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Radon Generation and Transport In Aged Concrete

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Concretes	Stationary Sources	13C
Radon	Generation	07B
Transport Properties		14G
Slabs		13M
Residential Buildings		

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ABSTRACT

This report presents the results of a study to characterize radon generation and transport in Florida concretes sampled from 12 to 45 year old residential slabs. This report also compares the measurements from the old concrete samples to previous measurements on newly-poured Florida residential concretes. Radon generation in the aged slabs was characterized in terms of concrete radium concentrations and radon emanation coefficients, and radon transport was characterized by radon diffusion coefficients and air permeability coefficients. The radium concentrations and radon emanation coefficients (0.11 ± 0.04) of the old concretes in this study are about the same as those measured previously for newly poured residential concrete samples. The measured radon diffusion coefficients ranged from $1.5\text{x}10^{-7}$ m^2 s^{-1} to $5.5\text{x}10^{-7}$ m^2 s^{-1}. On the average, these values are about a factor of two higher than average values for new residential concretes. The measured air permeability coefficients also average about a factor of two higher than those for new concretes.

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Section 1

INTRODUCTION

Diffusion can be a significant mechanism for radon entry into dwellings (Scott and Gordon 1978; Loureiro et al. 1990). While the diffusive flux of radon through concrete floors is much smaller than the advective or diffusive flux of radon through cracks in the floor, the predominance of the intact floor area over the crack area may compensate for the difference in the fluxes. Thus, it is desirable to examine the radon transport properties of concrete used in floor slabs to better assess radon entry into dwellings.

1.1 SCOPE

This report characterizes the radon generating and transport properties of Florida concretes sampled from the floor slabs of 12 to 45 year old homes. Radon generation is characterized in terms of radium concentrations and radon emanation coefficients. Radon transport is characterized in terms of radon diffusion coefficients and air permeability. Rogers and Associates Engineering Corporation (RAE) conducted this work as part of the Florida Radon Research Program (FRRP), sponsored by the Florida Department of Community Affairs. A previous companion report focuses on newly-poured residential concretes (Rogers et al. 1994). The same measurement procedures used for the previous work with new concrete samples were used for characterizing the older concretes in this report.

1.2 BACKGROUND

Radon generation and transport data from scientific literature are reported by Rogers et al. (1994) for the radium concentration (Ra), the radon emanation coefficient (E), the diffusion coefficient (D), and the air permeability coefficient (K) for concretes. The literature also contains references to the effects of aging on the strength-related properties of concrete. For example, Wood (1991) presents the compressive strength, flexural strength, and modulus of elasticity for concrete samples up to 20 years old. The compressive strength data increase with age and fit a least squares quadratic expression with a correlation coefficient of $r = 0.96$. The data also indicate that the compressive strength reaches about 90 percent of its maximum value in about 5 to 10 years.

Only one specific study on the age effects of either D or K for concrete was found in the literature. Martialay (1987) reported measurements of air permeability for six concrete slabs made over a period of 20 years. The slabs were constructed with identical compositions. They had a water-to-cement ratio of 0.37, which is much less than values for typical residential concretes. Martialay's K values increased with the applied air pressure. The initial K values ranged from 2.4×10^{-14} m^2 to 2.0×10^{-13} m^2, with an average of 9.2×10^{-14} m^2 for the lowest pressure tested, which was 3.9×10^{4} Pa. The factor of eight spread in these values indicates the effects of heterogeneity among the replicate samples. The average K values for the lowest pressure are shown in Figure 1-1 as a function of time (t). Martialay reported that a quadratic expression fit the data very well. The curve in Figure 1-1 is a least squares quadratic fit to Martialay's averaged data. It is given by

$$K = 2.7\text{x}10^{-14} + 1.3\text{x}10^{-13}\, t - 2.9\text{x}10^{-15}\, t^2 \tag{1-1}$$

The fitted equation has a correlation coefficient of $r > 0.999$. The data and curve indicate that K reached its maximum value at about 20 years and that K increased to about 80 percent of its maximum value at 12 years. Thus, most of the increase in K occurred in the first 10 to 12 years.

