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Light weight concrete: ^{226}Ra, ^{232}Th, ^{40}K contents and dose reduction assessment

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Abstract

Four types of light weight concrete (LWC) commonly used in Hong Kong, namely, autoclave aerated concrete (plus lime), autoclave aerated concrete (plus Pulverized Fuel Ash or PFA), concrete with synthetic aggregate 'Leca' and concrete with polystyrene bean as aggregate were measured for their ^{226}Ra, ^{232}Th and ^{40}K contents using high-resolution gamma spectrometry. All the radionuclide contents except those for the PFA autoclave aerated concrete were below the world averages of building materials. The Ra-equivalents for these four LWC were 49.6, 249, 122 and 44.2 Bq kg^{-1}, respectively, and were much smaller than a recommended limit of 370 Bq kg^{-1} for construction materials for dwellings. The gamma-dose rate for an indoor environment with partition walls built with LWC was estimated to be about 20×10^{-8} Gy h^{-1}, which corresponded to a reduction in the effective dose of about 0.25 mSv y^{-1} when compared to that obtained for an indoor environment built with normal concrete (NC) only. The Rn exhalation rates from the three lowest Ra-equivalent LWC were calculated as 0.509, 1.28, and 0.335 mBq m^{-2} s^{-1}, respectively, which corresponded to a reduction in the indoor Rn concentration of around 14 Bq m^{-3} and reduction in the tracheobronchial dose reaching 1 mSv y^{-1} by using the James lung-dosimetry model, when compared to the case of NC. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Building materials; Dose reduction; Ra-equivalent; Gamma dose; Radon

1. Introduction

Most of the buildings in Hong Kong are high rise, and people seldom work or live on the ground floor. As such, the main source of indoor ^{222}Rn (referred to as Rn in the rest of this paper) in Hong Kong is the concrete used as building materials. Light weight concrete (LWC) was introduced for use for partition walls in public housing in Hong Kong some 10 years ago. LWC has an air-dry density below 1850 kg m^{-3} (Federation Internationale de la Precontrainte, 1983) as compared to 2350 kg m^{-3} of normal concrete (NC). LWC finds a wide range of applications, from insulation to structural applications. However, in Hong Kong, it is typically limited to the non-structural use in non-load bearing partition walls.

As LWC does not contain the crushed granite of NC, which has been found elsewhere to be the main source of Rn (Yu et al., 1992a), their Rn exhalation properties should be very different from those of the NC. Four types of LWC materials are commonly used

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in Hong Kong, namely, autoclave aerated concrete (plus lime), autoclave aerated concrete (plus Pulverized Fuel Ash or PFA), concrete with synthetic aggregate 'Leca' and concrete with polystyrene bean as aggregate. In the present investigation, the radionuclide contents of these LWC have been determined using high-resolution gamma spectrometry. The results have been compared with those of NC. The possible reduction in the indoor gamma-dose rate and the Rn dose through the use of LWC, when compared to the use of NC only, have also been assessed theoretically.

2. Methodology

The detector used in present studies was an E.G.&G. Ortec GMX 35210 n-type coaxial high purity germanium crystal of 55.2 × 72 mm with a relative efficiency of 35%. This was positioned inside a lead shield of cavity size 51 × 63.6 cm and thickness 11.5 cm. The integrated background in the lead shield from about 6 keV to 3.2 MeV was 1.8 cps. The type of cryostat configuration was Pop Top.

To carry out the calibration, a standard sample and a background sample were prepared. The ingredients of the basal materials (Yu et al., 1992a) chosen to form the background and standard sample consisted of SiO_2, Al_2O_3, CaO_2 and $CaCO_3$ mixed in a fixed ratio. The basal materials, which have very low radionuclide concentrations, provides a weight and a density similar to the LWC samples to be measured.

The basal materials were mixed thoroughly and homogeneously in a tray and dried at 700°C in an oven until a constant weight within ±1 g was achieved. The standard sample, in addition to the basal materials, contained known amounts of ^{238}U–^{226}Ra in equilibrium, ^{232}Th and ^{40}K for the purpose of calibration.

Standard and background samples of net weights 0.7 kg, filled into a 1 l Marinelli beaker were used in the calibration. Control of data acquisition and storage was carried out using E.G.&G. Ortec MAESTRO II A64-BI software. For detection, the background sample was measured for 3.47 d to obtain a background gamma spectrum. The standard sample was measured after at least 25 days to allow for Ra–Rn equilibrium. It was then measured for 1 d.

