

## LABORATORY ASSESSMENT OF CEMENTITIOUS COATINGS AS A BARRIER TO RADON GAS ENTRY

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### ABSTRACT

This paper assesses the effectiveness of cementitious coatings as barriers to radon gas entry. Twelve commercially available brushed-on coatings were evaluated for air permeability and radon diffusion as cast samples to determine their individual radon gas transport properties. The sealant materials were also applied to standard ingredient (1:2:4 cement-to-sand-to-pea gravel) concrete samples. Water to cement ratios were varied to change the radiological transport properties of the concrete. The radon gas transport properties of the concrete samples were evaluated before and after the sealant application utilizing three innovative test systems: a porosity, a permeability and a diffusion apparatus. Laboratory experiments also measured the thickness of the cementitious coating as well as evaluated the relative adherence of the sealants to a concrete substrate. Details of these innovative experimental setups and procedures are discussed. The experimentation has identified two cementitious coatings that can be employed as *superior* radon gas barriers: Polysulfide (with a diffusion coefficient of  $D = 5.91 \times 10^{-8} \text{ cm}^2/\text{s}$  and an average radon diffusion coefficient percent reduction of 98.4%) and Epoxy-no filler (with a diffusion coefficient of  $D = 5.05 \times 10^{-8} \text{ cm}^2/\text{s}$  and an average radon diffusion coefficient percent reduction of 97.7%). The results of this study have shown that the application of cementitious coatings can be utilized an effective alternative tool in radon-resistant residential construction technology.

### INTRODUCTION

Concrete is a porous material which easily allows radon gas to flow through it. When used as a building material, concrete allows radon gas to enter indoor air by the mechanisms of advection and diffusion. Sealant materials applied to the interior surfaces of concrete walls and floorings may reduce the amount of radon gas which passes through the concrete, thus, providing an alternative radon mitigation tool (US EPA 1992; US EPA 1994; Maas 1997).

In order to assess the cementitious coatings as a passive radon mitigation instrument, several test systems were designed, fabricated and implemented. These systems included: a porosity, a permeability and a diffusion apparatus. The sealant materials were evaluated in the following manner:

1. Sealants were tested for permeability and diffusion coefficients as a cast sample in an aluminum holder.
2. Two concrete materials were tested for porosity, permeability, diffusion and strength.
3. Sealant materials were evaluated on concrete materials for permeability and diffusion reduction.
4. Sealants were tested for adherence to concrete samples using ASTM C794-93 (1994a) as a guide.
5. Sealants were measured for coating thickness on concrete samples.

A literature search was performed to determine the properties required of a cementitious coating to act as a radon gas barrier. This research consisted of comparing properties, common applications and prior test results of cementitious coating materials (Abu-Jarad and Fremlin 1983; Archibald and DeSouza 1993; Archibald et al.; ASM

1990; Culot et al. 1978; Pohl et al 1980; Ruppertsberger 1990). There were also several sealant materials and data which were provided by manufacturers who have marketed their products as radon barriers.

The initial concrete test samples were of standard composition 1:2:4 (cement-to-sand-to-pea gravel) with a standard water to cement ratio (w/c) of 0.50 (Hool 1918, USBR 1938). To change the radiological transport properties of the concrete, the w/c ratio was varied to -0.12. The concrete sample dimensions were 4" in length by 3.5" in diameter. Two different batches of concrete were produced and are shown in Table 1. Also shown in Table 1 is the average porosity of the two concrete batches which were tested using the gas expansion method as detailed by Maas (1997).

**Table 1. Concrete sample compositions.**

	Batch A (standard)	Batch B (-12%w/c)
Portland Cement I (lbs.)	8.55	8.49
Sand (lbs.)	16.4	16.8
Pea Gravel (lbs.)	32.7	33.7
Water (lbs.)	4.35	3.85
Water/Cement Ratio (w/c)	0.51	0.45
Porosity (%)	21.2	33.4

The concrete samples were removed from their holders 24 hours after casting and placed in a high humidity chamber (90%-100%) for 30 days as per ASTM C192-90a concrete test specimen specifications (ASTM 1994b). From the same batches, compression testing and adhesion testing samples were also produced as per ASTM C794-93 test (ASTM 1994a). Complete details of the concrete sample preparations are contained in Maas (1997) and are not repeated here, for brevity.

## METHODOLOGY

### Permeability tests

The advective flow of radon gas through concrete is directly related to its permeability. Standard ASTM testing for concrete permeability consists of a water permeation test. In this test, the permeability coefficient is proportional to the viscosity of the permeating fluid. Therefore, water permeation tests are not representative of the permeation of radon gas in concrete. Hence, a permeability apparatus that measures the flow of gas through concrete as a function of pressure gradient was required. The permeability coefficients during this study were determined for air since it is extremely difficult to control the radon concentration during a permeability test run. It is assumed the difference between permeability coefficients of radon and air in concrete is minimal because of the inert behavior of radon.