1.3 REPORT CONTENTS

Section 2 of this report summarizes the previous measurements on new concretes from Rogers et al. (1994), plus the D measurements of an additional new residential concrete and a new polymer concrete. This information is used in this report to provide a baseline for comparison with the present measurements on older concrete samples. Section 3 describes the present samples, the measurement techniques, and the results. The measured values for Ra, E, D, and K from the aged samples are interpreted and discussed in Section 4. Section 5 presents the conclusions of this study.

Section 2

MEASUREMENTS ON NEW FLORIDA CONCRETES

2.1 PREVIOUS MEASUREMENTS

Measurements of radon generation and transport were made on 25 samples of new residential concretes from Florida, as reported by Rogers et al. (1994). The Ra concentrations in the new concrete samples ranged from 0.5 to 2.4 pCi g^{-1}, with an average of 1.2 pCi g^{-1} and a standard deviation of 0.6 pCi g^{-1}. The E values ranged from 0.02 to 0.17, with an average of 0.08 and a standard deviation of 0.04. The measured dry densities of the new samples averaged 2.06×10^3 kg m^{-3} with a standard deviation of 81 kg m^{-3}, and ranged from 1.91×10^3 kg m^{-3} to 2.26×10^3 kg m^{-3}. Similarly, the average total porosity of the samples was 0.21 ± 0.03. These data serve as a useful baseline for estimating the effects of aging on Florida residential concretes.

The D values for these samples ranged from 2.1×10^{-8} to 5.2×10^{-7} m^2 s^{-1}, with an arithmetic mean of 1.9×10^{-7} m^2 s^{-1} and a standard deviation of 1.4×10^{-7} m^2 s^{-1}. The 95 percent confidence in the mean was $\pm$ 5.8×10^{-8} m^2 s^{-1}, assuming a Student's t distribution. The D values generally decreased with increasing concrete density (d), and with increasing water-cement ratio. Figure 2-1 illustrates the variation of D with the concrete density. The line shown in Figure 2-1 is a least squares fit to the measured data as reported by Rogers et al. (1994). The data used for the fit also include six other literature values. The least-squares expression is

$$D = 0.084 \exp(-0.0064d) \tag{2-1}$$

where

D = radon diffusion coefficient (m^2 s^{-1})

d = concrete density (kg m^{-3}).

The fitted line has a correlation coefficient of $r = 0.73$.

