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EFFECTS OF USING LIGHT-WEIGHT CONCRETE ON INDOOR RADON CONCENTRATION IN HIGH-RISE BUILDINGS

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Abstract — Light-weight concrete (LWC) (or drywall construction) has been used for partition walls in public housing in Hong Kong for about 10 years. A previous laboratory investigation showed that all types of LWC had considerably smaller Rn exhalation rates than those from normal concrete (NC), and could thus theoretically reduce the indoor Rn concentrations and the corresponding radiation dose from Rn. In the present investigation, a survey of Rn exhalation rates and indoor Rn concentrations at 39 dwelling sites built using LWC were carried out using charcoal canisters and γ-spectroscopy. The mean Rn exhalation rate and the mean Rn concentration were around 1.6 mBq.s^{-1}.m^{-2} and 19 Bq.m^{-3}, respectively, which were significantly smaller than the corresponding values of 12 mBq.s^{-1}.m^{-2} and 33 Bq.m^{-3} for NC sites. The statistical t-test showed that both the mean Rn exhalation rate and the mean Rn concentration for NC and LWC sites walls were different at the 100% confidence level. The Rn exhalation rate from an LWC surface was, on average, only about 14% of that from an NC surface, while the Rn concentration in an LWC site was, on average, about 58% of that in an NC site, which were significant. A person living at an LWC site receives an average annual equivalent dose smaller than one living at an NC site by an amount as large as 1 mSv. Therefore, the use of LWC for partition walls can be a simple and economical way to reduce the indoor Rn concentrations and the corresponding radiation dose from Rn. Furthermore, the mean Rn concentration theoretically predicted from the mean Rn exhalation rate agreed excellently with that from measurements.

INTRODUCTION

It is now established that the tracheobronchial deposition of radon progeny in the human body can lead to lung cancers. Large-scale case–control studies of indoor radon and lung cancer have been carried out(1–9). The two case–control radon studies in China(1,8) showed significantly higher radon concentrations than those in Hong Kong(10): the one for Sheyang in China recorded a median radon concentration of 85 Bq.m^{-3} and 20% above the concentration of 148 Bq.m^{-3}(1), the one for Gansu recorded a mean radon concentration of 198 Bq.m^{-3} and 64% above the concentration of 148 Bq.m^{-3}(8) while the one for Hong Kong recorded a mean radon concentration of 27 Bq.m^{-3} and none above the concentration of 148 Bq.m^{-3}(10).

Most of the buildings in Hong Kong are high rise, and people seldom work or live on the ground floor, so the main contribution to indoor concentrations of ^{222}Rn (referred to as Rn in the rest of this paper) in Hong Kong should come from the concrete used as the building materials.

Light-weight concrete (LWC) (or drywall construction) was introduced for use for partition walls in public housing in Hong Kong about ten years ago. LWC has an air-dry density below 1850 kg.m^{-3}(11) as compared to 2350 kg.m^{-3} of normal concrete (NC). LWC can be classified broadly into three major groups by the method of production; they are aerated concrete, no-fine concrete and light-weight aggregate concrete. Aerated concrete is obtained by introducing foam bubbles inside the cement matrix or the sand cement grout. In Europe, it is also called ‘gas concrete’. By varying the foam–cement–sand ratio, concrete densities ranging from 300 to 1600 kg.m^{-3} can be obtained. No-fine concrete, as its name implies, is concrete without any fine aggregate. By eliminating the fine particles of size less than 5 mm, voids are created within the cement matrix which reduce the concrete density and provide insulating properties but still retain considerable compressive strength. Light-weight aggregates employed in LWC have a wide range of sources which can be natural materials, processed natural materials or synthetic substance from processed by-products or environmental wastes.

