1999_12

LABORATORY MEASUREMENTS OF THE RADON GAS DIFFUSION COEFFICIENT FOR A FRACTURED CONCRETE SAMPLE AND RADON GAS BARRIER SYSTEMS

Wessam Z. Daoud and Kevin J. Renken
University of Wisconsin-Milwaukee
Mechanical Engineering Department
Radon Reduction Technology Laboratory
3200 North Cramer Street
Milwaukee, WI 53211
USA

ABSTRACT

Radon diffusion through cracked concrete is a major radon entry route in residential construction. This paper presents the preliminary experimental results of the influence of cracks on the radon gas diffusion coefficient through concrete. Concrete samples of 10.16 cm (4") length and 8.89 cm (3.5") diameter and standard 1:2:4 composition (cement:sand:pea gravel) with a water:cement ratio of 0.51 were utilized in the experimentation. An average fracture of 1.27 mm (0.05") in width, 10.16 cm (4") in length and 8.89 cm (3.5") in diameter was prefabricated into the concrete sample using a metallic shim. The cracked concrete samples were also tested in combination with two types of laboratory proven radon gas barriers that have been shown to be effective on intact concrete samples. These barriers include: two thin-film membranes (Polyethylene Naphthalate and Polyethylene Terephthalate Glycol) and a cementitious sealant (Polysulfide) which were tested in combination with the cracked concrete sample for radon gas diffusion. Details of the innovative experimental setup and procedures are discussed. The preliminary results of this study have shown that the employment of an effective thin-film membrane has the potential to significantly reduce the diffusion of radon gas through a fractured concrete slab.

INTRODUCTION

A major pathway for indoor radon gas entry is through cracks in the concrete foundation. The two major driving mechanisms for this ingression of radon soil gas through the concrete and its fractures is advection and diffusion. Diffusion is usually considered the second major driving force, but can sometimes solely result in high indoor radon concentrations. Therefore, barriers that can retard radon gas diffusion through fractured concrete will increase the resistance of the building against elevated indoor radon gas levels (Nowak and Song 1990).

Several mathematical and numerical models have been developed to describe the diffusive transport of radon gas through a concrete fracture and a finite or semi-infinite medium (Landman 1982; Dimbylow and Wilkinson 1985; Dimbylow 1987; Schery et al. 1988). There exists minimal experimental data on the diffusion of radon gas through fractured concrete, a situation which simulates true conditions of residential construction. Results on the effectiveness of radon gas barriers in combination with fractured concrete are even more scarce. This paper presents the preliminary results of an experimental investigation to measure the diffusion coefficient of fractured concrete and the effectiveness of two types of radon gas barriers in combination with the fractured concrete. Two laboratory-proven thin-film membranes as well as a commercial sealant are tested for the effective retardation of radon gas diffusion through fractured concrete.

METHODOLOGY

Concrete Samples

Table 1 describes the composition used to formulate our concrete samples. These concrete test samples were of standard composition 1:2:4 (cement:sand:pea gravel) with a standard water: cement ratio (w/c) of 0.51 (Hool 1918; USBR 1938). Aluminum sample holders were used to mold and contain the concrete samples as shown in Fig. 1. Each cast sample was approximately 8.89 cm (3.5") in diameter and 10.16 cm (4") in length and simulated a typical Wisconsin poured-concrete basement foundation. To create the prescribed fracture in the concrete sample, a metallic shim with average dimensions of 1.27 mm (0.05") thickness, 8.89 cm (3.5") width and 10.16 cm (4") length was placed into the holder as the concrete was poured (Fig. 2). The concrete samples and metallic shims were removed from their holders 24 hours after casting and placed in a high humidity chamber for 30 days as per ASTM specifications (ASTM 1994). After curing, the samples were allowed to dry at ambient conditions for approximately one week. The samples were then placed back into the cylindrical aluminum holders and the edges were sealed with a laboratory-proven cementitious epoxy so that one-dimensional radon gas diffusion was prevalent (Daoud 1998).

