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# 1 RADIOLOGICAL CHARACTERIZATION AND EVALUATION OF 2 HIGH VOLUME BAUXITE RESIDUE ALKALI ACTIVATED 3 CONCRETES

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## 18 **Abstract**

19  
20 Bauxite residue, also known as red mud, can be used as an aggregate in concrete products.  
21 The study involves the radiological characterization of different types of concretes containing bauxite  
22 residue from Ukraine. The activity concentrations of radionuclides from the <sup>238</sup>U, <sup>232</sup>Th decay series  
23 and <sup>40</sup>K were determined for concrete mixture samples incorporating 30, 40, 50, 60, 75, 85 and 90 %  
24 (by mass) of bauxite residue using gamma-ray spectrometry with a HPGe detector. The studied  
25 bauxite residue can, from a radiological point of view using activity concentration indexes developed  
26 by Markkanen, be used in concrete for building materials and in road construction, even in  
27 percentages reaching 90 % (by mass). However, when also occupational exposure is considered it is  
28 recommended to incorporate less than 75 % (by mass) of Ukrainian bauxite residue during the  
29 construction of buildings in order to keep the dose to workers below the dose criterion used by  
30 Radiation Protection (RP) 122 (0.3 mSv/a). Considering RP122 for evaluation of the total effective  
31 dose to workers no restrictions are required for the use of the Ukrainian bauxite residue in road  
32 construction.

## 34 **Key words**

35  
36 Activity concentration, activity concentration index, effective dose, bauxite residue, concrete

37

## 38 1. Introduction

39  
40 Bauxite residue, also known as red mud, is a major byproduct that is produced during the  
41 refining of the aluminum ore by means of the Bayer process. For every ton of alumina produced, 1-  
42 1.5 t of bauxite residue is generated. It is estimated that about 120 Mt of bauxite residue was produced  
43 worldwide in 2007. [Power et al., 2011] In China alone, about 30 Mt of bauxite residue was generated  
44 in 2009, of which only 4 % was utilized. [Power et al., 2009] The disposal-costs may add up to 5 %  
45 of the alumina production cost. [Gu et al., 2012] Furthermore, improper storage of bauxite residue  
46 can lead to harmful contamination of water, land and air in the surrounding area because of its high  
47 alkalinity. Strong environmental concerns are linked to the disposal of bauxite residue. The treatment  
48 and utilization of bauxite residue is both of environmental and economic significance.

49 In recent years, many studies have investigated different application possibilities for bauxite  
50 residue. Several studies focus on the reuse of bauxite residue as an additive for construction materials  
51 and among other on the use in ceramics cements. [Sglavo et al., 2000 (part 1+2); Pontikes et al., 2007;  
52 Tsakiridis et al., 2004; Pascual et al., 2009; Pan et al., 2002 and 2003; Ke et al., 2014] However, due  
53 to the low chemical activity of bauxite residue its application in membranes is limited [Sglavo et al.,  
54 2000 (part 1+2)] and in several cases, an energy intensive preliminary pre-treatment is required.

55 Early studies already reported that the use of alkaline activation can allow for a considerable  
56 increase in bauxite residue incorporation rates for cements and concretes without reducing their  
57 physio- mechanical characteristics. [Patent Krivenko, 1996; Rostovskaya, 1994; Glukhovsky, 1989]  
58 The properties of alkaline activated cements and concretes are highly competitive to traditional  
59 cement concretes.

60 To make the reuse practices economically viable a sufficiently high fraction of bauxite residue  
61 needs to be incorporated in the concrete. In the current work it is demonstrated that it becomes  
62 possible to formulate high volume bauxite residue alkali activated cements and concretes with  
63 incorporation rates of bauxite residue in the concretes reaching 90 % (by mass).

64 An important aspect that needs to be dealt with when incorporating larger percentages of  
65 bauxite residue in concrete, concerns the radiological properties. The UNSCEAR report (2000)  
66 reported activity concentrations for the bauxite ore of 0.4-0.6 kBq kg<sup>-1</sup> for individual radionuclides  
67 from the <sup>238</sup>U-series and 0.3-0.4 kBq kg<sup>-1</sup> for individual radionuclides from <sup>232</sup>Th-series. For  
68 Hungarian bauxite ore activity concentrations up to 0.8 kBq kg<sup>-1</sup> <sup>226</sup>Ra and up to 0.5 kBq kg<sup>-1</sup> <sup>232</sup>Th  
69 were published. [Somlai et al, 2008] The average activity concentrations of bauxite residues produced  
70 in several European and non-European countries were reported by Nuccetelli et al. (2015, (1)). For  
71 the considered bauxite residues an overall average activity concentration of 0.34 kBq kg<sup>-1</sup> <sup>226</sup>Ra, 0.48  
72 kBq kg<sup>-1</sup> <sup>232</sup>Th and 0.21 kBq kg<sup>-1</sup> <sup>40</sup>K was obtained. For Ukrainian bauxite residue activity  
73 concentration of 0.16 kBq kg<sup>-1</sup> <sup>226</sup>Ra, 0.33 kBq kg<sup>-1</sup> <sup>232</sup>Th and 0.053 kBq kg<sup>-1</sup> <sup>40</sup>K were reported.  
74 [U.D.C. 691.5] In general most authors consider the activity concentrations of <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K

75 for the radiological evaluation of bauxite residue and construction materials based on the bauxite  
76 residue. [Nuccetelli et al., 2015 (2); Turhan et al., 2011 and 2014; Viruthagiri et al., 2013; Kovacs et  
77 al., 2012 and 2013; Somlai et al., 2008] Other radionuclides in the decay chains are rarely evaluated  
78 to assess the secular equilibrium in the decay chains. Since for NORM containing construction  
79 materials in general the secular equilibrium will be disturbed this aspect will be dealt with in this  
80 study in detail by analyzing a broad selection of radionuclides using gamma spectrometric analysis.

81 For the synthesized concretes based on bauxite residue aggregates the current work aims to  
82 investigate the radiological properties in order to control and prevent radiological problems upon  
83 large scale application. Therefore, this study will verify if the reuse meets the requirements of the  
84 new Euratom Basic Safety Standards (EU-BSS) and occurs according to the principles set by the  
85 Construction Products Regulations. [CE, 2014, CPR 305/2011] The EU-BSS covers the issue of  
86 NORM (naturally occurring radioactive materials) in industrial applications and the reuse of by-  
87 products from NORM processing industries in building materials. The EU-BSS uses an index  
88 developed by Markkanen [Markkanen, 1995] for the screening and evaluation of the public exposure  
89 from building materials that are permanently incorporated in buildings. The CPR lays down essential  
90 requirements for construction works in general. According to the CPR the construction works must  
91 be designed and built in such a way that the emission of dangerous radiation will not be a threat to  
92 the health of the occupant or neighbours. Methodology for dose assessment and classification of  
93 construction materials in view of their gamma emitting properties, linked to the implementation of  
94 the CPR, is still under development. Markkanen (1995) proposed another index specifically to  
95 evaluate the exposure to the public caused by “materials used for constructing streets and  
96 playgrounds”. Both indexes, developed by Markkanen and part of the Finnish legislation [STUK,  
97 2010] on natural radiation, are used to assess the public exposure and will be used in the current study.  
98 For the evaluation of the occupational exposure this study will follow the approach proposed by  
99 Radiation Protection (RP) 122 part II.