To determine the permeability coefficient of air in concrete, the one-dimensional form of Darcy's law was used:

$$Q = - \left[ \frac{kA\Delta P}{\mu L} \right] \quad (1)$$

where,

- Q = volumetric flow rate through the concrete sample
- k = permeability coefficient

- A = cross-sectional area of the concrete sample
- $\Delta P$  = pressure gradient across the concrete sample
- $\mu$  = viscosity of air
- L = length of the concrete sample

Darcy's Law in this form is valid for sufficiently slow, unidirectional, steady-state flow in the direction of the length of the samples.

Fig. 1 is a schematic of the permeability apparatus that was designed, fabricated and employed to measure the volumetric flow rate and pressure gradient of Darcy's Law. The volumetric gas flow rate was calculated from the ideal gas law and the molecular volume of air with the measured pressure increase, temperature and volume of the low pressure chamber during the test (Maas 1997).

$$Q = mV_{air} \frac{\Delta n}{\Delta t} = mV_{air} \frac{P_i V}{RT \Delta t} \quad (2)$$

where,

- $mV_{air}$  = molecular volume of air
- $\Delta n$  = mass increase in low chamber
- $\Delta t$  = unit of time over which the pressure and mass increase
- $P_i$  = pressure increase in the low chamber
- V = volume of low chamber
- R = gas constant
- T = temperature in low chamber

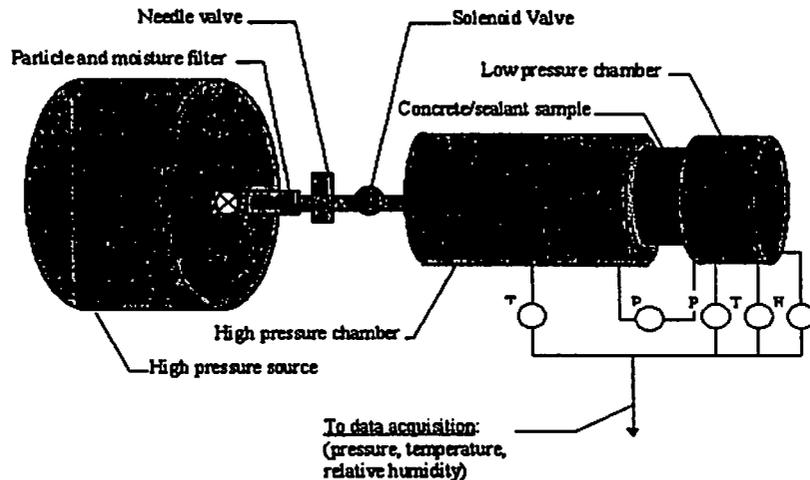


Fig. 1. Schematic of permeability apparatus.

#### Diffusion tests

Diffusion can be a significantly large contributor to indoor radon levels (Renken and Rosenberg 1995). Therefore, a method to measure the diffusion coefficients of the concrete, the sealant and the concrete/sealant samples was developed. One-dimensional Fick's Law with decay neglected was used in this study to determine the diffusion coefficients of the samples.

$$J = D \frac{dC}{dx} \quad (3)$$

where,

- J** = radon flux through concrete per unit cross sectional area  
**D** = diffusion coefficient  
 $\frac{dC}{dx}$  = concentration gradient in the direction of x

Sampling of the chamber concentrations at the beginning and end of each diffusion run allowed for the measurement of the average radon concentration gradient and the radon flux. These values were then used in eqn (3) to calculate the diffusion coefficient. The neglect of the decay term was compensated for within the concentration gradient and radon flux calculations by calculating the amount of radon that would have been present in the chambers if decay would not have occurred. This was accomplished via the standard decay equation:

$$C = C_0 \exp(-\lambda t) \quad (4)$$

where,

- C** = concentration after decay for time t  
**C<sub>0</sub>** = initial concentration  
**λ** = decay constant for radon

Using Fick's second law, the time required to steady state was estimated by applying the appropriate initial and boundary conditions and determining the concentration profile:

$$\frac{\partial^2 C}{\partial x^2} = \frac{1}{D} \frac{\partial C}{\partial t} \quad (5)$$

The initial and boundary conditions for this partial differential equation were:

- |         |            |           |  |
|---------|------------|-----------|--|
| $x = x$ | $t \leq 0$ | $C = 0$   | initially radon gas free sample                                      |
| $x = 0$ | $t > 0$    | $C = C_0$ | concentration in source chamber at time t is $C_0$                   |
| $x = L$ | $t > 0$    | $C = 0$   | concentration in collection chamber is approximately 0 at any time t |

Solving eqn (5) and applying the results to Fick's Law yields the following:

$$J = \frac{DC_0}{L} \left( t - \frac{L^2}{6D} \right) - \frac{2LC_0}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \exp\left( \frac{-Dn^2\pi^2 t}{L^2} \right) \quad (6)$$

For very large values of t or at steady state, the exponential term approaches zero and eqn (6) becomes:

$$J = \frac{DC_0}{L} \left( t - \frac{L^2}{6D} \right) \quad (7)$$

A plot of the flux (J) versus time (t) for eqn (7) yields a time intercept of:

$$t_{ss} = \frac{L^2}{6D} \quad (8)$$

where,

- $t_s$  = time to reach steady state
- $L$  = length of sample
- $D$  = diffusion coefficient of sample

Eqn (8) was used to determine the time to steady state required for all samples. Hence, all samples were run for this required time prior to the initial sampling of chambers.