Radon Gas Barriers Tested

In this investigation two different types of radon gas barriers were tested in combination with the fractured concrete samples: a thin-film membrane and a cementitious coating or sealant. Table 2 details these radon gas barriers which were laboratory proven for their superior effectiveness to retard radon gas diffusion through intact (non-fractured) concrete samples (Maas and Renken 1997; Daoud and Renken 1999). Thin-film membranes are defined as flexible solid sheeting materials (e.g., plastic, polyethylene, polyester, etc.) which are typically installed between the soil and the building foundation to prevent indoor radon soil gas entry. More specifically, a 0.0762 mm (3 mil) thick Polyethylene Naphthalate membrane and a 0.127 mm (5 mil) thick Polyethylene Terephthalate Glycol (PETG) membrane were used in combination with the fractured concrete samples as detailed in Fig. 3. Here, the flexible thin-film membrane was placed adjacent to the concrete so as to securely cover the fracture on one side while being exposed to a high concentration level of radon gas on the other side.

Figure 4 shows the experimental setup for the cementitious coating/fractured concrete sample. This Polysulfide polymer-based joint sealant used on the fractured concrete is a non-sag, cold - applied, chemical-curing type of synthetic rubber compound. It is typically used for sealing, caulking and glazing applications on buildings and other types of construction. The sealant is advertised to resist sunlight, rain, snow, ozone, aging, shrinkage and the daily and seasonal cyclic changes in temperature. The Polysulfide was brushed-on to the surface of the fracture and allowed to dry for more than 24 hours before testing. This test configuration simulated residential sealing of a concrete slab with a commercial sealant.

Experimental Setup

In this investigation, the effective radon gas diffusion coefficients through the concrete samples and radon gas barriers were calculated by using Fick's Law (Renken and Rosenberg 1995). Fick's Law as applied to a slab of concrete experiencing one-dimensional fixed concentration differences with isobaric and isothermal conditions is expressed as:

$$J = D_{eff} \frac{\Delta C}{\Delta x} \tag{1}$$

where,

J = radon flux through the concrete cross-sectional area
$D_{eff.}$ = effective radon gas diffusion coefficient
ΔC = radon gas concentration difference across the concrete sample
Δx = thickness of the concrete sample.

An effective radon gas diffusion coefficient ($D_{eff.}$) is defined for the fractured concrete sample, the thin-film membrane/fractured concrete samples and the cementitious sealant/fractured concrete sample. Here, the word *effective* refers to a system measurement.

Figure 5 is a schematic of the experimental system used to measure the effective radon gas diffusion coefficients through the fractured concrete samples and radon gas barriers. Two continuous radon monitors were used to measure the radon concentrations in both the Source and Collection Chambers. These monitors utilized a Lucas scintillation cell and a photomultiplier tube to count the number of alpha emissions given-off by the radon gas present. A diaphragm pump was used in each loop to assure that the air and radon gas was thoroughly mixed. A filter is placed at the entrance of each scintillation cell to remove dust and radon daughter products within the air stream. Two flow meters were used to monitor the flow rates since the calibrated sensitivity of the continuous radon monitors were dependent on the flow rate. The radon source (a commercially available passive radon gas source) was used to build-up the radon gas concentration in the Radon Gas Source Chamber. The Source Chamber was attached to the facial area of the fractured concrete sample/radon gas barrier while the Collection Chamber was attached to the rear face of the fractured concrete sample. This arrangement allowed the full facial area of each concrete sample to be exposed to the radon-air mixture. Toggle valves and other hardware were employed to create the desired radon gas flow configuration. The method employed by Maas and Renken (1997) was used to determine the time necessary for steady state to be achieved prior to the initial sampling of the chambers.

A sensitive pressure transducer monitored the pressure differential across the concrete samples so that pure diffusion transport mechanism could be verified. Environmental conditions (e.g., relative humidity, temperature and barometric pressure) were measured with high-accuracy sensors. A modern PC-data acquisition system was employed to read the electrical signals of the sensors and radon monitors and to observe and record the data. The main apparatus was contained in an environmental chamber that maintained the temperature and humidity levels constant. Complete details of the experimental setup and procedures are contained in Daoud (1998) and are not repeated here, for brevity.

RESULTS

The results of the radon gas diffusion measurements for the fractured concrete sample, the thin-film membrane/fractured concrete samples and the cementitious sealant/fractured concrete sample are now discussed. In addition, a simple indoor diffusive entry rate calculation is presented to highlight the potential of tested radon gas barriers.