100

## 101 **2. Materials and methods**

### 102 **2.1 Description of the studied concrete samples and their constituents**

103  
104 Cylindrical concrete specimens ( $d$ = typically 50 mm for P-series samples and typically 46 mm  
105 for C-series samples;  $h$ = typically 30 mm for P-series and typically 37 mm for C-series) with various  
106 incorporation rates of bauxite residue were prepared. Bauxite residue, in its state as it was produced  
107 as part of fine aggregate to produce alkali activated concrete, was incorporated directly in the  
108 specimen. In both casted (C-series) and semi-pressed (P-series) concrete specimens the  
109 aluminosilicate component was represented by a granulated blast-furnace slag with basicity modulus

110 of 1 and content of glassy phase of 80. The compositions of concrete mixtures produced by the semi-  
111 dry pressing technique (P1 – P5) and by the high slump casting technique (C1-C4) are given in Table  
112 1. The pressing technique allows production of prefabricated products like tiles, bricks and etc. The  
113 casting technique allows production of pre-casted and on-site casted construction materials and is  
114 often applied for concrete structures on the basis of Portland cement and concrete. The different types  
115 of samples are representative for the most common ways that concretes are produced and applied.  
116 Two different samples with the same red mud bauxite concentration (P5 and C3 contain both 40 %  
117 red mud by mass; P4 and C2 contain both 50 % red mud by mass) were characterized by gamma-ray  
118 spectrometry to demonstrate that the impact of the production (casting or pressing) method is  
119 negligible from a radiological point of view.

120 A cement of the following composition (by mass) was chosen: 87 % slag (Ground-granulated  
121 blast-furnace slag), 5 % OPC (Ordinary Portland Cement), 4 % Na<sub>2</sub>CO<sub>3</sub> and 4 % Na<sub>2</sub>O·SiO<sub>2</sub>·5H<sub>2</sub>O.  
122 All cement constituents were milled until a Blaine fineness of 350-450 m<sup>2</sup>/kg (specific surface) was  
123 obtained.

124 Bauxite residue from Ukraine was used in the experiments. It has the following mineralogical  
125 composition (by mass): 25-27 % hematite, 25-28 % goethite, 4.5-6.5 % rutile and anatase, 15-17 %  
126 hydrogarnets, 6-7 % sodium aluminosilicate hydrate and 2.5-3.0 % calcite.

127 Local river sand with maximum grain size of 1.2 mm and bauxite residue with particle sizes  
128 varying from 50 to 1000 µm were used as aggregates.

## 129 **2.2 Radiological analysis**

130  
131 Bauxite residue samples for gamma-ray spectrometry were transferred to radon tight Teflon  
132 containers and stored for at least 21 days for secular equilibrium to be established between <sup>226</sup>Ra and  
133 its daughters. The sample mass ranged from 111 to 136 g (dry mass). The sample density ranged from  
134 1.9 to 2.2 g/cm<sup>3</sup>. The sample containers were positioned on a holder 11.4 mm on top of a HPGe-  
135 detector. This detector is located in the above ground Radionuclide Metrology Laboratory at the  
136 European Commission's Joint Research Centre in Geel, Belgium. The HPGe detector was a coaxial  
137 detector with a relative efficiency of 46 % (FWHM: 1.41 at 662 keV and 1.86 at 1332 keV) with a  
138 shield composed of 1 mm Cu and 10 cm low-activity Pb. The measured percent dead time ranged  
139 from 0.02 % to 0.04 % for all samples. The samples were measured for a period ranging from 3 to 8  
140 days.

141 Data acquisition and spectrum analysis were performed using Canberra's Genie 2000  
142 software. The full energy peak efficiencies,  $\epsilon$ , were calculated using Monte Carlo simulations with  
143 the EGSnrc Monte Carlo code. [Kawrakow et al. 2011] The computer model of the detector has been  
144 validated through participation proficiency testing exercises. The model uses measured dimensions  
145 of the sample, composition of the sample and the detector as input. The simulations assume that the

146 gamma-ray emissions are isotropic and uncorrelated. All calculations assume that the radionuclides  
147 are homogeneously distributed in the sample and that the sample material is homogeneously  
148 distributed in the sample container. The use of Monte Carlo calculations has the additional benefit  
149 that the correction for coincidence summing which occurs in decays with cascading gamma-rays is  
150 obtained in the same calculation as the FEP efficiency.

151 Gamma-rays emitted by the radionuclides occurring in natural decay series of  $^{238}\text{U}$  and  $^{232}\text{Th}$   
152 as well as  $^{235}\text{U}$  and  $^{40}\text{K}$  were investigated. An overview of the investigated emission lines is given in  
153 Table 2. For each radionuclide with multiple gamma-rays, a weighted mean of the activity was  
154 calculated taking into account the activity of the different gamma-rays. The nuclear decay data was  
155 taken from the Decay Data Evaluation Project (DDEP) tables. [DDEP website] The  $^{208}\text{Tl}$  activity has  
156 been divided with the branching factor (0.3594).

157 The 186 keV peak is a doublet with contributions from  $^{235}\text{U}$  and  $^{226}\text{Ra}$ . The activity of  $^{235}\text{U}$  is  
158 calculated after subtracting the contribution from  $^{226}\text{Ra}$  to the 186 keV peak. The  $^{226}\text{Ra}$  activity was  
159 determined by its daughters,  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$ . The activity concentration (in this paper meaning the  
160 activity per unit mass) was determined by dividing the final activity determined for each radionuclide  
161 (the mother radionuclide in cases with short-lived daughters) by the measured dry mass of the sample.

162 The uncertainties of the obtained activity concentrations are the combined standard  
163 uncertainties calculated according to the GUM (Guide to the expression of uncertainty in  
164 measurement). [JCGM WG1 2008] When combining several gamma-rays to one radionuclide and  
165 several daughters to one mother radionuclide using weighted means, the correlated parameters were  
166 added separately in quadrature in order not to obtain unrealistic and far too low final uncertainties.