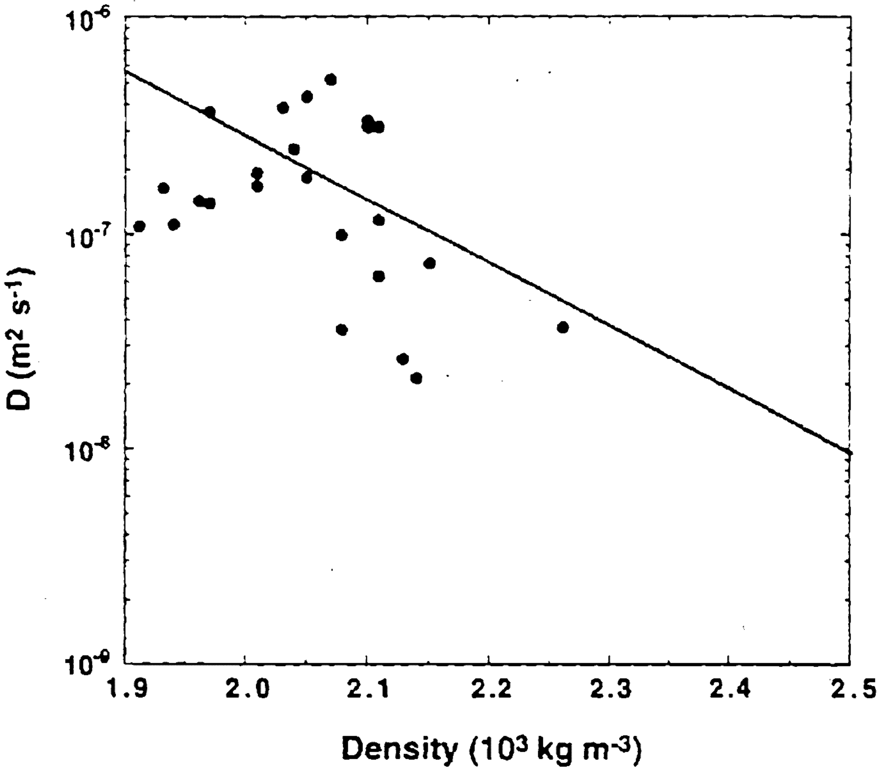

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Figure 2-1. Radon diffusion coefficients measured in new residential concrete (from Rogers et al. 1994). The line is a least-squares fit to the data.

Air permeability measurements also were made on 21 of the new concrete samples. The data from these measurements, shown in Figure 2-2, ranged from 8.0×10^{-18} to 7.1×10^{-16} m^2, with a geometric mean of 1.3×10^{-16} m^2, with a geometric standard deviation of 3.5. The K values also generally increased with decreasing concrete densities. The line in Figure 2-2 is a least-squares fit to the data. This least-squares expression is represented by

$$K = 2.2\times10^{-5} \exp(-0.0126d) \tag{2-2}$$

This fitted line has a correlation coefficient of $r = 0.80$.

2.2 MEASUREMENTS ON OTHER NEW CONCRETE SAMPLES

One of the aged concrete samples was only about one year old and therefore was not included in the aged concrete analysis. However, its D and K values were measured and were consistent with the values for new concretes presented in Section 2.1. The sample, designated as sample B, had a density of 2.10 g cm^{-3}, and a porosity of 0.19. Its measured D value was 2.0×10^{-7} m^2 s^{-1} and its measured K value was 4.4×10^{-17} m^2.

RAE also tested a polymer concrete for comparison to the conventional floor-slab concrete samples. The sample was supplied by Enviromates, Inc., located in Pensacola, Florida. The Ra-226 content of the polymer concrete sample was less than 0.1 pCi g^{-1}, and its D value was less than 7.3×10^{-10} m^2 s^{-1}. Thus, if it is economically practical, the polymer-based concrete could serve as an effective barrier against the diffusion of radon into residences.

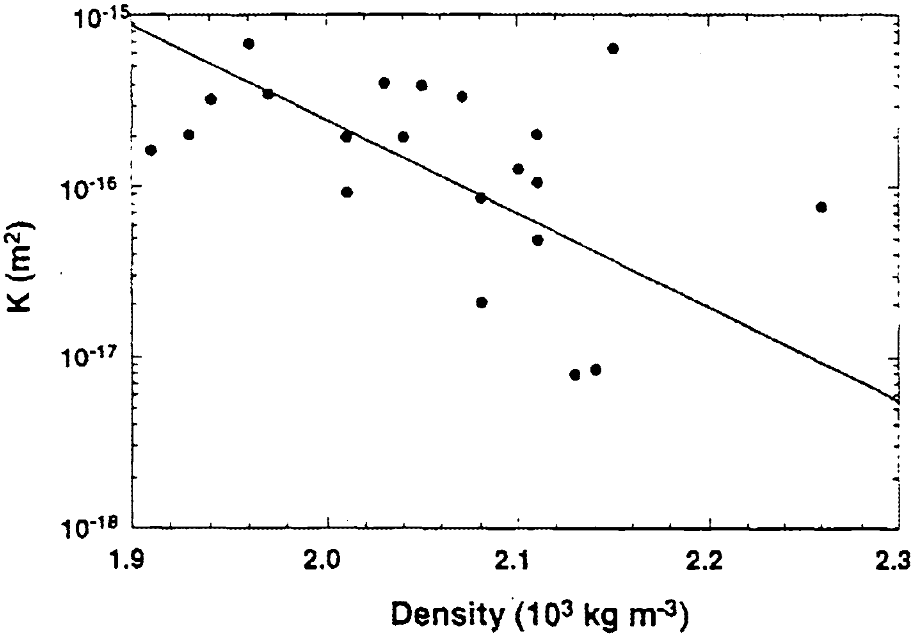

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Figure 2-2. Air permeability measurements of new residential concrete (Rogers et al. 1994). The line is a least-squares fit to the data.

