RADON EMANATION OF BUILDING MATERIAL—IMPACT OF BACK DIFFUSION AND DIFFERENCE BETWEEN ONE-DIMENSIONAL AND THREE-DIMENSIONAL TESTS

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Abstract—**Small-scale chamber experiments were conducted to investigate the radon emanation rates of commonly used building materials such as bare concrete, granite, red brick, and sand brick. It has been found that back diffusion caused by the accumulation of radon in the indoor environment has significant influence on the radon emanation rate. The radon emanation rate can be expressed as the summation of an initial emanation rate and the product of a specific back diffusion coefficient and the indoor radon level. In some occasions the radon emanation rate can be significantly lower than its initial value. A database was developed summarizing results from 26 samples. The influence of relative humidity on the radon emanation characteristics has also been discussed. Separate tests were done by coating the four sides of the building material with silicone gel to simulate a one-dimensional radon diffusion geometry. The results show that a factor has to be included when the three-dimensional test results are used to describe one-dimensional geometry, such as radon emanation from building wall surfaces.**

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Key words: radon; diffusion; air sampling; contamination

INTRODUCTION

RADON IS considered as one of the major contributors to indoor air pollution that imposes significant health hazard to building occupants. Building services engineers are concerned with the impact of different types of building materials on radon gas accumulation in the indoor environment. In Asian cities where high rise buildings dominate the building sector, contribution from building material to radon pollution has been documented. Their experience is different from European countries or the United States where buildings are mainly low rise. Radon pollution in Hong Kong has been related to high radon emanation rates from building materials, especially materials from China where the soil radium content has been found to be high. Many papers have been published on radon emanation rates of commonly used building materials. Radon emanation rate studies have been conducted in many other countries, as well as in Hong Kong, covering a very wide range of building materials, especially concrete products. Early data published by UNSCEAR (1977) reported a range of 0.52–2.86 Bq m^{-2} h^{-1} for concrete used in the U.S. and in other European countries. Stranden et al. (1984) reported a range of 0.08–0.21 Bq m^{-2} h^{-1} for brick and a mean of 0.50 Bq m^{-2} h^{-1} for sand products used in European countries. Dijk and Jong (1991) reported a range of 1.51–6.2 Bq m^{-2} h^{-1} for concrete and a mean of 0.29 Bq m^{-2} h^{-1} for brick used in European countries. Measurement results from another Asian city (Taiwan) showed a range of 0.0756–10.26 Bq m^{-2} h^{-1} for granite, a range of 0.216–0.576 Bq m^{-2} h^{-1} for concrete, and a range of 0.0936–0.126 Bq m^{-2} h^{-1} for red brick (Chen et al. 1993).

Similar tests have also been conducted by other researchers in Hong Kong, and relatively higher radon emanation rates were measured. Tso et al. (1994) showed that the radon emanation rate for red brick was around 9 Bq m^{-2} h^{-1} and that for concrete was 12.96 Bq m^{-2} h^{-1}. Much higher radon emanation rates were reported by Yu et al. (1996) showing a range of 18–30 Bq m^{-2} h^{-1} for concrete block (samples with Ordinary Portland Cement and PFA).

Very few studies have considered the effect of back diffusion on radon emanation rate. Molecular diffusion has been regarded as the main mechanism in radon transport. The transport mechanism can be expressed in terms of Fick's Laws for mass transfer, including the effect of the material porosity and radon generation rate inside the material due to the radium content. Radon emanation rate is proportional to the gradient of the radon level at the surface of the material, specified by the appropriate boundary conditions. One dimensional solution has been widely used in theoretical treatments. Back diffusion is caused by the accumulation of radon-laden air in the indoor environment and has been found to have strong impact on the radon emanation characteristics of building materials, as expressed by the one-dimensional