LWC finds a wide range of applications, from insulation to structural applications. However, in Hong Kong, it is limited to the non-structural use in non-load bearing partition walls. As LWC does not contain the crushed granite for NC, which has been found to be the main source of Rn(12), its Rn exhalation properties should be very different from that of the NC. Five types of LWC materials were used in Hong Kong, namely, autoclave aerated concrete (plus lime), autoclave aerated concrete (plus Pulverized Fuel Ash or PFA), concrete with synthetic aggregate ‘Leca’, concrete with polystyrene bean as aggregate, and concrete with wood fibre as aggregate (plus PFA). In a previous laboratory investigation, Yu *et al*(13) showed that all these LWC had considerably smaller Rn exhalation rates than those from NC, and could thus reduce the indoor Rn concentrations and the corresponding radiation dose from Rn.

In the present investigation, the objective is to assess the reduction of Rn exhalation rates and indoor Rn concentrations in realistic situations where LWC is used. A survey of Rn exhalation rates and indoor Rn concentrations at 39 dwelling sites built using LWC were carried out from August to November 1998, and the results were compared with those for dwelling sites built using NC.

METHODOLOGY

The standardised charcoal canisters with diameters of 10.16 cm and weights of 70 g, and the measurement system recommended by the US EPA (Environmental Protection Agency) and in the EERF (Eastern Environmental Radiation Facility) were employed for measurement of the indoor Rn concentration. The methodology was developed by Cohen and Cohen(14) and George(15). There are two reasons behind the use of the short-time charcoal canister method instead of the long-term track etching technique, namely, detailed data available for comparisons were also collected using the charcoal canister method(10,16), and the ^{220}Rn concentrations recorded for indoor environments in Hong Kong were high(10) and ^{220}Rn could influence ^{222}Rn measurements with the track etching technique(17). The reproducibility and accuracy of the detectors were checked periodically through comparisons of readings among the detectors, calibrations in radon chambers and intercomparison programmes.

The exposed charcoal canisters were placed at least 1 m from the walls, ceiling and the floor and were away from windows and doors. The exposure time was 2 to 3 d. After sampling, the exposed charcoal canisters were sealed and stored for at least 3 h for the Rn decay to reach equilibrium, and were then measured by using the NaI(Tl) gamma spectrometer. The Rn concentration was deduced from the total counts in the region containing the three characteristic peaks of the Rn progeny (295 keV and 352 keV γ rays from ^{214}Pb and 609 keV γ rays from ^{214}Bi). The measurement time was 10 min. The measurement system was calibrated using a standard canister spiked with a known activity of ^{226}Ra and sealed permanently. The background count in the region containing the three characteristic peaks was around 300 cpm. For a measurement time of 10 min, the minimum detection limit (MDL) represented by 3σ of the background was around 11 Bq.m^{-3}.

The measurements of Rn exhalation from concrete surfaces used the same standardised charcoal canisters and measuring system of a NaI(Tl) gamma spectrometer, the same region containing the three characteristic peaks, and the exposure and measurement duration. Details of the method were described in Reference 16. For exposure, the charcoal canisters were sealed with silicone sealer against the surfaces of partition walls built with LWC to stop air leakage. After sampling, the exposed charcoal canisters were removed from the surface, sealed, and stored for at least 3 h for the Rn decay to reach equilibrium. The Rn activities inside the canisters were again determined by counting the gamma ray photons in the region containing the three characteristic peaks of the Rn progeny. For a measurement time of 10 min, the minimum detection limit (MDL) represented by 3σ of the background was around 1 mBq.s^{-1}.m^{-2}.

RESULTS AND DISCUSSION

The measured Rn exhalation rates and the Rn concentrations for the 39 dwelling sites are shown in Table 1, together with the building ages (A). It can be seen that there are values (bound values) of Rn exhalation rates and Rn concentrations which are less than the respective MDLs. There are no standard ways to treat these bound values when the mean value and the standard deviation are to be obtained. Here we calculated the means and standard deviations with two different treatments of these bound values, i.e. in method (A) taking the MDL values to be the bound values (which inevitably led to an overestimation of the means), and in method (B) taking half the MDL values to be the bound values. The mean Rn exhalation rate and the mean Rn concentration ($\pm$1 SD) for the data for all the 39 dwelling sites were 1.7 ± 0.9 mBq.s^{-1}.m^{-2} and 20 ± 11 Bq.m^{-3}, respectively, using method (A), and were 1.6 ± 1.0 mBq.s^{-1}.m^{-2} and 18 ± 13 Bq.m^{-3}, respectively, using method (B).