Section 3

MEASUREMENTS ON AGED FLORIDA CONCRETES

3.1 SAMPLE DESCRIPTION

Twenty-two concrete samples were obtained from residential floor slabs in Miami, Boca Raton, Pompano Beach, and Delray Beach. The slab ages ranged from 12 to 45 years. Duplicate samples were obtained at 11 separate locations. Each sample consisted of a 0.09-m diameter cylinder core-drilled through the slab (generally 0.10 m long). Table 3-1 gives the general description of the samples and the sample densities. The samples from location B were about one year old; consequently, their results were not included in the analyses of results for the older samples. The concrete densities ranged from 1.96×10^3 kg m^{-3} to 2.12×10^3 kg m^{-3}. The descriptions and estimates of the extent of their alkali-aggregate reaction, shown in the last two columns of Table 3-1, are from visual observations of the samples. The extent of observable alkali-aggregate reaction generally increased with age, and should also depend on the type of aggregate.

3.2 MEASUREMENT METHODS

The measurements of D, K, Ra, and E were made with the same equipment and procedures used by Rogers et al. (1994). The porosity of the concrete samples was determined both from the measured dry density, as described by Rogers et al. (1994), and from an air intrusion method. The density method gives an estimate of the total porosity (p_t), and the intrusion method gives an estimate of the interconnected porosity (p_i). The interconnected porosity is more closely related to the transport of radon through concrete.

To prepare the samples for the diffusion measurements, each cylinder was epoxied into standard diffusion sample holders (Williamson and Finkel 1991) using an epoxy that has negligibly low radon diffusion and permeability coefficients. The air permeability measurements were also made in the same diffusion sample holder to minimize disruptive handling of the samples.

TABLE 3-1. GENERAL DESCRIPTION OF AGED CONCRETE SAMPLES

Sample Location	Description	Age (yr)	Dry Density (10^3 kg m^{-3})	Hardness of Aggregate	Carbonate Reactivity Aggregate
A	mortar grey, angular and subrounded aggregate, white with little light brown, D_{max}=1.9 cm, well-sorted low porous limestone, contains 50 percent aggregate	12	2.07	Hard	None
B	mortar dark grey, angular aggregate, white and some light brown, D_{max}=1.9cm, well sorted low porous limestone, contains 55 percent aggregate	1	2.10	Hard	None
C	mortar white, uniformly sand cement mixed, angular and subrounded aggregate, white, D_{max}=1.3 cm, well sorted medium porous limestone, contains 45 percent aggregate, cement may include lime	25	1.99	Medium	Moderate
D	mortar grey, angular and subrounded aggregate, white and some light brown, D_{max}=1.9 cm, nonuniformly-sorted low porous limestone included crystal and friable types, contains 55 percent aggregate	18	2.01	Most hard, a few soft	Mild
E	mortar white, angular and subrounded aggregate, white and some light brown, D_{max}=1.9 cm, soft, fine and well-sorted low porous limestone, contains 45 percent aggregate, cement may include lime	20	2.07	Soft	Severe
F	mortar white, angular and subrounded aggregate, white and some light brown, D_{max}=1.3 cm, soft, fine and well sorted low porous limestone, contains 45 percent aggregate, cement may include lime	14	2.09	Most hard, a few soft	Mild

(Continued)