Fractured Concrete

Table 3 summarizes the average radon gas diffusion coefficients for the fractured concrete sample. The experimental uncertainty of the radon gas diffusion coefficients was estimated to be approximately ±10% (Daoud 1998). The average diffusion coefficient of the cracked concrete sample was 1.08 x 10^{-3}cm^2/s with a standard deviation of 1.01 x 10^{-4} cm^2/s. Table 4 provides a comparison of values of the radon gas diffusion coefficient for intact concrete samples from several notable studies. Comparing the fractured concrete data with previous intact concrete diffusion tests shows an order of magnitude or an approximate 800% increase in the radon gas diffusion coefficient (Daoud and Renken 1999). As expected, the prescribed fracture in the concrete sample introduced an enhanced pathway for the radon gas to penetrate through the concrete and create a significantly larger value of $D_{eff.}$.

Radon Gas Barriers

Table 3 also shows the average effective radon gas diffusion coefficient for the fractured concrete in combination with the three tested radon gas barriers. As indicated, the Polyethylene Naphthalate and Polyethylene Terephthalate Glycol (PETG) thin-film membranes were very capable in blocking the radon gas diffusion through the cracked concrete sample with effective radon gas diffusion coefficients of 1.66 x 10^{-5} cm^2/s and 1.61 x 10^{-5} cm^2/s, respectively. Both membranes significantly reduced the effective diffusion coefficient of the membrane/concrete combination by an average of 98.5%. The cementitious sealant was less effective in blocking the radon gas diffusion through the fractured concrete sample, but did provide a barrier to nearly match the results of the intact concrete diffusion coefficient. The Polysulfide realized an average value of $D_{eff.}$ = 7.93 x 10^{-4} cm^2/s which produced a 26.9% reduction as compared to the fractured sample alone. As previously mentioned, the Polysulfide sealant was applied to only the crack, while the thin-film membranes covered the entire facial area of the fractured concrete sample. Hence, more effective coverage area on the fractured concrete sample was treated by the thin-film membranes than the sealant. Therefore, a difference in the effectiveness between the two types of barriers was expected even though their performances on intact concrete were quite comparable (Maas and Renken 1997; Daoud and Renken 1999).

Indoor Entry Rate Application

The above results are now utilized in a simple application to highlight the potential that these radon gas barriers have to significantly reduce the diffusion of radon gas through a fractured concrete slab. The simple model by Nazaroff and Nero (1988) is employed to estimate the indoor radon concentration:

$$I = \left(\frac{S_v + I_o \lambda_v}{\lambda_v + d} \right) \tag{2}$$

where,

I = indoor air radon concentration
S_V = entry rate per unit volume of radon
I_O = radon concentration in outdoor air ~ 0.4 pCi/L (Sextro 1988)
λ_V = ventilation rate = 0.1 ACH
d = decay constant for radon = 0.0076/hr.

In this application, the radon gas diffusive entry is assumed to be due to a concentration gradient across the building foundation with a zero pressure differential. The following parameters and values are assumed in the calculation:

ΔC = average radon concentration in the soil = 2,700 pCi/L (Nagda 1994)
Δx = thickness of concrete slab = 0.10 m (4")
V = volume of structure = 1000 m^3
A_S = surface area of basement foundation = 140 m^2

The effective radon gas diffusion coefficients of the fractured concrete sample, the thin-film membrane/fractured concrete and sealant/fractured concrete configurations from Table 4 and the average diffusion coefficient of the intact concrete from Daoud and Renken (1999) are used to estimate the indoor radon gas concentrations due to diffusive entry. The calculated results are summarized in Table 5. As illustrated, the fractured concrete result produces the largest indoor radon concentration (14.0 pCi/L), while the utilization of either thin-film membrane can significantly reduce the equilibrium indoor radon gas concentration (0.58 pCi/L). The Polysulfide sealant shows a reduction in diffusive entry (10.4 pCi/L), but is overshadowed by the intact concrete result (1.76 pCi/L).

CONCLUSIONS

Laboratory measurements on the diffusion coefficient of a fractured concrete sample and on radon gas barriers in combination with the fractured concrete sample were reported. As expected, the experimental results have shown that the prescribed fracture in the concrete greatly increases the diffusive flow of radon gas through the concrete. Employment of both Polyethylene Naphthalate and Polyethylene Terephthalate Glycol (PETG) thin-film membranes on the surface of the fractured concrete can significantly reduce the radon gas diffusion through the fractured concrete. The cementitious sealant (Polysulfide) was shown to be less effective due to its application to the facial crack area only. These preliminary results have shown that thin-film membranes should be considered as an effective method of reducing radon gas diffusive entry in residential construction.