The four types of LWC samples (as mentioned in Section 1) were collected from building sites or from building-materials markets. The samples were ground into powder using ball mills. The ground LWC samples were then sieved through the test sieve of mesh size 300 μm. The fine powders obtained were collected into the Marinelli beaker of size 1 l and sealed with paraffin film. The net weights of the LWC samples were 0.7 kg to match the standard and background samples used in the calibration. Each sample was measured for at least 25 days after the sample was prepared, to allow for Ra–Rn equilibrium.

The time taken to measure the LWC samples were different, namely, 5, 10, 20 and 40 h, for the lime autoclave aerated concrete, PFA autoclave aerated concrete, 'Leca'-concrete and polystyrene-concrete, respectively. The difference in measurement time was mainly due to our desired level of relative uncertainty. After detection, a library-directed analysis of the spectrum was carried out to yield the radionuclide activities of the LWC sample.

3. Results and discussion

3.1. Radionuclide contents

The radionuclide contents for the four types of LWC are shown in Table 1. All the radionuclide contents, except those for the PFA autoclave aerated concrete, were below world averages for building materials: (^{226}Ra: 50 Bq kg^{-1}, ^{232}Th: 50 Bq kg^{-1}, ^{40}K: 500 Bq kg^{-1}) (UNSCEAR, 1993). The ^{226}Ra and ^{232}Th contents of the PFA autoclave aerated concrete, 86.0 ± 1.98 and 109 ± 4.26 Bq kg^{-1}, were much higher than the world averages.

The average radionuclide contents of the cement, sand and granite used for building materials in Hong Kong were previously measured by Yu et al. (1992a) as shown in Table 2. According to the building regulations in Hong Kong, to each 45 kg of cement, 0.07 m^3 of fine aggregates (sand) and 0.12 m^3 of coarse aggregates (granite) should be added to make concrete (Tso et al., 1994). According to this proportion, and taking the density of sand and aggregate to be 2.25 and 2.7×10^3 kg m^{-3}, respectively (Tso et al., 1994), the average concentrations for the radionuclides of ^{226}Ra, ^{232}Th and ^{40}K were 133, 96 and 897 Bq kg^{-1}. The values were much higher than the world averages of building materials, but the ^{232}Th concentration was still lower than that of the PFA autoclave aerated concrete (109 Bq kg^{-1}).

Radiological evaluation of construction materials is based on concentrations of the radionuclides ^{226}Ra, ^{232}Th and ^{40}K. The common approach is to use the Ra-equivalent (Ra_{eq}, in Bq kg^{-1}) (Hamilton, 1971): $Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K$ where C_{Ra}, C_{Th} and C_K are the radionuclide concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in Bq kg^{-1}. The Ra_{eq} values for the lime autoclave aerated concrete, PFA autoclave aerated concrete, 'Leca'-concrete and polystyrene-concrete were thus 49.6, 249, 122 and 44.2 Bq kg^{-1}, respectively. From the average concentrations for the radionuclides of ^{226}Ra, ^{232}Th and ^{40}K in building materials in Hong Kong mentioned above, the Ra-equiv-

Table 1
Contents of ^{226}Ra, ^{232}Th, ^{40}K in investigated light weight concrete

	Radionuclide contents (Bq kg^{-1} $\pm\sigma$)		
	^{226}Ra	^{232}Th	^{40}K
Autoclave aerated concrete (plus lime)	15.6 ± 1.12	14.7 ± 2.21	169 ± 3.54
Autoclave aerated concrete (plus PFA)	86.0 ± 1.98	109 ± 4.26	91.1 ± 4.56
Concrete with synthetic aggregate 'Leca'	39.4 ± 1.03	45.0 ± 2.02	244 ± 2.92
Concrete with polystyrene bean as aggregate	10.3 ± 0.412	20.4 ± 0.898	60.7 ± 1.09

alent of NC was calculated as 340 Bq kg^{-1}. As such, all LWC had smaller Ra$_{\mathrm{eq}}$ than NC.