TABLE 3-1. CONTINUED

Sample Location	Description	Age (yr)	Dry Density (10^3 kg m^{-3})	Hardness of Aggregate	Carbonate Reactivity Aggregate
G	mortar grey, angular and subrounded aggregate, white and some light brown, D_{max}=1.9 cm, well-sorted medium porous limestone, contains 45 percent aggregate	45	1.96	Medium	Moderate
H	mortar white, angular and subrounded aggregate, D_{max}=1.9 cm, well sorted low porous limestone with some dark grey and light brown conglomerate, contains 50 percent aggregate, cement may include lime	20	2.03	Medium	Moderate
I	mortar white, angular aggregate, white, some grey and light brown, Dmax=1.9 cm, well-sorted low porous limestone, contains 45 percent aggregate, cement may include lime	15	2.12	Medium	Moderate
J	mortar grey, uniformly mixed sand and cement, angular and subrounded aggregate, D_{max}=1.9 cm, well-sorted medium porous limestone, contains 50 percent aggregate	40	2.09	Medium	Moderate
K	mortar light grey, uniformly mixed sand and cement, angular and subrounded aggregate, white, D_{max}=1.6 cm, well-sorted limestone, medium porosity, contained 50 percent aggregate	21	1.98	Medium	Moderate
L	mortar grey, angular and subrounded aggregate, white and some light brown, D_{max}=1.0 cm, soft, well-sorted medium porous limestone, contains 45 percent aggregate	36	2.01	Soft	Severe

The air intrusion method was used to measure the interconnected porosity with the concrete samples in the same diffusion sample holders. The sample holder was sealed closed on one end and evacuated using a vacuum pump. Air was then introduced back into the sample, and the volume of air needed to re-establish equilibrium with the ambient pressure was measured with a bubble-burette system. Appendix A provides a more detailed description of this procedure.

The Ra concentration measurements were made with the sealed-can, gamma counting method. The emanation coefficients were determined by extracting the free radon from the sealed can into a Lucas cell, and counting to determine the free radon-222 concentration.

3.3 MEASUREMENT RESULTS

Table 3-2 presents the results of the D, K, Ra, E, p_i, and p_t measurements on the samples of the aged concretes.

TABLE 3-2. MEASUREMENT RESULTS

				*	*		
No.	Age (yr)	$D(m^2\ s^{-1})$	$K(m^2)$	$Ra(pCi\ g^{-1})$	E	p_i	p_t
A-1	12	$3.5x10^{-7}$	$2.2x10^{-16}$	1.7	0.085	**	0.20
A-2	12	$1.5x10^{-7}$	$2.6x10^{-16}$			**	0.20
C-1	25	$2.3x10^{-7}$	$1.5x10^{-15}$	0.9	0.13	0.25	0.23
C-2	25	$3.4x10^{-7}$	$1.5x10^{-15}$			0.25	0.24
D-1	18	$4.2x10^{-7}$	$1.4x10^{-16}$	2.1	0.03	0.18	0.23
D-2	18	$3.9x10^{-7}$	$1.4x10^{-16}$			0.17	0.22
E-1	20	$1.8x10^{-7}$	$5.7x10^{-17}$	0.9	0.19	0.12	0.20
E-2	20	$2.4x10^{-7}$	$8.0x10^{-17}$			0.12	0.20
F-1	14	$2.0x10^{-7}$	$7.5x10^{-17}$	1.5	0.11	0.15	0.19
F-2	14	$2.1x10^{-7}$	$7.5x10^{-17}$			0.16	0.19
G-1	45	$2.3x10^{-7}$	$3.9x10^{-16}$	1.0	0.06	0.2	0.24
G-2	45	$2.5x10^{-7}$	$6.4x10^{-16}$			0.24	0.24

(Continued)

TABLE 3-2. CONTINUED

No.	Age (yr)	D(m^2 s^{-1})	K(m^2)	Ra(pCi g^{-1}) *	E *	p_i	p_t
H-1	20	4.9x10^{-7}	5.3x10^{-16}	0.6	0.13	0.24	0.22
H-2	20	3.7x10^{-7}	8.9x10^{-16}			0.24	0.22
I-1	15	1.8x10^{-7}	1.1x10^{-16}	1.7	0.14	0.18	0.21
I-2	15	2.4x10^{-7}	5.3x10^{-17}	1.8	0.12	0.17	0.16
J-1	40	3.1x10^{-7}	4.7x10^{-15}	0.5	0.12	0.19	0.19
J-2	40	3.5x10^{-7}	3.4x10^{-16}	0.3	0.17	0.2	0.20
K-1	21	4.8x10^{-7}	4.4x10^{-16}	1.3	0.14	0.22	0.24
K-2	21	5.5x10^{-7}	4.4x10^{-16}			0.22	0.24
L-1	36	3.2x10^{-7}	3.7x10^{-16}	2.2	0.11	0.21	0.22
L-2	36	2.8x10^{-7}	2.9x10^{-16}			0.21	0.23