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solution of the mass diffusion equations. However, very few experimental data have been found to verify the influence of back diffusion on radon emanation rate. Chao et al. (1997) macroscopically investigated the radon emission and back diffusion effect of building materials using a small chamber test method. Maraziotis (1996) used diffusion-based equations to study the behavior of radon recoil and diffusion processes inside the materials. Detailed investigation of the influence of back diffusion characteristics on the radon emanation rate of building material forms the main objective of this paper. The building materials tested in this study are concrete, sand brick, red brick, and granite. Concrete is commonly used as building construction in Hong Kong. It is estimated that concrete contributes to about 80% of the construction materials used in Hong Kong by weight. Red brick and sand brick are popular in some construction work even though the fire resistance of them are not as strong as that of concrete. Granite is commonly used as a decorative material in buildings, and it is estimated that it contributes to about 1% by weight in the construction industry. However, the relatively high radon emanation rate from granite has been a concern to the industry recently. The paper also compares the difference between radon emanation from a three dimensional configuration and a one-dimensional configuration. Here the one-dimensional configuration refers to the test specimen being coated at four sides and radon can only diffuse in the axial direction. For the three-dimensional configuration, no coating is applied on the test specimen and radon gas can diffuse in all directions.

EXPERIMENTAL SET UP AND THEORETICAL APPROACH

Experiments have been conducted using the closed chamber approach developed by Chao et al. (1997). Small impervious PVC containers of volume 14,900 mL were used in the experiments. A schematic diagram of the chamber is shown in Fig. 1. Each chamber was equipped with temperature and humidity sensors‡ and a small 12 V DC circulation fan (7 cm diameter and 4 blade) for mixing purpose. The inlet and outlet were located on top of the chamber lid. The inlet tube was extended down to the bottom of the chamber to provide better circulation and mixing. In order to minimize gas leakage, epoxy§ was applied around the hose connection points on the chamber. A gasket was also wrapped around the rim of the chamber and was inserted between the lid and the main body of the chamber to reduce leakage.

Before starting the measurements the chambers were purged by nitrogen gas with a flow rate of 4 L min^{-1} for more than 20 min. The radon level inside each chamber was close to zero before the test. Small contain-

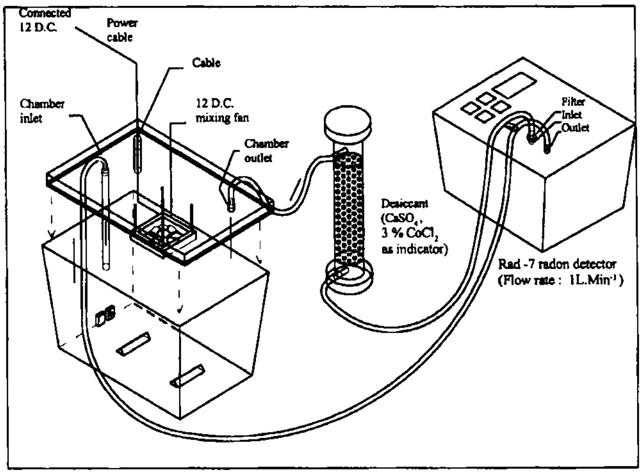

Fig. 1. Experimental setup of the chamber test.

ers filled with water with different air/water interface areas were placed in each chamber to control the relative humidity inside the test environment. The water content in the chamber depends on the balance between the vapor emission from the water surface and the absorption ability of the desiccant, which was fairly constant over the measurement period. It has been found that throughout our measurement period the fluctuation was around 3%.