Fig. 2 is a schematic of the diffusion apparatus used in this investigation. The entire apparatus was contained within an environmental chamber which provided control of temperature and relative humidity. Continuous radon monitors were used to measure the radon concentration in the both 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.

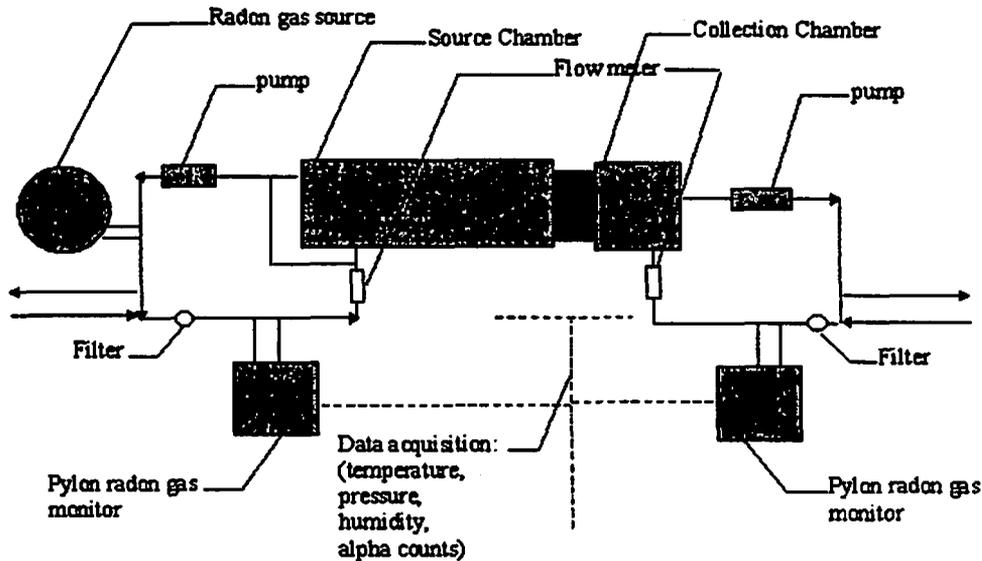


Fig. 2. Schematic of diffusion apparatus used for both concrete and sealant diffusion coefficient measurements.

## RESULTS

The laboratory results discussed here consist of permeability and diffusion coefficients for the concrete, the cementitious coatings and the coated concrete samples. In addition, adhesion and compression test results are also presented.

### Permeability results

The cementitious coatings all exhibited excellent permeability coefficients as they were 2 to 3 orders of magnitude smaller than the average Batch A concrete permeability coefficient, with the exception of the Versaflex 1 latex sealant. The lowest permeability coefficient reported was the aluminum filled epoxy at  $5.15 \times 10^{-16} \text{ cm}^2$ . Table 2 and Fig. 3 show the reduction capabilities of the sealants. Table 2 displays the sealant permeability coefficient and the concrete sample permeability coefficient, respectively, for both Batch A and B as well as the permeability coefficient of the concrete sample after the application of the cementitious coating. Fig. 3 highlights the percent reduction of the permeability coefficient for both batches of concrete samples with the employment of the specific cementitious coating.

Not all sealant materials were tested for permeability and diffusion as a cast in place sample. These sealants included the Flexane polyurethane, Damtite ceramic powder, Moxie sealer 1500, Moxie flooring sealer II and the Daran SL143 latex. The Moxie International sealants and the Damtite ceramic powder were not cast as sealant testing discs because they required the concrete substrate to function properly. The Flexane polyurethane sealant was cast, but because of its poor adhesion to the aluminum testing holder it pulled away from the holder during permeability testing. The Daran SL143 latex material chemically reacted with both the aluminum and steel sample holders.

The very high permeability coefficients for Batch B concrete samples show that any sealant placed on an equally high permeable concrete ( $k \cong 10^{-9} - 10^{-12} \text{ cm}^2$ ) would greatly reduce the permeability.

Table 2. Permeability reduction capabilities of cementitious coatings.