* Ra & E Values generally obtained for 1 sample per pair

**Not measured

The D values ranged from 1.5x10^{-7} m^2 s^{-1} to 5.5x10^{-7} m^2 s^{-1}, with an arithmetic mean of 3.1x10^{-7} m^2 s^{-1} and a standard deviation of 1.1x10^{-7} m^2 s^{-1}. The 95 percent confidence interval about the mean was 2.6x10^{-7} to 3.6x10^{-7} m^2 s^{-1}.

The K values ranged from 5.3x10^{-17} m^2 to 4.7x10^{-15} m^2, with a geometric mean of 2.7x10^{-16} m^2 and a geometric standard deviation of 3.1. The 95 percent confidence interval about the mean was 1.6x10^{-16} to 4.4x10^{-16} m^2.

The Ra concentrations for the aged concrete samples ranged from 0.3 pCi g^{-1} to 2.2 pCi g^{-1}, with an arithmetic mean of 1.3 pCi g^{-1} and a standard deviation of 0.6 pCi g^{-1}. The E values ranged from 0.03 to 0.19, with an arithmetic mean of 0.11 and a standard deviation of 0.04.

Except for samples C and H, the p_i values were all generally less than or equal to the p_t values, within measurement uncertainties. The p_i values exceeded the p_t values by about 8 percent for samples C and H. The p_i values ranged from 0.12 to 0.25, with an arithmetic mean of 0.19, and the p_t values ranged from 0.16 to 0.24 with a mean of 0.21. Thus, the ratio of the average p_i to p_t was 0.88. The relative uncertainties associated with the duplicate measurements were 21 percent for the D data, 37 percent for K, 15 percent for the radium concentrations, and 30 percent for the radon emanation coefficients. Section 4 provides an interpretation and discussion of these data, and Appendix B contains a detailed discussion of their quality assurance analyses and results.

Section 4

DISCUSSION

In this section the data from the aged concrete measurements are analyzed and compared to the new concrete data summarized in Section 2.

4.1 DIFFUSION COEFFICIENTS

The D values for the aged concretes average about a factor of 1.6 greater than for the new concretes. This difference in the means is significant at the 95 percent level of confidence. However, since D varies with density, this difference may be attributed to differences in concrete density. The densities and total porosities of the new and aged concrete samples are equivalent within the measured variations. Their means differ by only a few percent. Thus, different density values should not account for the differences in the D values between the new and aged concrete samples. This fact is further illustrated in Figure 4-1, which presents the aged concrete D values as a function of density. The line in Figure 4-1 is the new concrete correlation, given in Equation 2-1. About two-thirds of the data points for the aged concrete are above the correlation line for the D_{cor} of new concrete. This result suggests that the D for concrete may increase slightly with age, independent of its density dependence.

In order to remove the density dependence from the aged concrete D values, the aged-concrete D values were divided by the estimate of each D value using the new-concrete correlation (Equation 2-1). The resulting ratio is the relative variation of the measured D values for the aged concrete from the new concrete correlation value. Biased deviations of this ratio from unity should then correlate with the age of the concrete if D increases with age, independent of density. The D/D_{cor} ratio is plotted in Figure 4-2 as a function of the age of the concrete. The average value of D/D_{cor} is 1.9. However, the data show no general trend with age. A linear least-squares fit to the data, also shown in Figure 4-2, has a correlation coefficient of only $r = 0.23$. Therefore, on the average, the D value for residential concretes more than 10 years old is about a factor of two higher than the average D value for new concrete in Florida, when