### 167 **2.3 Activity concentration indexes as screening tools for public exposure**

168

169 The activity concentration index for building materials ( $\text{ACI}_{\text{BM}}$ ), proposed by Markkanen and  
170 implemented in the COUNCIL DIRECTIVE 2013/59/EURATOM (EU-BSS), is calculated using the  
171 activity concentration of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  (Equation 1). [CE, 2014; Markkanen, 1995] The activity  
172 concentration index for materials used for streets and playgrounds ( $\text{ACI}_{\text{SP}}$ ), as defined by Markkanen,  
173 is calculated using the activity concentration of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  and  $^{137}\text{Cs}$  (Equation 2). [Markkanen,  
174 1995] More information on the models used for both indexes is shown in Table 3. Note that an  $\text{ACI}_{\text{BM}}$   
175  $> 1$  indicates an effective gamma dose larger than 1 mSv/a whereas an  $\text{ACI}_{\text{SP}}$  indicates an effective  
176 gamma dose larger than 0.1 mSv/a: both indexes were designed for different dose models. To  
177 calculate the ACIs secular equilibrium is assumed between  $^{232}\text{Th}$  and  $^{228}\text{Ra}$  and between  $^{226}\text{Ra}$  and its  
178 two daughters  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$ . The used activity concentration of  $^{232}\text{Th}$  is in reality the activity  
179 concentration of  $^{228}\text{Ac}$  and the activity concentration of  $^{226}\text{Ra}$  is in reality the weighted mean between  
180 the activity concentrations of  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$ .  $^{40}\text{K}$  and  $^{137}\text{Cs}$  were directly measured using their  
181 respective gamma emission lines at 1460.8 keV and 661.6 keV.

$$182 \quad ACI_{BM} = \frac{Ac_{226Ra}}{300 \text{ Bq/kg}} + \frac{Ac_{232Th}}{200 \text{ Bq/kg}} + \frac{Ac_{40K}}{3000 \text{ Bq/kg}} \quad (1)$$

$$183 \quad ACI_{SP} = \frac{Ac_{226Ra}}{700 \text{ Bq/kg}} + \frac{Ac_{232Th}}{500 \text{ Bq/kg}} + \frac{Ac_{40K}}{8000 \text{ Bq/kg}} + \frac{Ac_{137Cs}}{2000} \quad (2)$$

184

185 With Ac as activity concentration of the mentioned radionuclide expressed in Bq/kg.

186

187 The uncertainty on the activity concentration indexes (u) is calculated using Equations (3) and (4).

188

$$189 \quad u(ACI_{BM}) = \sqrt{\left(\frac{1}{300}\right)^2 u^2 (Ac_{226Ra}) + \left(\frac{1}{200}\right)^2 u^2 (Ac_{232Th}) + \left(\frac{1}{3000}\right)^2 u^2 (Ac_{40K})} \quad (3)$$

190

$$191 \quad u(ACI_{SP}) =$$

$$192 \quad \sqrt{\left(\frac{1}{700}\right)^2 u^2 (Ac_{226Ra}) + \left(\frac{1}{500}\right)^2 u^2 (Ac_{232Th}) + \left(\frac{1}{8000}\right)^2 u^2 (Ac_{40K}) + \left(\frac{1}{2000}\right)^2 u^2 (Ac_{137Cs})} \quad (4)$$

193

194 Where  $u(Ac_{226Ra})$  is the uncertainty on the activity concentration of  $^{226}\text{Ra}$ ,  $u(Ac_{232Th})$  is the uncertainty  
 195 on the activity concentration of  $^{232}\text{Th}$ ,  $u(Ac_{40K})$  is the uncertainty on the activity concentration of  $^{40}\text{K}$ ,  
 196 and  $u(Ac_{137Cs})$  is the uncertainty on the activity concentration of  $^{137}\text{Cs}$ .

## 197 **2.4 Dose assessment for occupational exposure**

198

199 Following RP 122 (part II) dose assessments were performed that consider the impact of  
 200 concrete containing bauxite residues following different scenarios for workers active in building  
 201 construction and road construction. All calculations of the different scenarios were performed using  
 202 the NIRS (Japanese National Institute on Radiological Sciences) database dose assessment tool. The  
 203 scenarios named in part 4.2. of RP122 part II as “4.2.6. Road constructions” and “Building  
 204 construction with NORM containing building materials” are listed on the NIRS website as  
 205 respectively “Road construction” and “Building construction” under “Dose assessment for workers  
 206 who handle NORM (including ores and building materials)”. Each scenario is characterized by  
 207 specific parameters listed in Table 3. In both scenarios the highest activity concentrations of all  
 208 measured radionuclides from the  $^{238}\text{U}$  decay series, from  $^{232}\text{Th}$  decay series and for  $^{40}\text{K}$  were taken  
 209 for different percentages of incorporated bauxite residue. RP 122 uses as dose criterion 0.3 mSv/year.  
 210 In this case the total effective dose (external, inhalation and ingestion dose) is calculated.

211 Important sources of uncertainty in the dose analysis are the uncertainty on the occupation  
 212 time, on the dust concentration and on the ingestion rate which are unknown. The models used for  
 213 the dose assessment are simplified models that do not correspond to actual situations. The uncertainty  
 214 shown in the results originates from the uncertainty on the activity concentration of the selected  
 215 radionuclide with the highest activity concentration.

216

### 217 3. Results and discussion

218  
219 Even at high incorporation rates of bauxite red mud, reaching 90 % by mass, the strength of  
220 the resulting concrete remains rather high (Table 1), allowing from a mechanical point of view to  
221 manufacture such construction products as brick for various applications, tiles, plates, etc. using the  
222 technology of semi-dry pressing. Alternatively, concrete constructions can be precasted or made on  
223 site by the casting technique.

224 A stepwise approach is used for the radiological evaluation of the considered applications of  
225 the newly synthesized concretes that contain bauxite residues as an aggregate: (1) The activity  
226 concentrations of several radionuclides occurring in the natural decay series of  $^{238}\text{U}$  and  $^{232}\text{Th}$  as well  
227 as  $^{235}\text{U}$  and  $^{40}\text{K}$  were determined using gamma-ray spectrometry while monitoring the secular  
228 equilibrium. (2) Activity concentration indexes are then used for initial screening of the public  
229 exposure regarding the use of the newly produced concretes as a building material or for constructing  
230 streets and playgrounds. (3) In addition, in order to also evaluate the occupational exposure, a dose  
231 assessment for construction workers, based on RP122 part II, is performed.