Current research in the laboratory is investigating other commercial sealants and thin-film membranes as well as concrete fracture size limitations with respect to radon gas diffusion transport.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Conrad V. Weiffenbach, Wisconsin Department of Health and Family Services for his input and the US EPA State Indoor Radon Grants Program for their sponsorship. We would also like to thank the following companies for their donation of the thin-film membranes and sealant materials: DuPont, Lustro Plastics and PolySpec Corporation.. Special thanks to Mr. Gregory Barske, former UWM ME Instrument Maker for his ideas and fabrication of the test systems.

REFERENCES

American Society for Testing Materials (ASTM). Standard practice for making and curing concrete test specimens in the laboratory. Annual Book of ASTM Standards. Designation C 192 - 90a.; 1994.

Culot, M.V.J.; Olson, H.G.; Schiager, K.J. Effective diffusion coefficient of radon in concrete, theory and method for field measurements. Health Physics. 30:263-270; 1976.

Daoud, W. Assessment of flexible thin-film membranes as a radon-resistant construction technique. Milwaukee, WI: University of Wisconsin – Milwaukee; December 1998 (M.S. Thesis).

Daoud, W.; Renken, K.J. Laboratory assessment of flexible thin-film membranes as a passive barrier to radon gas diffusion. In: Proceedings of Radon in the Living Environment Workshop. Athens, Greece; April 19-23, 1999.

Dimbylow, P.J. The solution of the pressure driven flow equation for radon ingress through cracks in concrete foundations. Radiation Protection Dosimetry. 18:163-167; 1987.

Dimbylow, P.J.; Wilkinson, P. The numerical solution of the diffusion equation describing the flow of radon through cracks in a concrete slab. Radiation Protection Dosimetry. 11:229-236; 1985.

Hool, G.A. Concrete Engineer's Handbook. McGraw-Hill, New York; 1918.

Landman, K.L. Diffusion of radon through cracks in a concrete slab. Health Physics. 43:65-71; 1982.

Leung, J.K.C.; Ng, C.; Tso, M.W. Radon release from building materials in Hong-Kong. Health Physics. 67:378-384; 1994.

Maas, J.J.; Renken, K.J. Laboratory assessment of cementitious coatings as a barrier to radon gas entry. In: The 1997 International Radon Symposium. 1.1 - 1.13 Cincinnati, OH: AARST; 1997.

Nagda, N. L. Radon: prevalence, measurements, health risks and control. ASTM Manual Series. Philadelphia, PA; 1994.

Nazaroff, W.W.; Nero, A.V. Radon and its decay products in indoor air. New York, NY: John Wiley & Sons; 1988.

Nowak M.; Song B.H. Evaluating radon resistance of films and sealants using perfluorocarbon tracer gases. In: The 1990 International Symposium on Radon and Radon Reduction Technology. Vol. V: VIII Atlanta, Georgia: EPA; February 19-23, 1990.

Renken, K.J.; Rosenberg, T. Laboratory measurements of the transport of radon gas through concrete samples. Health Physics. 68:800-808; June 1995.

Rogers, V.C.; Nielson, K.K.; Lehto, M.A.; Holt, R.B. Radon generation and transport through concrete foundations. EPA-600/R-94-175. US EPA, Research Triangle Park, NC; 1994.

Schery, S.D.; Holford, D.J.; Wilson, J.L.; Phillips, F.M. The flow and diffusion of radon isotopes in fractured porous media: Part 2, semi-infinite media. Radiation Protection Dosimetry. 24:191-197; 1988.

Sextro, R. Radon in dwellings. In: Radon and the Environment. Park Ridge, New Jersey: Noyes Publications. 78; 1988.

Snoddy, R. Laboratory assessment of the permeability and diffusion characteristics of Florida concretes, phase I, methods development and testing. EPA-600/R-94-053. US EPA, Research Triangle Park, NC; 1994.

United States Bureau of Reclamation (USBR). Concrete manual: a manual for the control of concrete construction. Denver, CO; 1938.