All the samples were placed in another PVC container at the right relative humidity condition for 1 wk before they were put into the chambers for radon measurement. During measurement, the samples were mounted on two metal bars with triangular cross sections inside the chamber (Fig. 1) so that the contact areas between the supporting metal bars and the samples were negligible. The solid state radon detector, Niton Rad7,‖ was used in this study. The Rad7 detector pulls samples of air through a fine inlet filter into a chamber for analysis. The filtered air decays inside the detector's chamber producing detectable alpha emitting progeny, particularly the polonium isotopes. The solid state detector converts alpha radiation directly to an electrical signal using an alpha spectrometry technique that is able to distinguish radon from thoron and signal from noise. The detector is sent back to the manufacturer for calibration twice every year. The calibration procedure is carried out in a well-controlled environmental chamber and the reading is compared to a master instrument. Overall calibration accuracy of the detector is 5% based on a sensitivity of 0.4 counts min^{-1} pC_i L^{-1}. Range of the monitor is from 0.1–5,000 pC_i L^{-1}. There has been some concern about dissolution of the radon into the PVC and that may serve as a reservoir of radon. In a previous study that used the same PVC chamber, Chao et al. (1997) compared the results from leakage tests to a simple

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§ ARALDITE™, Ciba Polymers Duxford, Cambridge CB2 4QA, England.

‖ Niton Rad7, Niton Electronic, 74 Loomis Street, P.O. Box 368, Bedford, MA 01730-0368.

material balance model. The results showed that the dissolution of radon into the PVC is negligible compared to leakage from the chamber. Leakage tests are described later in this paper.

In the measurement, the detectors were used to continuously monitor the radon levels inside the radon chambers. The data collection rate in the tests was set to one per hour. Drying desiccant was used to reduce the water content of the air before going into the RAD7 monitor. An intermittent sampling mode was used in the sampling procedure, and throughout the measurement period the desiccant was saturated with water. No desiccant replacement was needed during the measurement period. In the measurement, the building materials were left inside the chamber for more than 100 h in order to show the growth of the radon concentrations.

The mass balance equation describing the radon concentration inside the chamber can be expressed as follows:

$$\frac{dC}{dt} = -\lambda C - DC + \frac{E_o A}{V} + \frac{q(C_o - C)}{V}, \qquad (1)$$

where D is defined as the back diffusion rate. This back diffusion rate is different from the mass diffusion coefficient for transport of radon gas inside the pore of the building material.

Eqn (1) can also be written in another way:

$$\frac{dC}{dt} = -\lambda C + \frac{(E_o - \alpha C)A}{V} + \frac{q(C_o - C)}{V}, \qquad (2)$$

where α is called the specific back diffusion coefficient.

Eqn (2) implies that the radon emanation rate can be expressed as

$$E = E_o - \alpha C. \qquad (3)$$

With this arrangement the radon emanation rate is assumed to be reduced linearly with the accumulation of radon in air. Eqn (3) comes from the solution of the following set of steady state mass diffusion equations for the geometry as shown in Fig. 2:

$$\frac{D_r}{\varepsilon}\frac{d^2C_B}{dz^2} - \lambda C_B + \phi = 0, \qquad (4)$$

with boundary conditions

$$C_B(z = 0) = C_{B1} \qquad C_B(z = L) = C_{B2}. \qquad (5)$$

D_r in eqn (4) is the mass diffusion coefficient of radon gas inside the pore of the material, which depends on pressure and temperature.

The radon emanation rate can be expressed in terms of the radon concentration gradient at the material surface:

$$E = -D_r \frac{dC_B(z)}{dz_{z=0 \text{ or } L}} \qquad (6)$$

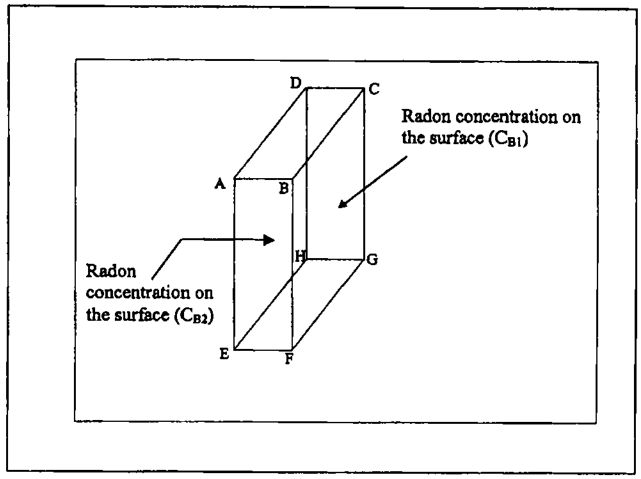

Fig. 2. The building material in radon chamber.