#### 232 3.1 Study of the activity concentrations

233  
234 As mentioned in the introduction, average activity concentrations of  $165 \text{ Bq kg}^{-1}$   $^{226}\text{Ra}$ ,  $328$   
235  $\text{Bq kg}^{-1}$   $^{232}\text{Th}$  and  $53 \text{ Bq kg}^{-1}$   $^{40}\text{K}$  are reported in Ukrainian national studies [U.D.C. 691.5, Register]  
236 for the Ukrainian bauxite residue. The results of the gamma spectrometric analysis of bauxite residue  
237 containing concrete mixtures produced by semi-dry pressing and casting are shown in Table 4 and  
238 Table 5.

239 When studying the  $^{238}\text{U}$  decay series (Table 4) for all samples and when comparing the activity  
240 concentrations of each radionuclide to the nearest decay product measurable via gamma-ray  
241 spectrometry ( $^{234}\text{Th}$  to  $^{234\text{m}}\text{Pa}$ ;  $^{234\text{m}}\text{Pa}$  to  $^{214}\text{Pb}$ ;  $^{214}\text{Pb}$  to  $^{214}\text{Bi}$  and  $^{214}\text{Bi}$  to  $^{210}\text{Pb}$ ) secular equilibrium  
242 seems to be present in all samples when considering the measurement uncertainty. Only minor  
243 deviations from secular equilibrium can be observed in the  $^{238}\text{U}$  decay series, for example for the  
244 sample P1, when comparing the activity concentration of  $^{234}\text{Th}$  to the activity concentration of  $^{214}\text{Pb}$   
245 or  $^{214}\text{Bi}$ . Generally speaking for the studied concrete mixtures the whole  $^{238}\text{U}$  decay series is in  
246 equilibrium or there are only minor deviations from equilibrium. Focusing on the  $^{232}\text{Th}$  decay series  
247 (Table 5) also in this case, no disequilibrium could be observed when studying the individual samples.  
248 The uncertainty on the activity concentration of  $^{212}\text{Bi}$  is higher in comparison with the other  
249 radionuclides of the chain. This is due to the fact that a limited number of counts is registered in the  
250  $1620.7 \text{ keV}$  peak of  $^{212}\text{Bi}$ , leading to limited counting statistics.



251 For all samples, the  $^{238}\text{U}/^{235}\text{U}$  activity ratio shows no deviation from the expected value of  
252 21.6 which indicates natural isotopic abundance. The measured  $^{235}\text{U}$  activity concentrations are  
253 shown in Table 4.

254 In none of the samples  $^{137}\text{Cs}$  was detected and the MDA (Minimum Detectable Activity  
255 concentration) was in all cases below 1 Bq/kg.

## 256 **3.2 Public exposure**

257  
258 Two ACIs, as described by Markkanen, are used to verify whether the bauxite concrete  
259 mixtures are safe to use considering public exposure. [Markkanen, 1995] Figure 1 shows the results  
260 of the  $\text{ACI}_{\text{BM}}$ , which focusses on building materials and is used by the COUNCIL DIRECTIVE  
261 2013/59/EURATOM (EU-BSS) [CE, 2014], discussed in 3.2.1. Figure 2 shows the results of the  
262  $\text{ACI}_{\text{SP}}$ , which focusses on streets and playgrounds, discussed in 3.2.2.

263

### 264 **3.2.1 The activity concentration index for building materials.**

265  
266 All the calculated  $\text{ACI}_{\text{BMS}}$  are below the EU-BSS threshold level of 1 and therefore from a  
267 radiological point of view the materials can be accepted for usage as building materials considering  
268 external exposure to the public. If, according to the EU-BSS, the  $\text{ACI}_{\text{BM}}$  exceeds this threshold level,  
269 the indoor external exposure to gamma radiation emitted by building materials in addition to outdoor  
270 external exposure, of 1 mSv per year needs to be verified.

271 When considering concrete for bulk applications in building materials, as is the case here, then  
272 the ACI is a reliable screening tool since it was designed for this type of scenario. For other types of  
273 materials next to concrete or for thin layer application it is advisable to use a density and thickness  
274 corrected index. [Nucetelli et al., 2015, (1)]

275

### 276 **3.2.2 The activity concentration index for streets and playgrounds.**

277  
278 All the calculated  $\text{ACI}_{\text{SPS}}$  are well below the threshold level of 1. This threshold level,  
279 proposed by Markkanen and used in the Finnish radiation protection regulation, corresponds to a dose  
280 criterion of 0.1 mSv per year.

281 This implies that from a radiological point of view, the mixtures are safe for public use as  
282 road, street and playground considering external exposure. [STUK, 2010; Markkanen, 1995] The  
283  $\text{ACI}_{\text{SP}}$  developed by Markkanen involves, next to the naturally occurring radionuclides, also  $^{137}\text{Cs}$  in  
284 the evaluation.

285

### 286 3.3 Occupational exposure

287  
288 Following RP 122 (part II) a simplified dose assessment was made that considers the impact  
289 of concrete containing bauxite residue on building and road construction workers. The results of the  
290 simulation are shown in Figures 3 and 4. In this case the total effective dose (external, inhalation and  
291 ingestion dose) is considered. The dose criterion used by RP122 is 0.3 mSv/a.

292

#### 293 3.3.1 Dose assessment for building construction worker.

294  
295 The mass incorporation of 75 % bauxite in the concrete mixtures already leads to effective  
296 doses above the dose criterion of 0.3 mSv/a (Figure 3). From the dose calculations it can be assessed  
297 that an incorporation rate of 60 % (by mass) provides an acceptable incorporation level to assure that  
298 the dose to the workers will not be higher than the dose criterion proposed by RP 122. Typically 95  
299 % of the calculated total dose could be assigned as external dose.

300

#### 301 3.3.2 Dose assessment for road construction worker.

302  
303 Even when using high incorporation rates of 90 % (by mass) for road construction the dose  
304 criterion of 0.3 mSv/a is not exceeded (Figure 4). From a radiological point of view, road construction  
305 workers are able to safely use bauxite concrete mixtures with high contents of bauxite red mud. In  
306 this case typically 85 % of the calculated total dose could be assigned as external dose.

307 As reported by Nuccetelli et al. (2015, (2)), average activity concentrations of bauxite residue  
308 are origin and therefore country dependent. For European countries activity concentrations for bauxite  
309 residue of up to  $379 \pm 43$  Bq/kg  $^{226}\text{Ra}$ ,  $472 \pm 23$  Bq/kg  $^{232}\text{Th}$  and  $21 \pm 11$  Bq/kg  $^{40}\text{K}$  (Greece) were  
310 found. In the world even activity concentration of 1047 Bq/kg  $^{226}\text{Ra}$ , 350 Bq/kg  $^{232}\text{Th}$  and 335 Bq/kg  
311  $^{40}\text{K}$  are reported (Jamaica). When assuming a dilution factor of 0.9 (90 % (by mass) incorporation of  
312 the bauxite residue) total doses up to 0.64 mS/a (Greece) and 0.89 mS/a (Jamaica) can be calculated  
313 for road construction workers. Also in this case the external dose is the main contributing factor (0.58  
314 mSv/a for workers in Greece; 0.8 mSv/a for workers in Jamaica) to the total dose of the workers.  
315 Therefore an adapted monitoring strategy, taking into consideration the way that variations in the  
316 origin of the incoming material occur over time, is required to ensure that the dose criteria are met.