Cementitious coatings	Pure sealant (cm <sup>2</sup> )	Batch A (cm <sup>2</sup> )	Batch A w/sealant (cm <sup>2</sup> )	% Reduced Batch A	Batch B (cm <sup>2</sup> )	Batch B w/sealant (cm <sup>2</sup> )	% Reduced Batch B
High solids epoxy	$1.11 \times 10^{-14}$	$4.59 \times 10^{-13}$	$2.08 \times 10^{-13}$	54.6	$4.57 \times 10^{-12}$	$2.54 \times 10^{-12}$	44.4
Epoxy - no filler	$1.31 \times 10^{-15}$	$3.19 \times 10^{-13}$	$2.16 \times 10^{-13}$	32.3	$1.26 \times 10^{-9}$	$3.33 \times 10^{-11}$	97.4
Aluminum filled epoxy	$5.15 \times 10^{-16}$	$2.77 \times 10^{-12}$	$1.34 \times 10^{-12}$	51.7	$4.10 \times 10^{-12}$	$4.08 \times 10^{-12}$	0.5
Flexane polyurethane	-	$1.70 \times 10^{-12}$	$7.75 \times 10^{-13}$	54.4	$8.20 \times 10^{-12}$	$5.21 \times 10^{-12}$	36.4
Polysulfide	$1.09 \times 10^{-15}$	$5.82 \times 10^{-12}$	$2.03 \times 10^{-13}$	96.5	$4.11 \times 10^{-9}$	$1.84 \times 10^{-12}$	99.9
Damtite ceramic powder	-	$2.51 \times 10^{-13}$	$3.59 \times 10^{-13}$	-	$9.06 \times 10^{-12}$	$2.18 \times 10^{-11}$	-
Versaflex 1 - latex	$5.19 \times 10^{-13}$	$4.99 \times 10^{-13}$	$3.79 \times 10^{-13}$	24.2	-	$3.46 \times 10^{-11}$	100
Moxie sealer 1500	-	$2.60 \times 10^{-13}$	$1.67 \times 10^{-13}$	35.8	$7.87 \times 10^{-12}$	$4.21 \times 10^{-11}$	-
Moxie flooring sealer II	-	$6.82 \times 10^{-13}$	$2.66 \times 10^{-13}$	61	$2.86 \times 10^{-10}$	$9.04 \times 10^{-11}$	68.4
Daran SL 143 - latex	-	$6.39 \times 10^{-13}$	$5.26 \times 10^{-13}$	17.6	$1.48 \times 10^{-12}$	$1.27 \times 10^{-12}$	13.8
Versaflex 9 - latex	$8.62 \times 10^{-15}$	$4.34 \times 10^{-13}$	$2.25 \times 10^{-13}$	48.1	$2.40 \times 10^{-9}$	$9.49 \times 10^{-12}$	99.6
Daratek XB 3631 - latex	$2.62 \times 10^{-15}$	$3.01 \times 10^{-13}$	$2.72 \times 10^{-13}$	9.56	$8.17 \times 10^{-11}$	$1.95 \times 10^{-11}$	76.1

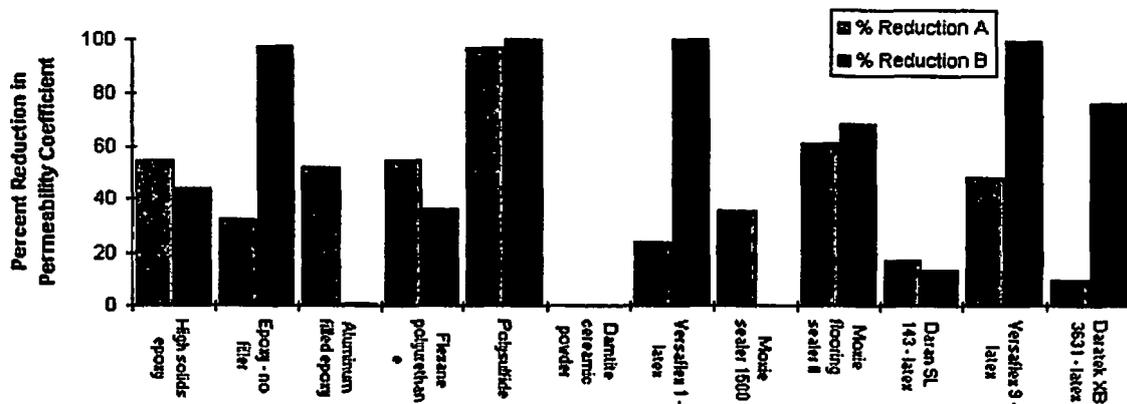


Fig. 3. Reduction of permeability coefficient with the application of cementitious coating.

The experimental uncertainty of the permeability coefficient was 11%, which included relative humidity effects (Maas 1997).

### Diffusion results

Diffusion tests for the sealant materials were performed with a time to steady state of 24 hours. These results are shown in Table 3. Steady-state times were then recalculated using the diffusion coefficients resulting from the 24 hour runs. Polysulfide was run with a time to steady state of 72 hours. The resultant diffusion coefficient required  $t_{ss} = 62.0$  hours, thus, resulting in an 85% increase in diffusion coefficient (from  $3.18 \times 10^{-8} \text{ cm}^2/\text{s}$  to  $5.91 \times 10^{-8} \text{ cm}^2/\text{s}$ ).