If $C_{Bi} = C_{B2} = C$, we have

$$E = \frac{\varepsilon\lambda l}{5}\left(\frac{\phi}{\lambda} - C\right). \qquad (7)$$

Comparing eqn (7) to eqn (3), the following expression is obtained:

$$E_o = \frac{\varepsilon l \phi}{5} \qquad (8)$$

The radon generation rate ϕ depends on the radium content of the material. More specifically, the radon generation rate should only include the portion of the radon gas that is kept in the pore of the material; otherwise the gas finds no way to diffuse into the air and does not contribute to the radon emanation rate from the material surface. The diffusion length $l=\sqrt{D_r/\lambda\varepsilon}$ depends on the porosity and mass diffusion coefficient of radon gas inside the material. Eqns (4)–(9) provide the mathematical foundation for eqn (3). It should be noted that the specific back diffusion coefficient represents an adjustment to the radon emanation rate due to variation of the boundary condition (eqn 5). With an increase of radon level in the indoor air, the radon concentration gradient between the interior of the material and the air is reduced. This leads to a decrease of the radon emanation rate as shown by eqn (7), which has the same form as eqn (3). The concentration C used in eqn (3) should be the radon gas concentration at the interface of the material and the air. However, due to lack of information of the interfacial radon level, C is assumed to be the radon level in air in our discussion.

In eqn (1), q/V is the leakage rate of the chamber. Leakage tests have been conducted using a tracer gas to quantify this value. Radon gas was used as tracer in the chamber leakage measurements. In the leakage test, a granite sample with high radon emanation rate was used so that the equilibrium radon level inside the chamber was around 4,000 Bq m^{-3}. Then the granite was taken out and the radon gas inside the chamber was allowed to undergo natural decay. The leakage rate of the chamber can be obtained based on the mass balance between chamber air and radon in the laboratory, which was monitored simultaneously by another monitor (Chao et al. 1997). In the experiments all chambers showed a leakage rate less than 0.002 air change per hour (ACH). In the study 26 samples of granite (11 samples), concrete (5 samples), red brick (5 samples), and sand brick (5 samples) were tested. Each material was tested twice in two different relative humidity conditions (30% and 90%). The dimensions of the concrete block, granite, sand brick, and red brick samples were were 21 cm×10 cm×6 cm (total emanation area 792 cm^2), 25 cm×8 cm×2 cm (total emanation area 532 cm^2), 21 cm×10 cm×6 cm (total emanation area 792 cm^2), and 21 cm×10 cm×6 cm (total emanation area 792 cm^2), respectively. Examples of the radon build up inside the chamber are shown in Figs. 3 and 4.

E_0 and α in eqn (2) were found by using the equilibrium radon level inside the chamber and the initial slope of the radon build up curve. Assuming q is constant and integrating eqn (1), the concentration of radon inside the chamber can be found as a function of time. The initial slope of the radon build up curve is found to be

$$\alpha = \frac{\varepsilon \lambda l}{5} \tag{9}$$

From eqn (10), the initial slope of the radon build up curve inside the chamber is measured and E_0 can be found. Once E_0 is identified, eqn (1) can be used to find D by putting the time derivative term to zero. α is evaluated using the expression $\alpha A/V = D$. From Figs. 3 and 4, it is found that the theoretical approach including the back diffusion effect agreed well with the experimental data.