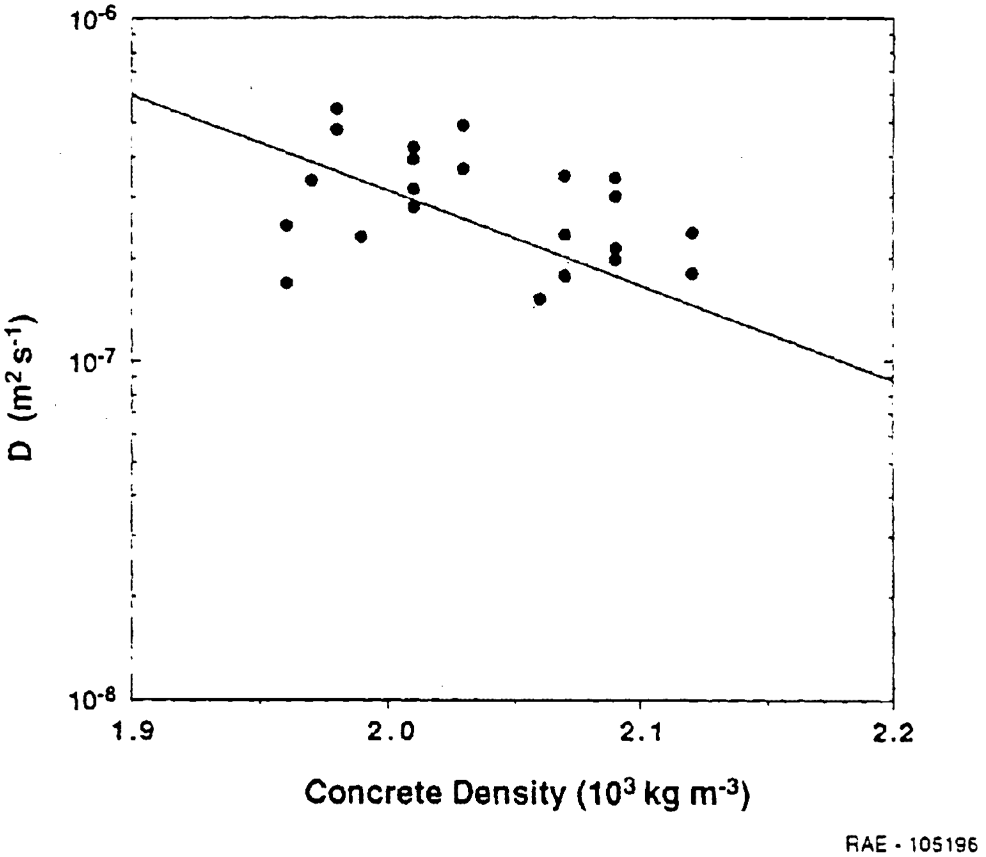

Figure 4-1. Diffusion coefficients for aged concrete (dots) and regression line for new concrete (Rogers et al. 1994).

corrected for density effects, but the D value for any one aged concrete sample is within the range of variability of D for new concrete.

The lack of a trend in D/D_{cor} with time for periods greater than 10 years generally is consistent with the trend in the literature for the change in K and the change in compressive strength with age, as discussed in Section 1. However, other unmeasured or unknown parameters may also influence D for aged concrete. As stated in Section 1, the alkali-aggregate reaction may occur over time in concrete. While this may contribute to an increase in D, there is no significant evidence in the present data to confirm this.

4.2 AIR PERMEABILITY

The variation of K with age is similar to the variation with D. On the average, the K value for the aged concrete is about 2.2 times greater than the K value for new concrete, and the range extends about six times higher than the range of K for new concrete. Both the aged and the new concrete K values are significantly less than the K values reported by Martialay.