**Table 3. Diffusion coefficients for cementitious coatings.**

Cementitious coatings	Sample number	Diffusion coefficient (cm <sup>2</sup> /s)	Required time to steady state (hours)
High solids epoxy	1	$6.22 \times 10^{-7}$	4.24
Epoxy - no filler	2	$5.05 \times 10^{-8}$	133
Aluminum filled epoxy	3	$3.85 \times 10^{-7}$	5.89
Polysulfide	5	$5.91 \times 10^{-8}$	62
Versaflex 1 - latex	7	$4.44 \times 10^{-7}$	2.65
Versaflex 9 - latex	11	$7.37 \times 10^{-8}$	13.7
Daratek XB3631 - latex	12	$9.23 \times 10^{-7}$	31.8

Table 4 reports the diffusion reduction capabilities of the cementitious coatings. More specifically, the diffusion coefficients for the sealants, the Batch A and B concrete samples as well as the Batch A and B samples with sealant are shown. Fig. 4 highlights the percent reduction in the diffusion coefficient with the application of a specific coating. The experimental uncertainty of the diffusion coefficient was estimated at 10% (Maas 1997).

**Table 4. Diffusion reduction capabilities of cementitious coatings.**

Cementitious coatings	Pure sealant (cm <sup>2</sup> /s)	Batch A (cm <sup>2</sup> /s)	Batch A w/sealant (cm <sup>2</sup> /s)	% Reduced Batch A	Batch B (cm <sup>2</sup> /s)	Batch B w/sealant (cm <sup>2</sup> /s)	% Reduced Batch B
High solids epoxy	$6.22 \times 10^{-7}$	$2.79 \times 10^{-4}$	$6.53 \times 10^{-5}$	76.6	$5.60 \times 10^{-4}$	$1.93 \times 10^{-4}$	65.5
Epoxy - no filler	$5.05 \times 10^{-8}$	$2.34 \times 10^{-4}$	$9.93 \times 10^{-6}$	95.8	$6.52 \times 10^{-4}$	$2.99 \times 10^{-6}$	99.5
Aluminum filled epoxy	$3.85 \times 10^{-7}$	$2.55 \times 10^{-4}$	$5.95 \times 10^{-5}$	76.7	$5.16 \times 10^{-4}$	$1.95 \times 10^{-4}$	62.1
Flexane polyurethane	-	$2.64 \times 10^{-4}$	$1.90 \times 10^{-4}$	28.1	$5.26 \times 10^{-4}$	$1.49 \times 10^{-4}$	71.6
Polysulfide	$5.91 \times 10^{-8}$	$3.69 \times 10^{-4}$	$1.04 \times 10^{-5}$	97.2	$8.57 \times 10^{-4}$	$3.25 \times 10^{-6}$	99.6
Damtite ceramic powder	-	$2.50 \times 10^{-4}$	$2.55 \times 10^{-4}$	-1.84	$4.76 \times 10^{-4}$	$3.88 \times 10^{-4}$	18.5
Versaflex 1 - latex	$4.44 \times 10^{-7}$	$2.06 \times 10^{-4}$	$4.87 \times 10^{-5}$	76.4	$7.87 \times 10^{-4}$	$4.36 \times 10^{-4}$	44.6
Moxie sealer 1500	-	$2.44 \times 10^{-4}$	$8.11 \times 10^{-5}$	66.8	$5.79 \times 10^{-4}$	$3.07 \times 10^{-4}$	46.9
Moxie flooring sealer II	-	$2.37 \times 10^{-4}$	$9.38 \times 10^{-5}$	60.4	$7.89 \times 10^{-4}$	$3.25 \times 10^{-4}$	58.8
Daran SL 143 - latex	-	$2.36 \times 10^{-4}$	$1.92 \times 10^{-4}$	18.6	$3.24 \times 10^{-4}$	$2.85 \times 10^{-4}$	12
Versaflex 9 - latex	$7.37 \times 10^{-8}$	$3.93 \times 10^{-4}$	$1.64 \times 10^{-4}$	58.3	$9.34 \times 10^{-4}$	$4.23 \times 10^{-4}$	54.7
Daratek XB 3631 - latex	$9.23 \times 10^{-7}$	$2.47 \times 10^{-4}$	$1.92 \times 10^{-4}$	22.3	$7.43 \times 10^{-4}$	$3.70 \times 10^{-4}$	50.3