RESULTS

A summary of the initial radon emanation rates E_0 and specific back diffusion coefficients α of the test

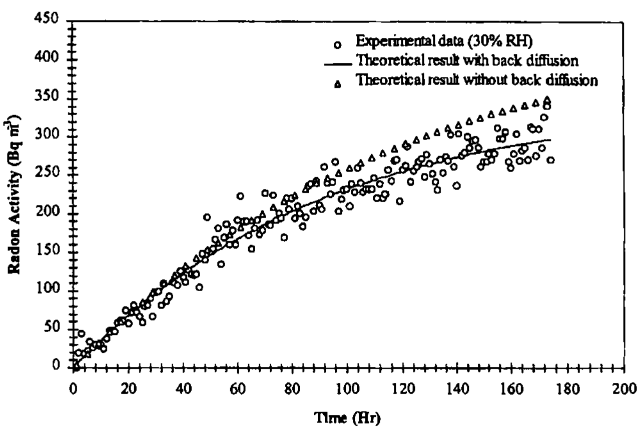

Fig. 3. Growth of radon level inside the test chamber (sand brick sample B at 30% relative humidity).

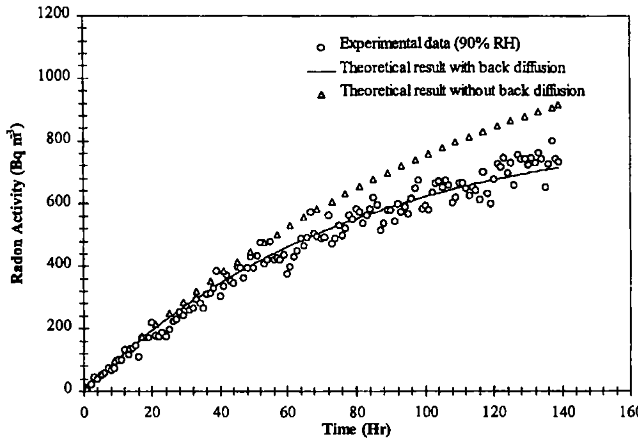

Fig. 4. Growth of radon level inside the test chamber (sand brick sample B at 90% relative humidity).

samples are shown in Table 1 for red brick, concrete, sand brick, and granite.

For red brick, the radon emanation rates did not vary too much. The average radon emanation rate at 30% relative humidity was 0.16 Bq m^{-2} h^{-1} and at 90% relative humidity was 0.44 Bq m^{-2} h^{-1}. For concrete, a significant variation in radon emanation rate was observed among the samples. No big difference was seen between low relative humidity case and high humidity case. The average emanation rates across all samples were 4.43 Bq m^{-2} h^{-1} and 4.42 Bq m^{-2} h^{-1} for 30% relative humidity and 90% relative humidity, respectively. Except for one sand brick sample, which showed a relatively higher radon emanation rate, the other four materials had similar radon emanation rates. The averages were 0.67 Bq m^{-2} h^{-1} and 1.64 Bq m^{-2} h^{-1} for 30% relative humidity and 90% relative humidity, respectively. Eleven samples of granite block (five green granite samples and six red granite samples) were tested and the variation was significant. The radon emanation rates varied from 0.38 to 13.44 Bq m^{-2} h^{-1}. The green granites showed an average of 0.56 Bq m^{-2} h^{-1} and 0.14 Bq m^{-2} h^{-1} at 30% relative humidity and 90% relative humidity, respectively. For red granite, the averages were 0.76 Bq m^{-2} h^{-1} and 0.97 m^{-2} h^{-1} at corresponding humidities. The highest radon emanation rates were found for a red granite sample with a shining element embedded inside. The large variation in radon emanation rates among the granite samples was probably due to their radium content. Detailed information of the material radium content can be obtained by gamma spectrum and chemical analysis. For this red granite sample, radon emanation rates were 13.44 Bq m^{-2} h^{-1} and 5.18 Bq m^{-2} h^{-1} for the two relative humidity cases. Back diffusion coefficients are also reported in the table and the variation seemed to be large among the samples.

The radon emanation rates obtained from this study have been observed to be higher than those obtained outside Asia but not as high as those measured in other local tests. A detailed examination of existing literature

Table 1. Radon emanation rate and back diffusion coefficient.