It has been recommended that the Ra$_{\mathrm{eq}}$ of construction materials for dwellings should be below 370 Bq kg^{-1} (see Somlai et al., 1998). In the present study we find LWC to have Ra$_{\mathrm{eq}}$ values much smaller than this upper bound while the average value for NC in Hong Kong has been found to be close to the recommended limiting value.

3.2. Indoor gamma-dose

The indoor gamma-dose rate contributed from ^{226}Ra, ^{232}Th and ^{40}K was estimated as follows. For a homogeneous distribution of radionuclides inside the building materials, for the calculation of the gamma-dose rate, an indoor environment has been viewed as an air cavity within an infinitely thick medium. According to the suggestions of UNSCEAR (1977), by considering a wall density greater than 50 g cm^{-2} and adopting a factor f of 0.75 to account for no emission from windows and doors (Yu, 1993; Yu et al., 1996a, 1996b), the indoor gamma-dose rate was given by

$$D = 6.41 \times 10^{-2} C_{\mathrm{Ra}} + 9.90 \times 10^{-2} C_{\mathrm{Th}} + 6.45 \times 10^{-3} C_{\mathrm{K}} \quad (1)$$

$$\left(10^{-8}\ \mathrm{Gy\,h^{-1}}\right)$$

From the average concentrations for the radionuclides of ^{226}Ra, ^{232}Th and ^{40}K in NC in Hong Kong mentioned above, the average indoor gamma-dose rate D_{NC} was found to be about 23.8 × 10^{-8} Gy h^{-1}. This was very close to the measured average values of 20.8 × 10^{-8} Gy h^{-1} of Yu et al. (1992a) from a survey of 69 sites and 27.6 × 10^{-8} Gy h^{-1} of Yu et al. (1992b) from a survey of 40 sites.

Table 2
The average radionuclide contents of the cement, sand and granite used for building materials in Hong Kong given by Yu et al. (1992a, 1992b)

	Radionuclide contents (Bq kg^{-1} $\pm\sigma$)		
	^{226}Ra	^{232}Th	^{40}K
Cement	19.2 ± 3.40	18.9 ± 4.00	127 ± 28.1
Sand	24.3 ± 4.90	27.1 ± 3.80	842 ± 521
Granite	202 ± 39.6	140 ± 13.4	1030 ± 175

The values of D_{LWC} for the lime autoclave aerated concrete, PFA autoclave aerated concrete, 'Leca'-concrete and polystyrene-concrete were calculated to be 3.54, 16.9, 8.55 and 3.07 × 10^{-8} Gy h^{-1}, respectively. As expected, all these values were much smaller than the dose for normal concrete, D_{NC}. However, in reality, LWC replaces NC for the partition walls only, so the indoor gamma-dose rate becomes $D = (f_{\mathrm{NC}} D_{\mathrm{NC}} + f_{\mathrm{LWC}} D_{\mathrm{LWC}})/f$, where f_{NC} and f_{LWC} are the factors for non-emission from windows and doors for NC and LWC, respectively. According to the room model for Hong Kong described by Yu et al. (1996a, 1996b), $f_{\mathrm{NC}} = 0.56$ and $f_{\mathrm{LWC}} = 0.19$ (note that $f_{\mathrm{NC}} + f_{\mathrm{LWC}} = f = 0.75$). No data exist for the market percentages of different kinds of LWC, so even shares were assumed in the present study. In this way, $D_{\mathrm{LWC}} \sim 8 \times 10^{-8}$ Gy h^{-1} and $D \sim 19.8 \times 10^{-8}$ Gy h^{-1}. Therefore, a reduction of around 17% of the indoor gamma-dose rate could be achieved by using LWC in partition walls. Using a conversion factor of 0.0613 (mSv per 10^{-8} Gy h^{-1}) (UNSCEAR, 1982) and an occupancy factor of 0.8, the annual effective doses received by a person either in an indoor environment built with NC and one built with partition walls made of LWC could be 1.46 and 1.21 mSv, respectively, being commensurate with a reduction of about 0.25 mSv in the case of use of LWC.

3.3. Rn dose

In a previous laboratory investigation, Yu et al. (1996a, 1996b) showed that all the four types of LWC studied in the present investigation had considerably smaller Rn exhalation rates than those from NC. Unfortunately, most of the measurements of Rn exhalation rates were below the minimum detectable limit (MDL; around 1.3 mBq m^{-2} s^{-1}), and positive detections were obtained only from the PFA autoclave aerated concrete. Therefore, we took recourse to estimates of the Rn exhalation rates of other types of LWC from their ^{226}Ra contents in order to assess the reduction in the Rn dose by using LWC.