317

### 318 4. Conclusion

319  
320 The current study demonstrates that the studied Ukrainian bauxite residue can, based on the  
321  $\text{ACI}_{\text{BM}}$  defined by the EU-BSS and the  $\text{ACI}_{\text{SP}}$  defined by Markkanen for streets and playgrounds, be

322 used for building materials and for road construction, even in percentages reaching 90 % (by mass)  
323 incorporation.

324           However when also considering occupational exposure and using the dose assessment models  
325 of RP122 (part 2) for building construction workers it becomes advisable to incorporate less than 75  
326 % (by mass) of bauxite red mud. Upon incorporating 75 % (by mass) bauxite residue or more a total  
327 effective dose higher than the dose criterion proposed by RP122 (0.3 mSv/a) was found. 60 % (by  
328 mass) of bauxite residue incorporation was found to be acceptable for building construction. For the  
329 case of road construction, based on the model proposed by RP122, 90 % (by mass) bauxite residue  
330 incorporation can be accepted also from the perspective of occupational exposure.

331           Considering the large variation in the activity concentration of the bauxite ore and resulting  
332 bauxite residues and considering that the ores accepted by industries and the processing of the ores  
333 will vary over time, the authors recommend that screening of the bauxite residues should determine  
334 the possible applications.

335           In order to evaluate reuse options for NORM residues, the COST Action NORM4Building  
336 recommends to use a holistic approach and to consider all aspects that can determine whether a  
337 specific reuse practice becomes possible. A holistic approach can only function if chemical,  
338 radiological, physical and mechanical data is available for a specific type of residue or construction  
339 material. Therefore in addition to this paper, a detailed study of the chemical, physical and mechanical  
340 properties of the discussed concretes is in preparation. [Krivenko et al., in preparation]

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349

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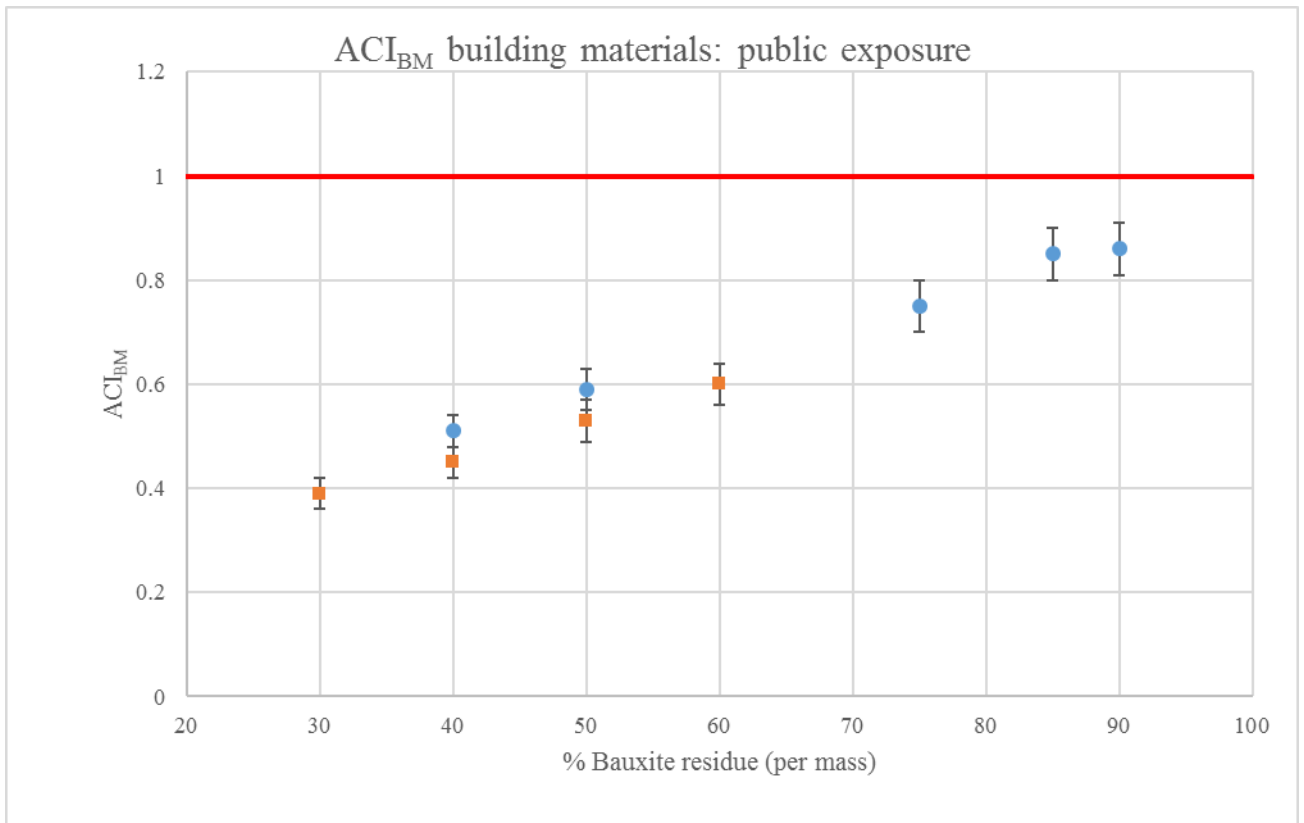
483 Table 5 Activity concentrations (Bq/kg, dry weight) of radionuclides from the  $^{232}\text{Th}$  decay series as  
484 well as for  $^{40}\text{K}$  (k=2) for the nine samples.

