	0.40 ± 0.07	106.4 ± 20.7	0.52 ± 0.10
Orhaneli	5	Range	0.23–0.44	58.5–111.7	0.29–0.55
		Mean ± SD	0.34 ± 0.08	85.4 ± 20.5	0.42 ± 0.10
Seyitömer	4	Range	0.12–0.25	31.7–62.6	0.16–0.31
		Mean ± SD	0.21 ± 0.06	53.5 ± 14.7	0.26 ± 0.07
Soma	5	Range	0.30–0.59	79.9–159.0	0.39–0.78
		Mean ± SD	0.43 ± 0.10	114.4 ± 27.2	0.56 ± 0.13
Tunçbilek	7	Range	0.26–0.38	68.6–99.7	0.34–0.49
		Mean ± SD	0.31 ± 0.04	78.4 ± 10.8	0.39 ± 0.05
Yatağan	7	Range	0.20–0.34	53.0–84.8	0.26–0.42
		Mean ± SD	0.28 ± 0.05	71.6 ± 11.1	0.35 ± 0.05
Yeniköy	3	Range	0.26–0.38	67.7–101.3	0.33–0.50
		Mean ± SD	0.32 ± 0.05	85.5 ± 13.9	0.42 ± 0.07

\* SD: Standard deviation.

The estimated results for the  $D_R$  and the corresponding  $E_{\text{eff}}$  are given in the fifth and sixth columns of Tables 5–7. The estimated  $D_R$  values for all the concrete mixture samples incorporating 10, 20 and 30 wt.% of FA range from 16.5 to 121.3 nGy h<sup>-1</sup>, 32.0 to 200.9 nGy h<sup>-1</sup> and 31.7 to 248.6 nGy h<sup>-1</sup>, respectively. From the data in Tables 5–7, the estimated mean values of  $D_R$  for all concrete mixture samples incorporating 10 and 20 wt.% of FA, except for the concrete mixture samples incorporating Kangal FA, are lower than the world average (populated-weighted) indoor absorbed gamma dose rate of 84 nGy h<sup>-1</sup> [1]. The estimated mean values of  $D_R$  for concrete mixture samples incorporating Kangal FA are higher than the quoted world average value.

It is seen from Tables 5–7 and Fig. 2 that the estimated mean values of the  $E_{\text{eff}}$  for all the concrete mixture samples are lower than the annual effective dose criterion of 1 mSv except the concrete mixture samples incorporating 30 wt.% of Kangal FA (1.01 ± 0.38), while all the concrete mixture samples incorporating 10 and 20 wt.% of FA are lower than the exemption level of annual effective dose of 0.3 mSv except for concrete mixture samples incorporating Kangal FA.

#### 4. Conclusion

For each sample in this study, the specific activity of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K, the activity indices (radium equivalent activity and the gamma index) used only as screening tools for ready-to-use building materials, the absorbed gamma dose rate in indoor air and the corresponding annual effective dose have been determined to evaluate the radiological safety aspects of the utilization fly ashes collected from the 11 coal-fired TPPs for production of concrete in Turkey. As can be seen clearly from Fig. 2., the all mean values of the gamma index are below the value of unity corresponding to an annual effective dose 1 mSv. Also, the mean values of the annual effective dose estimated for all the concrete mixture samples incorporating three different percentages of FA are lower than the annual effective dose criterion of 1 mSv except for the concrete mixture samples incorporating 30 wt.% of Kangal FA. Finally, the results of the present study show that the concrete mixture samples are within the recommended safety limit and do not pose

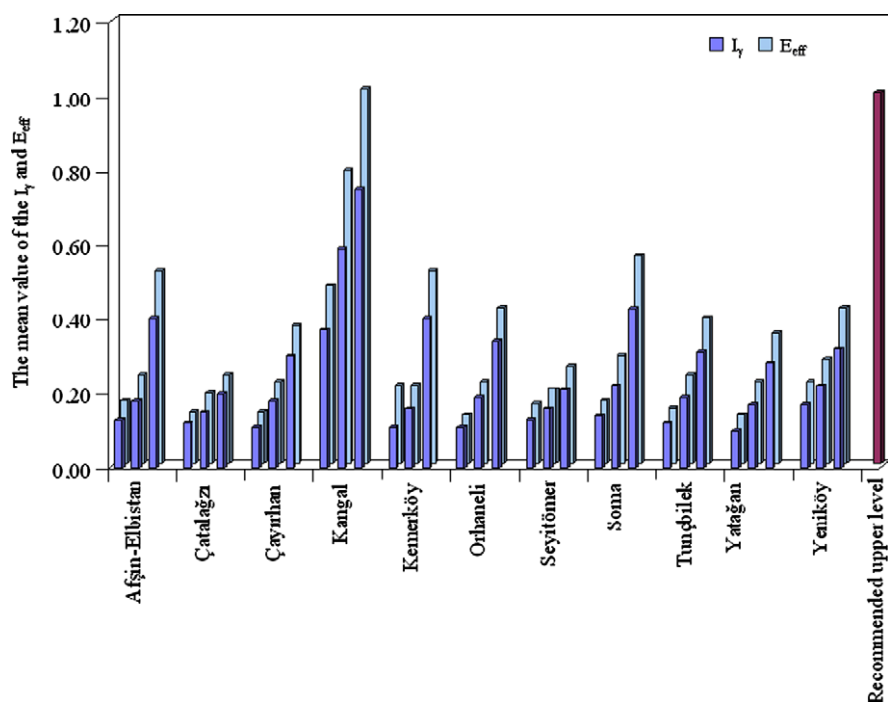


Fig. 2. Comparison of the mean values of gamma index ( $I_\gamma$ ) and the effective dose rate ( $E_{eff}$ ) of the concrete mixture samples incorporating 10, 20 and 30 wt.% of FA the 11 TPPs with the recommended upper level.

any significant source of radiation hazard, except for the concrete mixture samples incorporating 30 wt.% of Kangal FA.

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