From the average Rn exhalation rate of 2.8 ± 0.2 mBq m^{-2} s^{-1} and ^{226}Ra content of 86 Bq kg^{-1} for the PFA autoclave aerated concrete, the Rn exhalation rate per unit concentration of ^{226}Ra was found to be $\varepsilon_{LWC} = 3.3 \times 10^{-2}$ mBq m^{-2} s^{-1} (Bq kg^{-1})$^{-1}$. Without other information, this value was adopted for other types of LWC. The calculated Rn exhalation rates from lime autoclave aerated concrete, 'Leca'-concrete and polystyrene-concrete were thus 0.509, 1.28, and 0.335 mBq m^{-2} s^{-1}, respectively. These values were consistent with the fact that all values were lower than the MDL of around 1.3 mBq m^{-2} s^{-1} (Yu et al., 1996a, 1996b). For reference, the ^{222}Rn exhalation rate from bare concrete was around 13 mBq m^{-2} s^{-1} (Yu et al., 1993).

Yu et al. (1996a, 1996b) employed the room model for dwellings in Hong Kong of Yu (1993) to estimate the reduction in the indoor Rn concentration $\Delta C_{\mathrm{Rn,\,i}}$ (Bq m^{-3}) by using LWC for partition walls as ΔC_{Rn}, i $= 1.26\Delta\varepsilon$, where $\Delta\varepsilon$ (mBq m^{-2} s^{-1}) was the difference between the Rn exhalation rates from NC and LWC surfaces. Assuming even market shares of different types of LWC, $\Delta\varepsilon \sim 11.7$ mBq m^{-2} s^{-1}, so $\Delta C_{\mathrm{Rn,\,i}}$ was calculated as around 14.7 Bq m^{-3}.

In a previous study, Yu et al. (1999) measured the indoor Rn concentrations from 62 dwelling sites with NC walls. From the 17 data within 10 year, the mean Rn concentration of NC sites was 32.8 ± 11.6 Bq m^{-3}. Therefore, the Rn concentration at LWC sites was predicted as about 18.1 Bq m^{-3}. The Rn concentration in an LWC site was, on average, about 55% of that in an NC site, which was significant.

The corresponding annual tracheobronchial (T-B) equivalent doses (mSv y^{-1}) were calculated for different common lung dose models, including the Jacobi–Eisfeld (J–E) model (Jacobi and Eisfeld, 1980), the James–Birchall (J–B) model (James et al., 1980), the James model (James, 1988) and the model of the U.S. National Research Council (NRC) (National Research Council, 1991). For the J–B and J–E models, the formulae for the conversion factors were taken from Ref. (Nuclear Energy Agency, 1983), i.e., ($5.0 + 62f_p$) and ($5.3 + 15f_p$) mGy WLM^{-1}, where f_p is the unattached fraction of the potential alpha energy concentration (PAEC) of radon progeny. One working level (WL) is defined as any combination of short-lived radon progeny in 1 L of air that will result in the emission of 1.3×10^5 MeV of PAEC from radioactive decay of radon progeny, and one working level month (WLM) corresponds to an exposure of 1 WL during the reference working period of one month (170 h per month). For the James model, the tracheobronchial dose ($T_{\mathrm{T-B}}$) was given by James (1988) as

$$T_{\mathrm{T-B}} = f_p D_u + (1 - f_p) D_a \quad (\mathrm{mGy\ WLM^{-1}}) \tag{2}$$

where D_u and D_a were the dose conversion factors for unattached and attached progeny, which were 150 and 7 mGy WLM^{-1}, respectively, for Rn progeny. For the NRC model, Eq. (2) was still valid. The dose conversion factors for Rn progeny for an adult male under light exercise were adopted for comparisons. In particular, factors corresponding to the nasal deposition according to Cheng et al. (1989) and corresponding to an activity median diameter (AMD) of 0.15 μm for attached progeny were used. Under such conditions, D_u and D_a were 80.9 and 7.86 mGy WLM^{-1}, respectively.