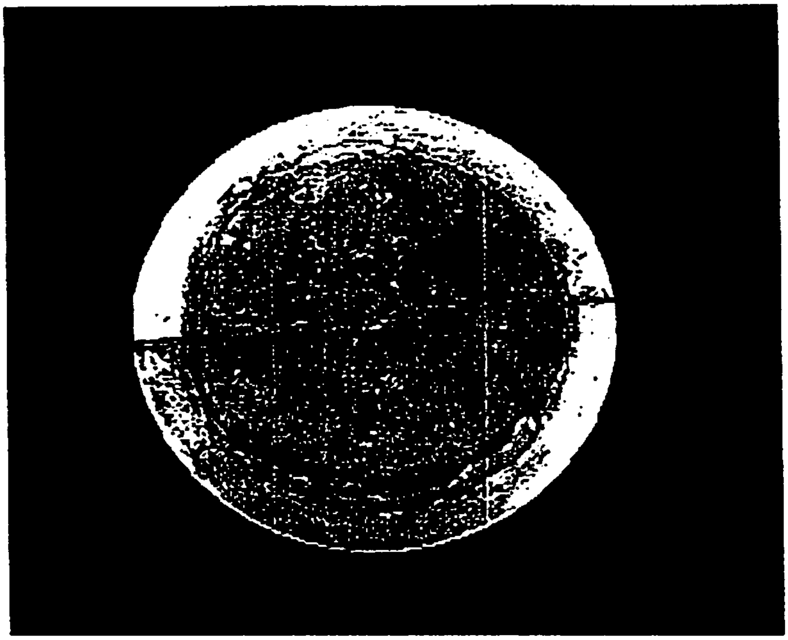

Fig. 1. Photo of fractured concrete sample in aluminum holder.

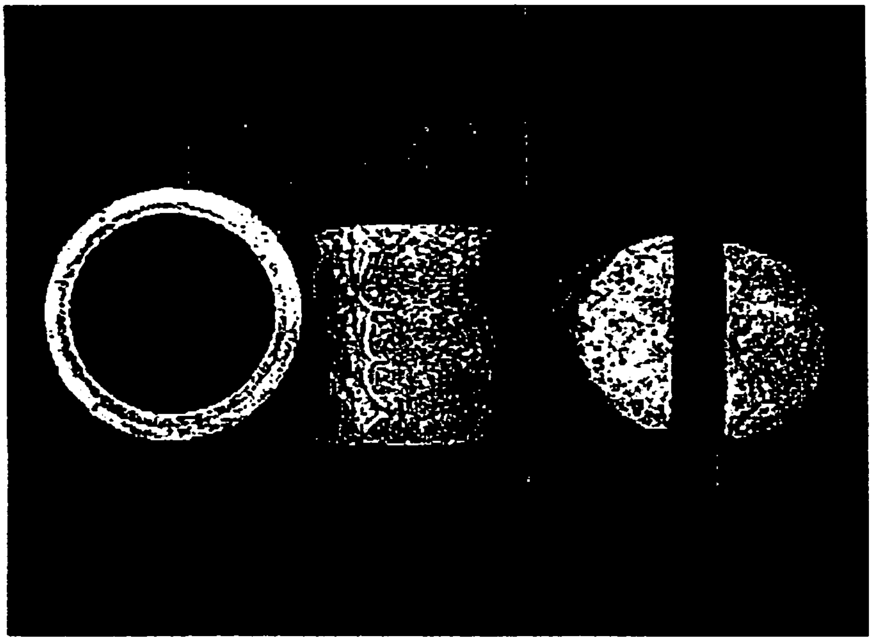

Fig. 2. Photo of metallic shim and fractured concrete sample.