Yu *et al*(16) measured the Rn exhalation rates from NC walls at 32 sites in a similar period of the year (October to December compared to August to November in the present study), with the building ages ranging between 0.4 and 31 y. The distribution of Rn exhalation rates with building ages is shown in Figure 1. The Rn exhalation rates from surfaces of LWC walls measured in the present study are also plotted in Figure 1, and it is clear that these values are significantly lower than those of NC walls. For a quantitative analysis, we only concentrate on sites with ages less than 10 y, since LWC was introduced in public housing in Hong Kong only about 10 y ago. From the 14 data within 10 y, the mean Rn exhalation rate ($\pm$1 SD) from surfaces of NC walls was 12 ± 10 mBq.s^{-1}.m^{-2}. The statistical t-test thus showed that the mean Rn exhalation rate from surfaces of NC and LWC walls were different at the 100% confidence level regardless of the use of results from method (A) or method (B). The Rn exhalation rate from an LWC surface was, on average, only about 14% of that from an NC surface.

In a previous laboratory investigation(13), Yu *et al* showed that all the five types of LWC used in Hong Kong had considerably smaller Rn exhalation rates than those from NC. The present results were largely consistent with the previous findings. In the laboratory investigation, most of the measurements of Rn exhalation rates were below the MDL (around 1.3 mBq.s^{-1}.m^{-2}), and positive detections were obtained only from the LWC with pulverised fuel ash (PFA) as a component of the raw materials. Whether these PFA–LWC materials dominate in Hong Kong remains a question for future studies.

In a previous study[10], Yu *et al* measured the indoor Rn concentrations from 62 dwelling sites with NC walls using similar charcoal canisters modified for active measurements in a similar period of the year (July to December compared to August to November in the present study). The building ages ranged between 3 and 32 y. The distribution of Rn concentrations with building ages is shown in Figure 2. The Rn concentrations from the dwelling sites with LWC walls measured in the present study are also plotted in Figure 2, and it is also clear that these values are significantly lower than those of NC sites. From the 17 data within 10 y, the mean Rn concentration ($\pm$1 SD) of NC sites was 33 $\pm$ 12 Bq.m^{-3}. The statistical t-test thus showed that the mean Rn concentration of NC and LWC dwelling sites were different at the 100% confidence level regardless of the use of results from method (A) or method (B). The Rn concentration in an LWC site was, on average, about 58% 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

Table 1. Rn exhalation rates and Rn concentrations for the 39 dwelling sites, with their average hours of natural ventilation and building ages.