The average equilibrium factor, F, of 0.21 and unattached fraction of 0.13 (Yu et al., 1996a) were employed in all the calculations. With an indoor occupancy factor of 0.8 and a tissue weighting factor of 0.06 for the T–B region, the dose conversion factors for the models of J–E, J–B, James and NRC became 0.0203, 0.0365, 0.0716 and 0.0485 mSv y^{-1} per Bq m^{-3}, which transformed to reductions in the T–B dose of 0.51, 0.28, 1.00 and 0.68 mSv y^{-1} for the observed reduction in RC of ~14 Bq m^{-3} by using LWC. Therefore, a person living at a site with LWC as partition walls receives an average annual equivalent dose smaller than that incurred by a person living at a site with NC only, by an amount as large as 1 mSv when using the James model, the latter being a significant reduction in annual dose. It is concluded that using LWC for partition walls can be a simple and economical way to reduce the indoor Rn concentrations and the corresponding radiation dose from Rn.

4. Conclusions

Four types of light weight concrete (LWC) commonly used in Hong Kong, namely, autoclave aerated concrete (plus lime), autoclave aerated concrete (plus Pulverized Fuel Ash or PFA), concrete with synthetic aggregate 'Leca' and concrete with polystyrene bean as aggregate were measured for their radionuclide contnets of ^{226}Ra, ^{232}Th and ^{40}K using high-resolution gamma spectrometry. All the radionuclide contents except those for the PFA autoclave aerated concrete were below the world averages of building materials: (^{226}Ra: 50 Bq kg^{-1}, ^{232}Th: 50 Bq kg^{-1}, ^{40}K: 500 Bq kg^{-1}) (UNSCEAR, 1993). The ^{226}Ra and ^{232}Th contents of the PFA autoclave aerated concrete, 86.0 ± 1.98 and 109 ± 4.26, were much higher than the world averages.

The average concentrations for the radionuclides of

^{226}Ra, ^{232}Th and ^{40}K in normal concrete (NC) were estimated to be about 133, 96 and 897 Bq kg^{-1}. The values were much higher than the world averages of building materials, but the ^{232}Th concentration was still lower than that of the PFA autoclave aerated concrete (109 Bq kg^{-1}). The Ra-equivalents (Ra$_{eq}$, in Bq kg^{-1}) for NC, lime autoclave aerated concrete, PFA autoclave aerated concrete, 'Leca'-concrete and polystyrene-concrete were 340, 49.6, 249, 122 and 44.2 Bq kg^{-1}, respectively. All LWC had Ra$_{eq}$ values much smaller than the suggested upper limit of 370 Bq kg^{-1} for construction materials for dwellings, while the average value for NC in Hong Kong was close to this upper-bound.

The average gamma-dose rate for an indoor environment built with NC was estimated to be about 24×10^{-8} Gy h^{-1}, which was very close to the measured average values. Assuming even market shares of different types of LWC, the gamma-dose rate for an indoor environment with partition walls built with LWC, was estimated to be about 20×10^{-8} Gy h^{-1}. Therefore, a reduction of around 17% of the indoor gamma-dose rate could be achieved by using LWC in partition walls compared to use of NC. The corresponding reduction in annual effective dose is estimated to be about 0.25 mSv.

The Rn exhalation rate of PFA autoclave aerated concrete was previously measured to be 2.8 ± 0.2 mBq m^{-2} s^{-1} (Yu et al., 1996a, 1996b), from which the Rn exhalation rate per unit concentration of ^{226}Ra could be calculated as $\varepsilon_{\mathrm{LWC}} = 3.3 \times 10^{-2}$ mBq m^{-2} s^{-1} (Bq kg^{-1})$^{-1}$. Adopting this value for other types of LWC, the Rn exhalation rates from lime autoclave aerated concrete, 'Leca'-concrete and polystyrene-concrete were calculated as 0.509, 1.28, and 0.335 mBq m^{-2} s^{-1}, respectively, being consistent with the fact that all values were lower than the MDL of around 1.3 mBq m^{-2} s^{-1} (Yu et al., 1996a, 1996b).

The reduction in the indoor Rn concentration by using LWC instead of NC for partition walls has been estimated to be around 14 Bq m^{-3}, which corresponds to reductions of 0.51, 0.28, 1.00 and 0.68 mSv y^{-1} in the tracheobronchial dose by using the Jacobi–Eisfeld model, James–Birchall model, James model and the model of National Research Council, respectively.

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