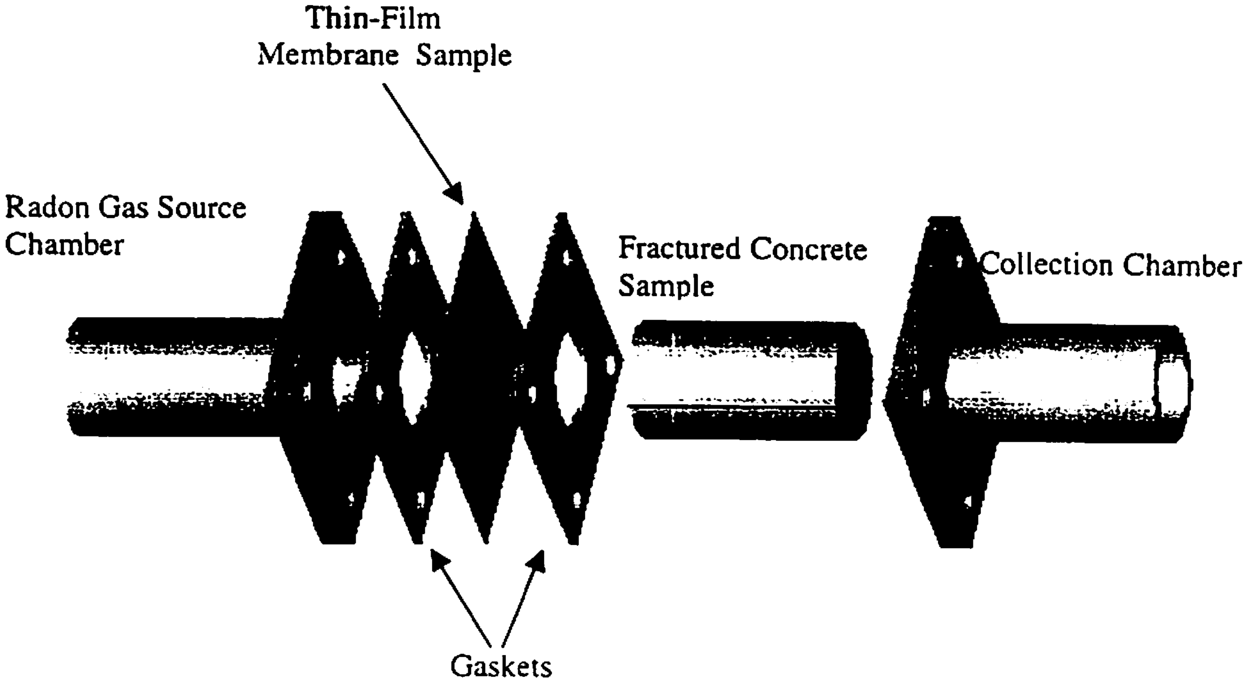

Fig. 3. Schematic of the thin-film membrane/fractured concrete sample configuration.

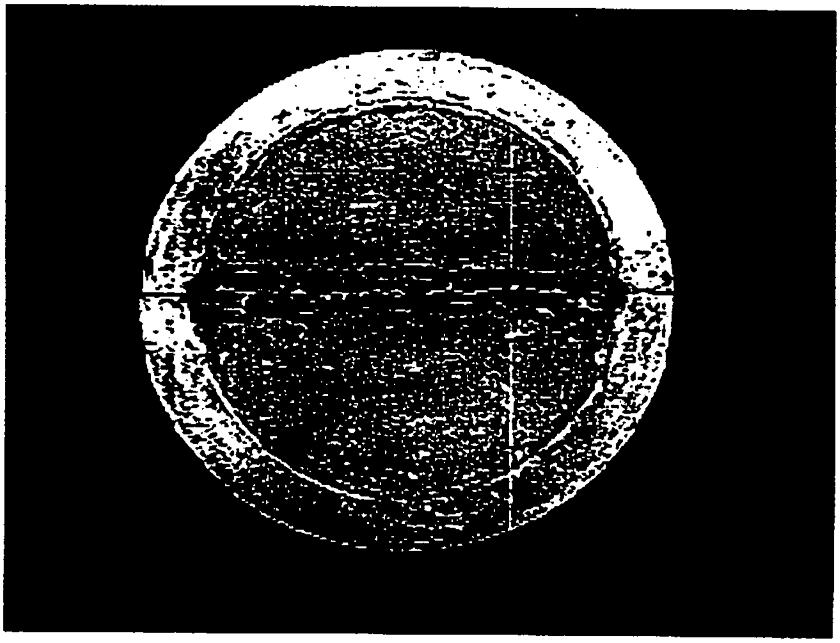

Fig. 4. Photo of fractured concrete sample with applied Polysulfide sealant.