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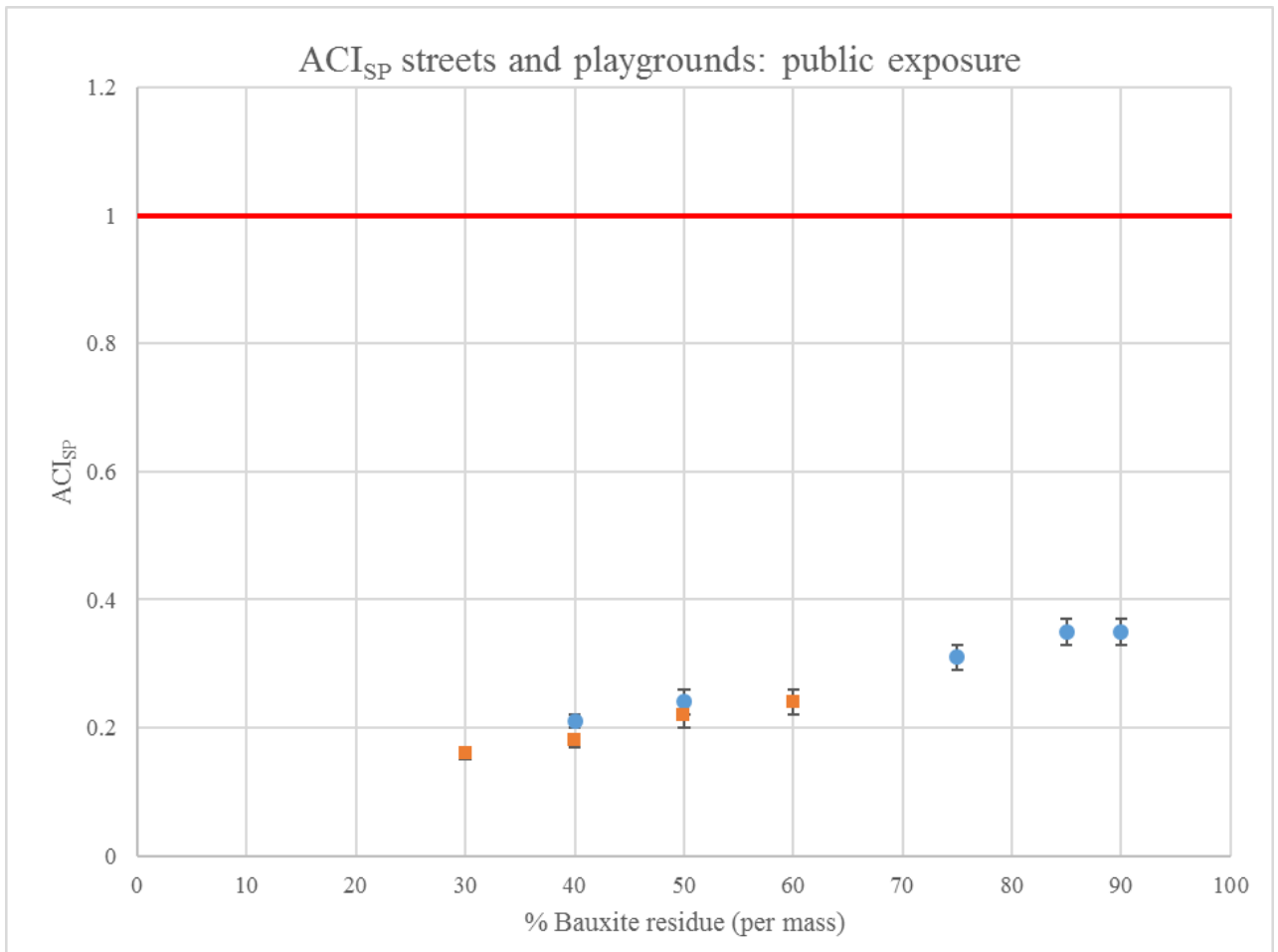
487 **Figures**

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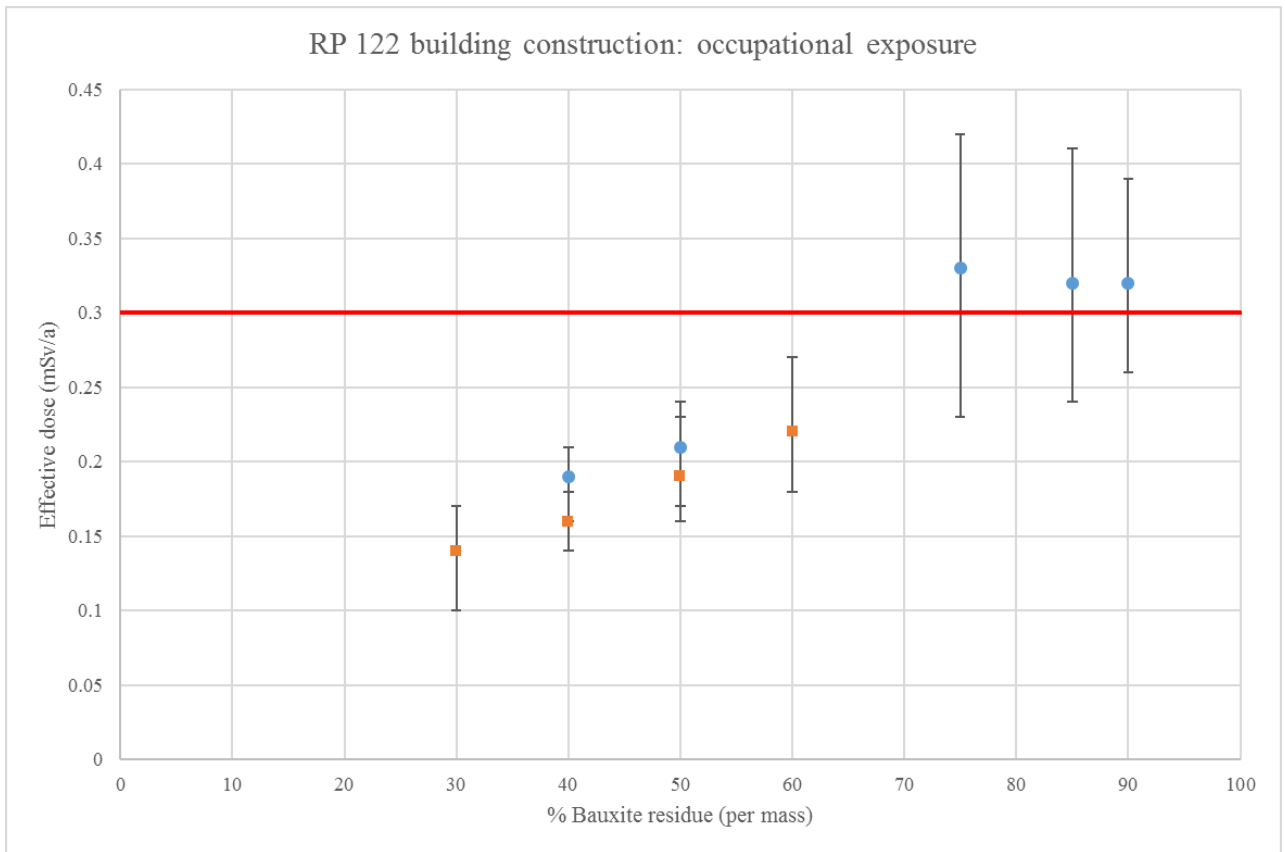