Average number of hours of natural ventilation	Age of building (y)	Rn exhalation rate (mBq.s^{-1}.m^{-2})	Rn concentration (Bq.m^{-3})
0	4	4.9 ± 1.1	<11
0	9	<1.1	11 ± 7
0	9	<1.1	15 ± 7
0	3	2.5 ± 1.0	22 ± 12
0	5	1.4 ± 1.1	26 ± 7
0	8	<1.1	30 ± 6
0	10	<1.1	33 ± 7
0	5	1.3 ± 1.1	33 ± 7
0	5	1.4 ± 1.1	37 ± 8
0	5	1.6 ± 1.0	41 ± 12
0	1.25	1.8 ± 1.0	41 ± 12
0	7	<1.1	59 ± 10
12	5	2.2 ± 1.1	26 ± 6
15	10	<1.1	15 ± 10
16	3	2.5 ± 1.0	22 ± 11
16	3	2.5 ± 1.1	22 ± 13
17	3	2.1 ± 1.0	<10
17	10	<1.2	15 ± 12
17	4	2.2 ± 1.0	26 ± 12
19	3	2.6 ± 1.0	15 ± 9
20	6	1.4 ± 1.1	<8.4
20	3	1.4 ± 1.0	19 ± 10
21	4.5	1.4 ± 1.0	22 ± 12
22	4	4.5 ± 1.0	15 ± 10
24	8	<1.1	<6.4
24	10	<1.1	7.4 ± 6.1
24	2	1.6 ± 1.0	<9.5
24	10	<1.1	<9.6
24	4.5	1.5 ± 1.0	<10
24	1	1.5 ± 1.1	<11
24	7	<1.1	<11
24	2	1.5 ± 1.1	<11
24	2	1.7 ± 1.0	11 ± 7
24	2	1.7 ± 1.0	11 ± 8
24	3	1.3 ± 1.1	<12
24	4	2.5 ± 1.0	19 ± 11
24	2	1.9 ± 1.0	22 ± 9
24	10	<1.1	22 ± 8
24	5	1.1 ± 1.1	26 ± 9

(J-E) model[18], the James–Birchall (J-B) model[19], the James model[20] and the model of National Research Council (NRC model)[21]. For the J-B and J-E models, the formulae for the conversion factors were taken from Reference 22, i.e. $(5.0 + 62f_p)$ and $(5.3 + 15f_p)$ mGy.WLM^{-1}, where f_p is the unattached fraction of the PAEC. For the James model, the tracheobronchial dose (T_{T-B}) was given in Reference 20 as

$$T_{T-B} = f_pD_u + (1-f_p)D_a \qquad (mGy.WLM^{-1}) \qquad (1)$$

where D_u and D_a are the dose conversion factors for unattached and attached Rn progeny, 150 and 7 mGy.WLM^{-1} respectively. For the NRC model, Equation 1 is still valid. The dose conversion factors for Rn progeny for an adult male under light exercise have been adopted for comparison. In particular, factors corresponding to the nasal deposition according to Cheng *et al*[23] and corresponding to an AMD of 0.15 μm for attached progeny have been used. Under such conditions, D_u and D_a are 80.9 and 7.86 mGy.WLM^{-1}, respectively.

The average equilibrium factor of 0.21 and unattached fraction of 0.13[24] have been employed in all the calculations. With an indoor occupancy factor of 0.8 and the 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 0.020, 0.037, 0.072 and 0.049 mSv.y^{-1} per Bq.m^{-3}, which transformed to reductions in the T-B dose of 0.51, 0.28, 1.0 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 one living at a site with NC only by an amount as large as 1 mSv when using the James model, which is a significant value. 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.

Since only the partition walls are made of LWC, and factors other than Rn exhalation could affect the indoor Rn concentration, the reduction in the Rn concentration was not as drastic as that in the Rn exhalation.

For calculation purposes, Yu *et al*[13] employed the room model for dwellings in Hong Kong of Reference 25 to estimate the reduction in the indoor Rn concentration $\Delta C_{Rn,i}$ (Bq.m^{-3}) by using LWC as $\Delta C_{Rn,i} = 1.26\Delta\epsilon$, where $\Delta\epsilon$ (mBq.s^{-1}.m^{-2}) was the difference between the Rn exhalation rates from NC and LWC surfaces. From the present results, $\Delta\epsilon$ is ~10 mBq.s^{-1}.m^{-2}, so $\Delta C_{Rn,i}$ is ~13 Bq.m^{-3} and the Rn concentration at LWC sites was predicted as about 20 Bq.m^{-3}, which was in excellent agreement with the present measured values of 20 ± 11 Bq.m^{-3} using method (A) and 18 ± 13 Bq.m^{-3} using method (B).