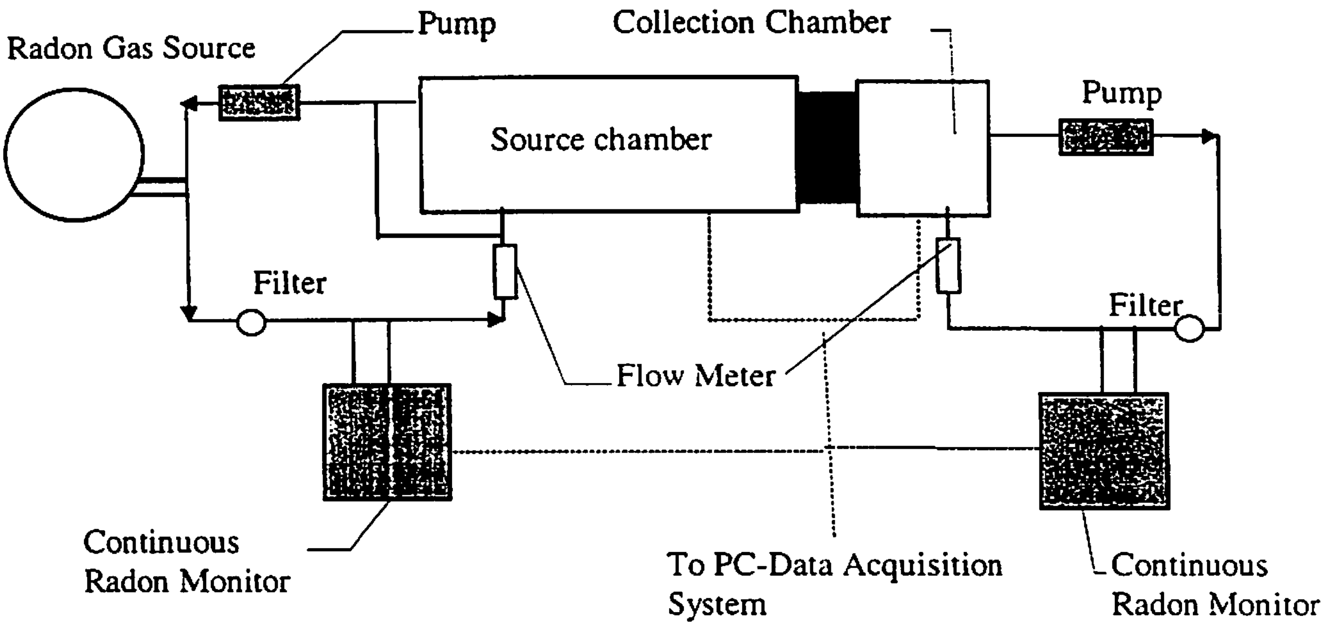

Fig. 5. Diffusion apparatus used to measure the radon gas diffusion coefficient for the fractured concrete sample and the radon gas barrier systems.

Table 1. Concrete sample composition.

Material	Sample (lbs.)
Portland Cement	5.2
Sand	10.4
Pea Gravel	20.8
Water	2.6

Table 2. Radon gas barriers tested in this study.

Commercial Name	Material Type	Manufacturer	Thickness (mil)	Density (g/cm^3)	D (cm^2/s)	Study
KALADEX® 1030	Polyethylene Naphthalate	DuPont	3.0	1.4	4.10×10^{-10}	Daoud and Renken (1999)
ULTROS®	Polyethylene Terephthalate Glycol (PETG)	Lustro Plastics	5.0	1.3	1.66×10^{-10}	Daoud and Renken (1999)
T-2235M®	Polysulfide	PolySpec Corporation	-	1.6	5.91×10^{-8}	Maas and Renken (1997)

Table 3. Average effective radon gas diffusion coefficients for fractured concrete sample and radon gas barrier systems.

Test	D_{eff} (cm^2/s)	% Reduction
Fractured Concrete	1.08×10^{-3}	-
Polyethylene Naphthalate	1.66×10^{-5}	98.5
PETG	1.61×10^{-5}	98.5
Polysulfide	7.93×10^{-4}	26.9

Table 4. Comparison of radon gas diffusion coefficients for intact concrete.

Study	D (cm^2/s)
Culot et al. (1976)	$(1.69 - 3.08) \times 10^{-4}$
Leung et al. (1994)	$(2.30 - 3.70) \times 10^{-5}$
Rogers et al. (1994)	$(0.46 - 1.8) \times 10^{-4}$
Snoddy (1994)	$(1.84 - 3.83) \times 10^{-4}$
Renken and Rosenberg (1995)	$(4.38 - 14.7) \times 10^{-4}$
Maas and Renken (1997)	$(2.06 - 3.93) \times 10^{-4}$
Daoud and Renken (1999)	$(0.97 - 1.22) \times 10^{-4}$

Table 5. Estimated indoor radon gas concentration due to diffusive entry.

Test	Indoor Radon Concentration Due to Diffusive Entry (pCi/L)
Fractured Concrete	14.0
Polyethylene Naphthalate	0.6
PETG	0.6
Polysulfide	10.4
Intact Concrete (Daoud and Renken 1999)	1.8