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 491 mixtures with different % (per mass) of bauxite residue incorporation. Blue spheres represent  
 492 the P-series, red squares represent C-series (k=2). Red line indicates threshold value of 1.  
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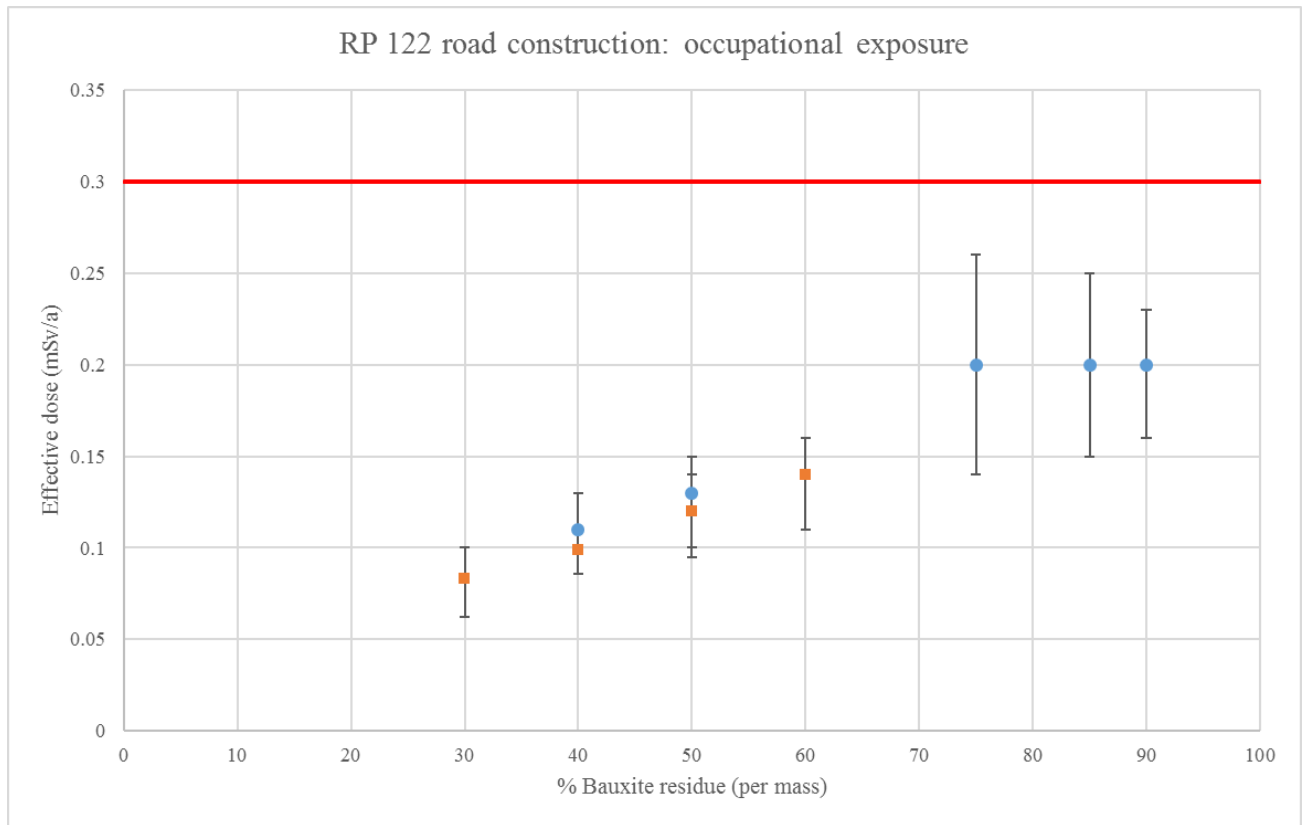




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 495 Figure 2: Activity concentration index for streets and playgrounds for different bauxite  
 496 concrete mixtures with different % (by mass) of bauxite residue incorporation. Blue spheres  
 497 represent the P-series, red squares represent the C-series (k=2). Red line indicates threshold  
 498 value of 1.  
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 502 different bauxite concrete mixtures with different % (by mass) of bauxite residue  
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 504 indicates the dose criterion of 0.3 mSv/ a proposed by RP122.  
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 509 different bauxite concrete mixtures with different wt.% of bauxite residue incorporation. Blue  
 510 spheres represent the P-series, red squares represent the C-series. The red line indicates the  
 511 dose criterion of 0.3 mSv/a proposed by RP122.  
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514**Tables**

515

516 Table 1 Concrete mixture design for semi-dry pressing (P=30 MPa) and slump casting.

Sample	Concrete mixture design, % (by mass); (100 % corresponds to dry mass)				Compressive strength MPa
	Cement	Bauxite Red mud	Sand	H <sub>2</sub> O	
P1	10	90	-	17	6.78
P2	15	85	-	17	5.45
P3	25	75	-	16	5.05
P4	25	50	25	14	10.0
P5	25	40	35	12	14.0
C1	25	60	15	32.5	15.0
C2	25	50	25	25.5	17.5
C3	25	40	35	23.5	23.5
C4	25	30	45	11.25	25.0

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518

Radionuclide	Energy (keV)	Probability of emission (%)	Radionuclide	Energy (keV)	Probability of emission (%)
<u><sup>234</sup>Th</u>	63.3	3.75	<u><sup>228</sup>Ac</u>	209.248	3.97
	92.38	2.18		328.004	3.04
	92.8	2.15		409.46	2.02
<u><sup>234m</sup>Pa</u>	766.361	0.323		463.002	4.45
	1001.026	0.847		755.313	1.03
<u><sup>214</sup>Pb</u>	241.997	7.268		772.291	1.52
	295.224	18.414		794.942	4.31
	351.932	35.6		911.196	26.2
<u><sup>214</sup>Bi</u>	609.312	45.49		968.96	15.9
	768.356	4.892		1588.2	3.06
	806.174	1.262		1630.618	1.52
	934.061	3.1	<u><sup>224</sup>Ra</u>	240.986	4.12
	1120.287	14.91	<u><sup>212</sup>Pb</u>	238.632	43.6
	1155.19	1.635	<u><sup>212</sup>Bi</u>	1620.738	1.51
	1238.111	5.831	<u><sup>208</sup>Tl</u>	277.37	6.6
	1280.96	1.435		583.187	85
	1377.669	3.968		763.45	1.8
	1401.5	1.33		860.53	12.4
	1407.98	2.389		2614.511	99.755
	1509.228	2.128	<u><sup>235</sup>U</u>	143.767	10.94
	1729.595	2.844		185.72	57
	1764.494	15.31		163.356	5.08
	1847.42	2.025		205.316	5.02
	2118.55	1.158	<u><sup>40</sup>K</u>	1460.822	10.55
	2204.21	4.913	<u><sup>137</sup>Cs</u>	661.652	84.99
	2447.86	1.548			
<u><sup>210</sup>Pb</u>	46.539	4.252			

522 Table 3: Field of application and relevant parameters that define the underlying models for the  
 523 Activity Concentration Indexes and the dose assessments based on RP122.