Material		30% Relative humidity		90% Relative humidity	
		Initial radon emanation rate E_0 (Bq m^{-2} h^{-1})	Specific back diffusion coefficient α (m h^{-1})	Initial radon emanation rate E_0 (Bq m^{-2} h^{-1})	Specific back diffusion coefficient α (m h^{-1})
Red brick	Highest	0.22	0.0077	0.50	0.0030
	Lowest	0.13	0.0012	0.39	0.0010
	Average	0.16	0.0037	0.44	0.0021
	Standard deviation	0.04	0.0025	0.05	0.0010
Concrete	Highest	9.82	0.0088	9.75	0.0010
	Lowest	1.38	0.0001	1.35	0.0000
	Average	4.43	0.0021	4.42	0.0005
	Standard deviation	3.19	0.0038	3.16	0.0004
Sand brick	Highest	1.05	0.0004	1.94	0.0020
	Lowest	0.51	0.0002	1.53	0.0002
	Average	0.67	0.0003	1.64	0.0008
	Standard deviation	0.22	0.0001	0.17	0.0007
Granite	Highest	13.44	0.0088	5.18	0.0018
	Lowest	0.38	0.0002	0.12	0.0001
	Average	1.82	0.0032	0.98	0.0010
	Standard deviation	3.85	0.0032	1.45	0.0006

revealed that amongst most of the reported tests, the conditions (temperature and relative humidity) of the experiments varied significantly. In some cases the conditions were not specified clearly. Radon emanation rate depends on the radium content inside the material. For example, a correlation indicated that radon emanation rate of concrete could vary from 0.5 to around 3 Bq m^{-2} h^{-1} if the radium activity concentration increased from 10 to 55 Bq m^{-3} (Quindos et al. 1989). However, there are also other sources indicating that no clear direction can be seen in radon emanation rate and radium content inside the material (Chen 1992). The issue is complicated as other parameters such as pore size and moisture content also play an important role. The distribution of radium inside the material cannot be overlooked either. If radium is distributed on the surface of the material, the radon emanation rate may be greater than for a sample with radium distributed more evenly throughout. Moreover, the concrete materials that are used in this study include both cement and aggregate. The aggregate comes from mainland China or local sources. The sizes of the aggregate in our concrete samples are 10 mm and 20 mm following the British Standard 882. In general, increasing the material pore size will increase the radon emanation rate as the radon gas can escape from the void to the ambient air. However, a non-uniform size distribution of the aggregate complicates the problem. Unfortunately, no detailed test has been conducted to investigate this effect as well as the impact of the radium content and distribution in the materials on the radon emanation characteristics.

It has been found that back diffusion can significantly affect the radon emanation rate of building material. The results of this study show that if the radon level in air was 200 Bq m^{-3}, the average radon emanation rate of concrete among the five samples was 90.5% at low relative humidity and 97.8% at high relative humidity ($E/E_0 \times 100\%$) of the initial value measured when the radon level was zero in the air. For sand brick the two average percentages at low and high humidities were 91.6% and 90.8% ($E/E_0 \times 100\%$), respectively. However, for red brick and granite the change was much more dramatic. The calculation was based on eqn (3) and zero emanation rate occurs when $C = E_0/\alpha$. This is the point when radon emanation is zero since the outside radon level provides an opposite force to counterbalance the radon emission from the material. The accuracy of this critical radon concentration depends on how reliably the back diffusion coefficient was determined from the initial slope of the radon build up curve as shown in Fig. 3. However, it is interesting that a critical radon concentration is observed. Even if the inaccuracy in finding α was as large as 100%, which is quite unlikely, the emanation rate of granite or red brick will still be approaching zero. In this perspective the use of initial emanation rate (E_0) in evaluating radon accumulation in indoor environment may overestimate the level if back diffusion effect is not considered.