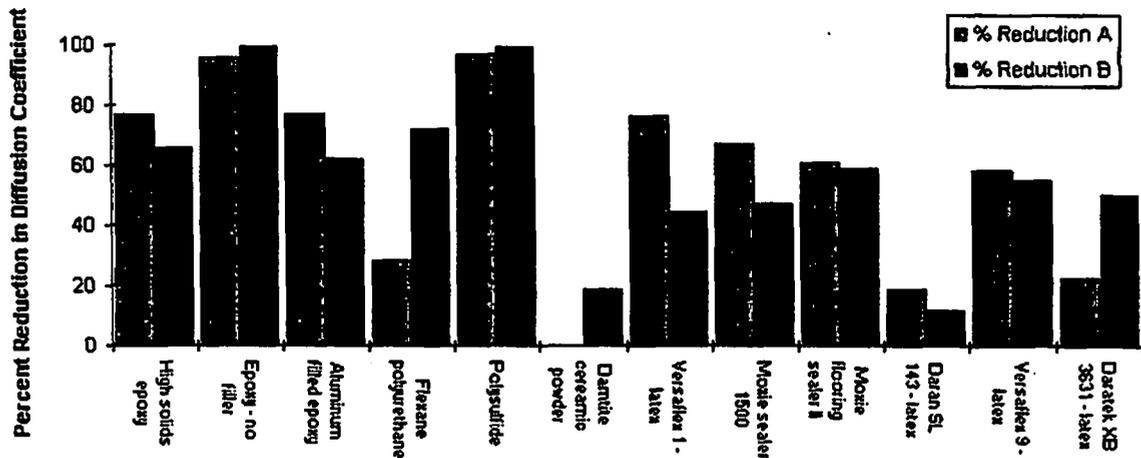


Fig. 4. Reduction of diffusion coefficient with the application of cementitious coating.

The most effective cementitious coatings for reducing the diffusive flow of radon gas were the Polysulfide (97.2% Batch A reduction and 99.6% Batch B reduction) and the Epoxy - no filler (95.8% Batch A reduction and 99.5% Batch B reduction). It should be noted that the reported diffusion coefficients for the sealant materials applied to the concrete samples assumes a homogeneous sample and does not represent the diffusion coefficient of the sealant material itself. Therefore, the sample thickness used in the diffusion coefficient calculations includes both the sealant and the concrete sample.

#### Cementitious coating thickness

The thickness of the coatings, as placed on the concrete samples, were measured with a paint inspection gage. A description of the inspection gage and the experimental procedures employed to measure the coating thicknesses are given in Maas (1997). Table 5 provides the average thickness of the cementitious coating with the measured range shown in parenthesis.

Table 5. Thickness of cementitious coatings on concrete samples.

Cementitious coatings	Batch A (mils)	Batch B (mils)
High solids epoxy	8.6 (3.5 - 10)	5.75 (3.5 - 8.5)
Epoxy - no filler	55 (50 - 60)	49.5 (47 - 55)
Aluminum filled epoxy	30.5 (17 - 49)	8.9 (3 - 17)
Flexane polyurethane	26.5 (21 - 33)	39 (27 - 50)
Polysulfide	27.4 (15 - 35)	29 (23 - 36)
Damtite ceramic powder	100	100 (75-125)
Versaflex 1 - latex	4.5 (2 - 7.5)	0.17 (0.1 - 0.2)
Daran SL143 - latex	15 (12.5 - 17.5)	10.6 (9 - 13)
Versaflex 9 - latex	1.7 (1 - 2.5)	< 1
Daratek XB 3631 - latex	0.8	2.5 (2 - 3)

The experimental uncertainty of the thickness of the coating is dependent upon the cutting tip used and ranged between 0.025 - 0.25 mils (Maas 1997).

#### Adhesion test results

Adhesion tests were performed on six of the sealant materials using procedures described in ASTM 704 03 (ASTM 1994a) with special modifications made to the testing procedure due to the nature of the sealants and the tensile testing machine used. The average force in pounds needed to pull the sealants from the concrete substrate are shown in Table 6. A brief explanation of the characteristics of each material during testing and the adhesion characteristics noted during the measurement of the thickness of the sealants is also reported in Table 6. The interlaboratory experimental uncertainty of this test ranged in value between 60% - 100% (ASTM 1994a).

**Table 6.** Adhesion tests for cementitious coatings on concrete substrate.

Cementitious coatings	Average force (lbs.)	Comments on adhesion test
High solid epoxy	15	ductile tearing manner
Epoxy - no filler	25	brittle cracking
Aluminum filled epoxy	not measurable	best of all sealants
Flexane polyurethane	35	very tough and elastic peel
Polysulfide	17	rubbery peel
Damtite ceramic powder	< 5	brittle cracking under low load

### APPLICATION OF LABORATORY RESULTS: RADON GAS ENTRY CALCULATIONS

To better understand the radon gas transport reducing capabilities of the cementitious coatings, entry calculations were performed to approximate the infiltration of radon gas to indoor air under typical conditions with and without the Polysulfide sealant applied (see Figs. 5 and 6). An entry rate per unit volume was calculated using Darcy's Law for the advective case and Fick's Law for the diffusive case. Then, using the simple model presented by Nazaroff and Nero (1988), the indoor radon concentration was calculated:

$$I = \left( \frac{S_v + I_o \lambda_v}{\lambda_v + d} \right) \quad (9)$$

where,

- I = indoor air radon concentration
- S<sub>v</sub> = entry rate per unit volume of radon
- I<sub>o</sub> = radon concentration in outdoor air
- λ<sub>v</sub> = ventilation rate
- d = decay constant for radon