	ACI <sub>BM</sub>	ACI <sub>SP</sub>	RP 122 Road Construction	RP 122 Building Construction
Geometry	Floor, ceiling, 4 walls	Plane	Plane	Floor, ceiling, 2 walls
Size geometry (m)	4 x 5 x 2.8 with thickness 0.2*	20 x 20 Thickness not specified	100 x 10 with thickness 0.4	3 x 4 x 2.5 with thickness 0.2
Density (kg/m <sup>3</sup> )	2350	2350	2000	2300
Dilution factor	/	/	1	1
Exposure time (h)	7000	500	1800	1800
Dust concentration (mg/m <sup>3</sup> )	/	/	1	0.5
Breathing rate (m <sup>3</sup> /h)	/	/	1.2	1.2
Direct ingestion (mg/h)	/	/	10	10
Dose criterion (mSv/a)	1	0.1	0.3	0.3
Exposure to workers/public:	Public	Public	Workers	Workers
Field of application:	Building materials	Streets, playgrounds and roads	Road construction	Building construction
Reference(s)	EC 2014; RP112	Markkanen, 1995; STUK, 2010	RP 122, NIRS database	RP 122, NIRS database

524 \* In Markkanen 1995 size is 12 x 7 x 2.8 m with thickness of 0.2 m  
 525

526 Table 4 Activity concentrations (Bq/kg, dry weight) of radionuclides from the  $^{238}\text{U}$  decay as well as  
 527 for  $^{235}\text{U}$  (k=2) for the nine test samples.

Series	$^{238}\text{U}$					$^{235}\text{U}$
	$^{234}\text{Th}$	$^{234\text{m}}\text{Pa}$	$^{214}\text{Pb}$	$^{214}\text{Bi}$	$^{210}\text{Pb}$	$^{235}\text{U}$
P1 (90 %)	$(11 \pm 2) \cdot 10$	$(9 \pm 2) \cdot 10$	$69 \pm 8$	$70 \pm 6$	$(12 \pm 4) \cdot 10$	$3.8 \pm 0.5$
P2 (85 %)	$(10 \pm 1) \cdot 10$	$(8 \pm 2) \cdot 10$	$68 \pm 6$	$68 \pm 6$	$(12 \pm 6) \cdot 10$	$4.3 \pm 0.5$
P3 (75 %)	$(9 \pm 2) \cdot 10$	$(8 \pm 2) \cdot 10$	$66 \pm 6$	$66 \pm 6$	$(12 \pm 6) \cdot 10$	$3.8 \pm 0.5$
P4 (50 %)	$(7 \pm 1) \cdot 10$	$(7 \pm 1) \cdot 10$	$53 \pm 6$	$52 \pm 4$	$(7 \pm 2) \cdot 10$	$3.3 \pm 0.4$
P5 (40 %)	$(7 \pm 1) \cdot 10$	$(6 \pm 1) \cdot 10$	$46 \pm 4$	$46 \pm 4$	$(5 \pm 2) \cdot 10$	$2.9 \pm 0.4$
C1 (60 %)	$(8 \pm 1) \cdot 10$	$(7 \pm 1) \cdot 10$	$49 \pm 6$	$48 \pm 2$	$(8 \pm 3) \cdot 10$	$3.5 \pm 0.4$
C2 (50 %)	$(7 \pm 2) \cdot 10$	$(6 \pm 1) \cdot 10$	$51 \pm 5$	$49 \pm 5$	$(6 \pm 2) \cdot 10$	$2.6 \pm 0.3$
C3 (40 %)	$(6 \pm 1) \cdot 10$	$(5 \pm 1) \cdot 10$	$42 \pm 4$	$40 \pm 4$	$(4 \pm 2) \cdot 10$	$2.5 \pm 0.3$
C4 (30 %)	$(5 \pm 2) \cdot 10$	$(5 \pm 1) \cdot 10$	$39 \pm 4$	$37 \pm 4$	$(2 \pm 2) \cdot 10$	$1.6 \pm 0.3$

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530 Table 5 Activity concentrations (Bq/kg, dry weight) of radionuclides from the  $^{232}\text{Th}$  decay series as  
 531 well as for  $^{40}\text{K}$  (k=2) for the nine test samples.

Series	$^{232}\text{Th}$					$^{40}\text{K}$
Sample (% by mass bauxite red mud)	$^{228}\text{Ac}$	$^{224}\text{Ra}$	$^{212}\text{Pb}$	$^{212}\text{Bi}$	$^{208}\text{Tl}$	$^{40}\text{K}$
P1 (90 %)	$(12 \pm 1)*10$	$(12 \pm 1)*10$	$(12 \pm 1)*10$	$(12 \pm 2)*10$	$(12 \pm 1)*10$	$(8 \pm 2)*10$
P2 (85 %)	$(12 \pm 1)*10$	$(12 \pm 1)*10$	$(12 \pm 1)*10$	$(11 \pm 2)*10$	$(12 \pm 1)*10$	$(8 \pm 2)*10$
P3 (75 %)	$(10 \pm 1)*10$	$(10 \pm 1)*10$	$(10 \pm 1)*10$	$(12 \pm 2)*10$	$(11 \pm 1)*10$	$(9 \pm 2)*10$
P4 (50 %)	$77 \pm 8$	$80 \pm 8$	$78 \pm 8$	$(7 \pm 1)*10$	$78 \pm 6$	$(8 \pm 2)*10$
P5 (40 %)	$65 \pm 6$	$63 \pm 8$	$66 \pm 6$	$(6 \pm 1)*10$	$65 \pm 6$	$(8 \pm 2)*10$
C1 (60 %)	$83 \pm 8$	$(8 \pm 1)*10$	$83 \pm 8$	$(7 \pm 2)*10$	$82 \pm 8$	$(6 \pm 1)*10$
C2 (50 %)	$69 \pm 7$	$71 \pm 9$	$70 \pm 7$	$(6 \pm 1)*10$	$70 \pm 7$	$(6 \pm 1)*10$
C3 (40 %)	$58 \pm 6$	$56 \pm 7$	$59 \pm 6$	$(5 \pm 1)*10$	$58 \pm 6$	$(6 \pm 1)*10$
C4 (30 %)	$48 \pm 5$	$49 \pm 7$	$49 \pm 5$	$(4 \pm 1)*10$	$48 \pm 5$	$(6 \pm 1)*10$

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