In the design of building ventilation systems, special consideration must be paid to the influence of back diffusion on the radon emanation rate. To maintain the indoor radon concentration at a certain level, the total radon emanation from the wall surfaces in the room must be estimated (Quindos et al. 1989). If back diffusion is not considered, the radon accumulation in the indoor environment will be overestimated. Back diffusion is also important when a study is performed in the indoor environment to quantify which factor is the main contributor of indoor radon pollution. The influence of back diffusion is greater when the indoor radon level is high. This effect is dominant in office buildings where the mechanical ventilation system is turned off in the

Table 2. Comparison of the radon emanation characteristics using sealed surfaces and non-sealed surfaces (30% relative humidity).

		Without sealing on surfaces		Sealing on 4 sides	
Material	Sample	Initial radon emanation rate E_o (Bq m^{-2} h^{-1})	Specific back diffusion coefficient α (m h^{-1})	Initial radon emanation rate E_o (Bq m^{-2} h^{-1})	Specific back diffusion coefficient α (m h^{-1})
Red brick	A	0.22	0.0029	0.25	0.0022
Red brick	B	0.17	0.0039	0.31	0.0047
Red brick	C	0.13	0.0077	0.29	0.0047
Red brick	D	0.13	0.0026	0.18	0.0019
Sand brick	A	0.55	0.0004	2.28	0.0011
Sand brick	B	0.64	0.0002	2.41	0.0007
Sand brick	C	1.05	0.0002	2.24	0.0012
Sand brick	D	0.51	0.0003	2.19	0.0005

evening. The accumulation of indoor radon in many office buildings in Hong Kong has risen to several hundreds or even over 1,000 Bq m^{-3}. It is this kind of situation that makes the consideration of back diffusion important.

An effect of relative humidity on the radon emanation rate was also noticed in the measurement result. For red brick, the radon emanation rate E_o at 90% RH almost tripled (278%) that at 30% RH. For concrete, there was no significant difference due to humidity change. For sand brick there was also a dramatic increase in the radon emanation rate (about 244%) when the RH was increased from 30% to 90%. However, for granite, the trend was not clear since some samples showed increasing radon emanation with the RH while the other showed the opposite. Even the radon emanation rate of granite was found to have a very wide range from as low as 0.12 Bq m^{-3} to as high as 13.44 Bq m^{-3}. The back diffusion coefficient also varied greatly reflecting significant differences in porosity and diffusion characteristics, as well as the radium content inside the material, as indicated in eqns (8) and (9). The actual water content inside the samples can be found by weighing the samples at the two humidity conditions. After the samples were weighed, it was found that the red bricks changed the most, from an average bulk density of 1,775 kg m^{-3} at 30% relative humidity level to 2,063 kg m^{-3} at 90% relative humidity level. Sand brick and concrete changed from 2,229 to 2,311 kg m^{-3} and from 2,327 to 2,410 kg m^{-3}, respectively, when the relative humidity level was raised. No significant change on bulk density was observed in the granite samples with humidity level, and the bulk densities were 3,058 kg m^{-3} for the green granite and 2719 kg m^{-3} for the red granite.

The influence of relative humidity on the measured radon emanation rates has also been documented by Fleischer (1987), Dijk and Jong (1991), Roelofs and Scholten (1994), and Yu et al. (1996). The presence of water in the internal pores may diminish the recoil energy of the emanating radon atoms so that a higher percentage of the emanating radon atoms are stopped in pores and do not diffuse into the surrounding air. This explains why in many studies higher radon emanation rates were found at higher moisture condition.

In some extreme cases the radon emanation rates of concrete and soil at high relative humidity conditions have been found to be twenty times higher than those at low relative humidity (Stranden et al. 1984). The experimental results for concrete, red brick, and sand brick in this study agreed with this argument, but granite did not show any trend. Explanations about this discrepancy have been discussed in the work by Fleischer (1987) and Dijk and Jong (1991) in their studies involving relative humidity from 0% to 100%. When the pores are saturated with water (at high relative humidity condition), the emanation rate will decrease due to the lower diffusion coefficient of radon in water in comparison to that in air (Stranden et al. 1984; Fleischer 1987; Barton and Ziemer 1986). Which effect (decrease in diffusion coefficient or capture of radon atoms in pores) dominates depends on the pore structure of individual material (Dijk and Jong 1991). This explanation can be applied in the tests reported herein, which indicate that the granite had a higher radon emanation rate at high relative humidity (90%) in some samples, but the opposite was observed in other samples.