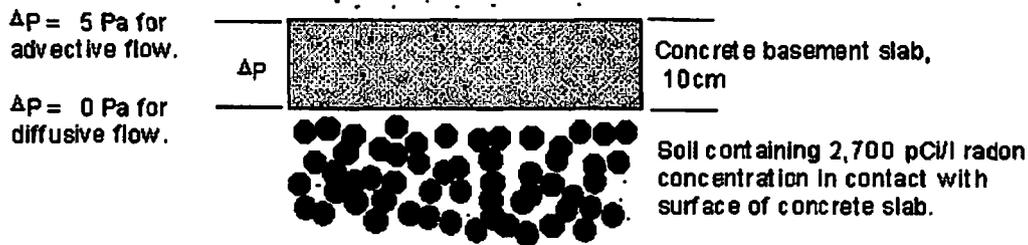


Fig. 5. Conditions present for advective and diffusive entry.

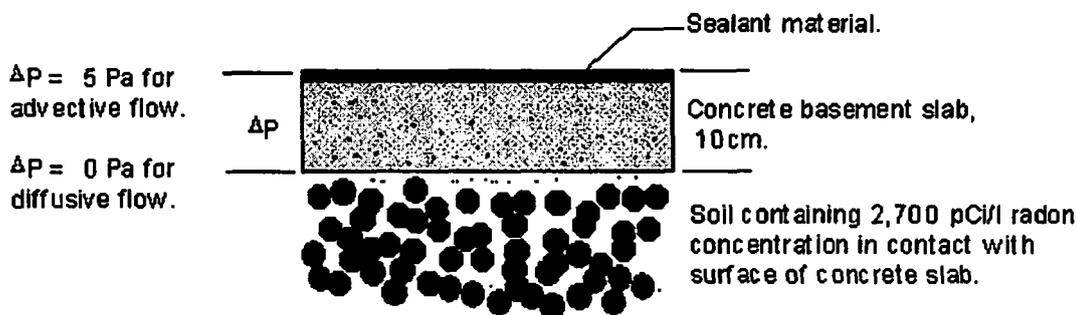


Fig. 6. Conditions present for advective and diffusive entry with the application of a cementitious coating.

#### Advective entry calculation

The radon gas entry rate per unit volume due to a typical pressure gradient of 5 Pa (Renken and Konopacki 1993) across a building foundation can be estimated using Darcy's Law. Utilizing eqn (1):

$$Q = \frac{-kA\Delta P}{\mu L} \quad (1)$$

where,

- $k_{avg} = 1.18 \times 10^{-16} \text{ m}^2$  (average permeability coefficient of Batch A concrete samples)
- $A = 140 \text{ m}^2$  (wall surface area of a typical basement)
- $\Delta P = 5 \text{ Pa}$  (pressure gradient across building foundation)
- $\mu = 1.846 \times 10^{-5} \text{ kg/m-sec}$  (viscosity of air at room temperature)
- $L = 0.10 \text{ m} \approx 4''$  (thickness of typical concrete basement slab)

First, the volumetric flow rate due to the permeability of the concrete is calculated as:  $Q = 4.47 \times 10^{-8} \text{ m}^3/\text{s} = 0.16 \text{ L/hour}$ . The average value for the radon concentration in soil gas is approximately 2,700 pCi/L (Nagda 1994). This entry rate and soil gas concentration will result in a radon entry rate of 435 pCi/hour. The typical dilution volume of a house is equal to  $10^3 \text{ m}^3 = 10^6 \text{ L}$ . Therefore, the diluted concentration is:  $S_v = 4.35 \times 10^{-4} \text{ pCi/L-hour}$ .

Assuming the only mechanism for removal of radon gas is decay,  $\lambda_v = 0$ , the equilibrium radon concentration is calculated from eqn (9) as:

$$I = S_v/d = 0.058 \text{ pCi/L} \quad (10)$$

#### Diffusive entry calculation

Diffusive entry is due to a radon concentration gradient across the building foundation when  $\Delta P = 0$ . The average concentration in soil is again approximately 2,700 pCi/L (Nagda 1994). Using eqn (3), the flux of radon atoms through a typical basement foundation can be estimated as:

$$J = D_{avg} \cdot \frac{dC}{dx} = D_{avg} \cdot \frac{\Delta C}{\Delta x} \quad (11)$$

where,

$$\begin{aligned} D_{avg} &= 2.59 \times 10^{-8} \text{ m}^2/\text{s} \text{ (average diffusion coefficient of Batch A concrete)} \\ \Delta C &= 2,700 \text{ pCi/L} = 2.7 \times 10^6 \text{ pCi/m}^3 \\ \Delta x &= 0.10 \text{ m (thickness of concrete basement slab)} \end{aligned}$$