CONCLUSIONS

(1) A survey of Rn exhalation rates and indoor Rn concentrations at 39 dwelling sites built using LWC were carried out from August to November 1998 using charcoal canisters and γ spectroscopy. The mean Rn exhalation rate and the mean Rn concentration (±1 SD) for all the 39 dwelling sites were 1.7 ± 0.9 mBq.s^{-1}.m^{-2} and 20 ± 11 Bq.m^{-3}, respectively, using method (A) of analysis, and were 1.6 ± 1.0 mBq.s^{-1}.m^{-2} and 18 ± 13 Bq.m^{-3}, respectively, using method (B) of analysis.

(2) From the data in Reference 16 for normal concrete (NC) with ages below 10 y, the mean Rn exhalation rate (±1 SD) from surfaces of NC walls was 12 ± 10 mBq.s^{-1}.m^{-2}. The statistical t-test showed that the mean Rn exhalation rate from surfaces of NC and LWC walls were different at 100% confidence level. The Rn exhalation rate from an LWC

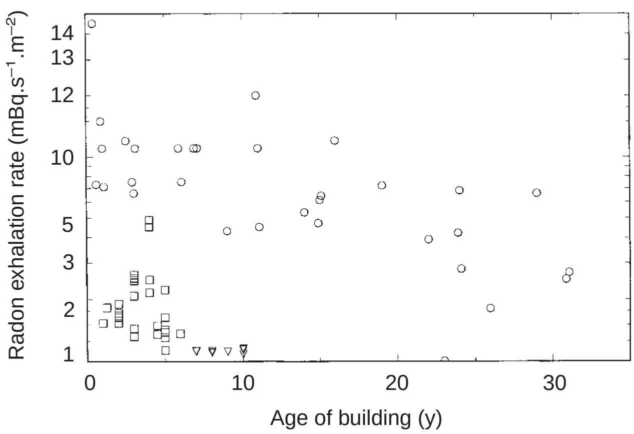

Figure 1. The distribution of Rn exhalation rates with age of buildings. (□) surfaces of LWC walls, (▽) surfaces of LWC walls (upper limits), (○) surfaces of NC walls (from Reference 16).

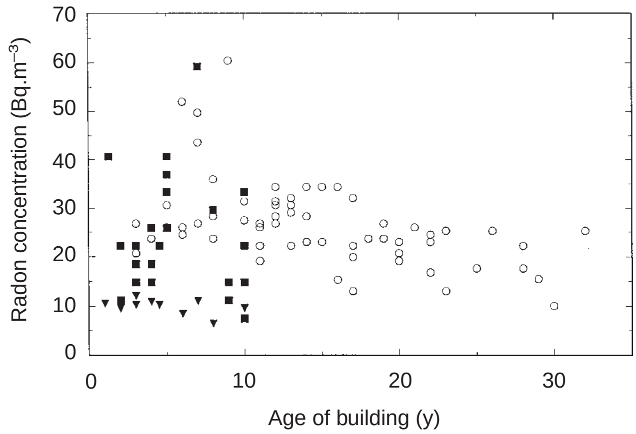

Figure 2. The distribution of Rn concentrations with age of buildings. (■) sites with LWC walls, (▼) sites with LWC walls (upper limits), (○) sites with NC walls only (from Reference 10).

surface was, on average, only about 14% of that from an NC surface.

(3) From the data in Reference 10 for dwelling sites with NC walls with ages below 10 y, the mean Rn concentration (±1 SD) was 33 ± 12 $Bq.m^{-3}$. The statistical t-test showed that the mean Rn concentration of NC and LWC dwelling sites were different at 100% confidence level. The Rn concentration in an LWC site was, on average, about 58% of that in an NC site, which is significant.

(4) The annual tracheobronchial equivalent doses from Rn were calculated with different common lung dose models. It was found that a person living at a site with LWC as partition walls receives an average annual equivalent dose 1 mSv lower than one living at a site with NC when using the James model, which is a significant value. 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.

(5) The mean Rn concentration theoretically predicted from the mean Rn exhalation rate agreed excellently with that from measurements.

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