The use of a one-dimensional solution (eqns 4–9) in the interpretation of three-dimensional emanation characteristics (the tests conducted in the chamber) requires further investigation. In many situations the one-dimensional case is more appropriate, such as radon emanation from building wall when the surface area is large compared to the thickness. In order to verify the difference in results of one-dimensional and three-dimensional tests, separate experiments were done using red brick and sand brick samples. In the one-dimensional test, four sides of the sample were coated with silicone rubber sealant. Sealant (3-mm-thick) was applied on four sides of the sample (surfaces ABCD, CDGH, GHEF, and EFAB in Fig. 2). In this case, only two faces were exposed to air, and radon emanation was limited to these two faces. Radon gas was restricted to diffuse in the axial direction only. This configuration was supposed to get a result based on eqns (4)–(9).

Results of red brick and sand brick samples A, B, C, and D at 30% relative humidity were obtained and are shown in Table 2. From Table 2 it was found that there was significant difference between the one-dimensional tests and three-dimensional tests. For red brick, radon emanation rates based on one-dimensional tests had an average 1.6 times higher than those from the three-dimensional tests. For sand brick, the ratio was as high as 3.3. The results make sense because with the four sides coated radon finds less surface area to come out, and the radon emanation flux will be higher provided that the radium content in the material is the same. Similar results were seen for the specific back diffusion coefficient. If this is the case, use of the radon emanation rate data based on three-dimensional experiments has to be done in a very careful manner and suitable adjustment has to be made. However, study is still on going and further results will be reported at a later date.

CONCLUSION

Radon emanation rates and back diffusion coefficients were measured for 26 building material samples using the closed chamber methodology. It has been found that there was a wide range of these characteristics among the materials. Back diffusion can have significant impact on the radon emanation rate, especially for red brick and granite. It is proposed that a critical indoor radon level exists above which radon emanation is balanced by back diffusion. Relative humidity was also found to have a significant influence on the radon emanation and back diffusion rates. However, the measurements were limited to small samples, and the theoretical approach was based on a one-dimensional mass diffusion equation. Separate experiments on one-dimensional tests indicate that a suitable factor has to be included to take into account the influence of three-dimensional factors in the one-dimensional solution. This paper reports some local data that are of importance to researchers in understanding the behavior of radon in these materials. However, the database has more of a local importance and detailed investigation of the radium content and pore characteristics inside the materials will probably lead to more useful information in a general perspective.

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APPENDIX

Nomenclature

t = time unit (h);
C = radon concentration inside chamber at time t (Bq m^{-3});
C_B = radon concentration inside building material (Bq m^{-3});
C_o = ambient radon level (Bq m^{-3});
λ = ^{222}Rn decay constant (7.553585×10^{-3} h^{-1});
D = back diffusion rate (h^{-1});
D_r = mass diffusion coefficient of radon gas (m^2 h^{-1});
α = specific radon back diffusion coefficient of building material (m h^{-1});
E_o = radon emanation rate of building material (at $C = 0$) (Bq m^{-2} h^{-1});
E = radon emanation rate of building material (at $C > 0$) (Bq m^{-2} h^{-1});
ϕ = radon generation rate inside building material (Bq m^{-3} h^{-1});
A = surface area of the sample (m^2);
V = effective volume of the chamber (m^3);
l = diffusion length (m);
q = leakage flow rate of the system (m^3 h^{-1});
ACH = leakage air exchange rate (q/V) of test chamber (h^{-1}); and
ε = material porosity.

■■