Using the concrete diffusion coefficient, the radon flux,  $J = 0.70 \text{ pCi/m}^2\text{-s}$ . If this amount of flux enters through a building of dilution volume equal to 1,000  $\text{m}^3$  with a surface area of 140  $\text{m}^2$ , then the total entry rate of radon,  $S_v = 0.35 \text{ pCi/L-hour}$ . The equilibrium concentration of radon is calculated from eqn (9) with  $\lambda_v = 0$ .

$$I = S_v/d = 47 \text{ pCi/L} \quad (12)$$

This indicates that diffusive entry can be a significant source of radon gas to the indoors under the condition of zero ventilation. It also shows that the radon transport method of advection can be insignificant when compared to the diffusion mechanism. It should be noted that a perfectly intact concrete slab (which eliminates the possible large contribution due to advection through cracks, seams and flaws in concrete floorings, slabs and walls) is assumed and the only removal mechanism of indoor radon gas is decay!

The indoor radon concentration due to diffusion for the Batch B concrete sample with and without the application of the Polysulfide sealant was determined using the same technique. The diffusion coefficient of the concrete sample before and after the application of the Polysulfide sealant is as follows:

$$\begin{aligned} D_c &= 8.57 \times 10^{-8} \text{ m}^2/\text{s} \text{ (Batch B concrete sample)} \\ D_s &= 3.25 \times 10^{-10} \text{ m}^2/\text{s} \text{ (Batch B concrete sample with Polysulfide sealant applied)} \end{aligned}$$

From these two diffusion coefficients it is estimated that the indoor air radon concentration could be reduced from 155 to 0.59 pCi/L with the application of the Polysulfide sealant. Again, it is assumed that the ventilation rate is zero and the only mechanism for the removal of radon gas is decay.

Table 7 reports the indoor air radon concentrations due to diffusive entry for all 12 cementitious coatings based on their respective concrete sample diffusion coefficients, before and after sealant application. These results are made with a ventilation rate of zero and 0.1 air changes per hour. Typical ventilation rates range from 0.1 to 1 air changes per hour and often exceed 1.0 air change per hour. As illustrated in Table 7, the utilization of an effective cementitious coating can significantly reduce the radon gas infiltration rate. The Polysulfide and Epoxy-no filler sealants exhibit optimal barrier qualities. These calculations assume a perfectly intact barrier placed throughout the entire surface area of the building foundation: walls and floorings (i.e., no pinholes, thin spots, bubbles, etc.).

**Table 7. Application of diffusion coefficient results with and without ventilation of indoor air.**

Cementitious coating	Diffusive entry without sealant (pCi/L)	Diffusive entry with sealant (pCi/L)	Diffusive entry without sealant and $\lambda_v = 0.1$ (pCi/L)	Diffusive entry with sealant and $\lambda_v = 0.1$ (pCi/L)
High solids epoxy	48.1	11.2	3.63	1.04
Epoxy - no filler	40.4	1.71	3.09	0.37
Aluminum filled epoxy	43.9	10.2	3.33	0.97
Flexane polyurethane	45.3	32.5	3.43	2.53
Polysulfide	63.6	1.8	4.72	0.38
Damtite ceramic powder	42.6	43.4	3.24	3.3
Versaflex 1 - latex	35.6	8.43	2.75	0.84
Moxie sealer 1500	41.7	13.9	3.18	1.22
Moxie flooring sealer II	41.1	16.3	3.14	1.4
Daran SL 143 - latex	40.5	33	3.09	2.56
Versaflex 9 - latex	68.1	28.4	5.03	2.25
Darateck XB 3631 - latex	42.3	32.9	3.22	2.56

### CONCLUSIONS AND RECOMMENDATIONS

Permeability coefficients were obtained utilizing an innovative constant pressure gradient test system. The permeability coefficients measured for cementitious coatings were several orders of magnitude lower than typical concrete indicating the potential for permeability reduction. The testing of the sealants on concrete samples showed substantial reduction in the permeability coefficients for concretes with high permeability ( $k > 10^{-12} \text{ cm}^3$ ). All tested sealants reduced the advective flow by over 60%.

The diffusion coefficient results for the sealant materials were three to four orders of magnitude lower than the diffusion coefficients for the concrete samples. This suggested that the diffusive flux could possibly be reduced substantially by the application of these cementitious coatings. The laboratory experiments with sealant materials applied to the concrete samples revealed that the amount of diffusive flux was greatly reduced by the application of certain sealant materials. Two sealants that showed outstanding promise were the Epoxy - no filler and Polysulfide which reduced the diffusive flux by over 97%.

Thus, the results of this experimental investigation indicate that cementitious coatings should be considered as an effective passive radon mitigation tool under certain conditions.

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