Figure 4-3 presents the K values for the aged concrete as a function of density. The figure also shows the correlation line of K versus density for the new concrete measurements. The effect of density on K can be reduced by again dividing the aged concrete values by the corresponding correlation estimate. The resulting ratios, shown versus concrete age in Figure 4-4, show no general trend with age. This is consistent with the results from Martialay, who reported that K for concrete reaches about 80 percent of its maximum value by about 12 years of age. Therefore, the decrease in K with density suggested in Figure 4-3 is a density trend that is not otherwise associated with concrete age.

4.3 RADIUM, EMANATION COEFFICIENT, DENSITY, AND POROSITY

The average radium concentrations, emanation coefficients, densities, and total porosities are the same for the aged Florida concretes as for the new concretes, within the measurement uncertainties. These variables also do not show any significant trends with age.

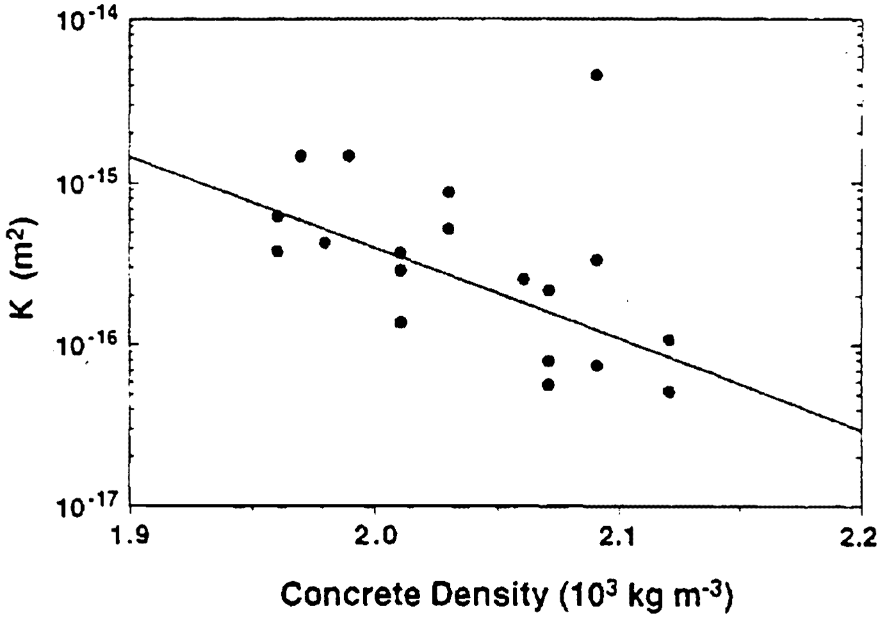

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Figure 4-3. Air permeability of aged concrete as a function of concrete density. The line is the correlation from the new concrete K values (Rogers et al. 1994).

Section 5
CONCLUSIONS

Radon diffusion and air permeability coefficients have been measured for Florida residential concretes ranging from 12 to 45 years old. In general, the D values for the aged concrete average about 1.6 times the values for the newly poured Florida concretes, but are within the range of D values for the new concretes. The aged K values also average about a factor of two higher than for the new concretes, but the range of K values increases by over a factor of 6 for the aged concretes. The Ra-226 concentrations and radon emanation coefficients for the aged concretes are about the same as for the new concretes.

Appendix A

METHODS FOR MEASURING THE EFFECTIVE POROSITY OF CONCRETE

This appendix contains the laboratory procedures used to measure the interconnected porosity of concrete samples.

A.1 EQUIPMENT

The following equipment is required to perform the interconnected porosity measurements:

1. Vacuum pump, 0.7 CFM,* 5-micron, 1/8-HP (Model DD20, Precision Scientific Group, Chicago, Ill., or equivalent).
2. Graduated burette, 100-cc (min) with two bottom vents as shown in Figure A-1.
3. Metal plate for connecting the top edge of the diffusion tube with the clear tubing (see Figure A-1). The plate must have a center hole and a hose barb for connecting the tubing.
4. Tubing, 1/4-inch O.D., 1/8-inch I.D., clear PVC, vinyl or equivalent.
5. Epoxy for mounting the concrete sample in the diffusion tube. DURO Master Mend 90-minute epoxy or equivalent.
6. Vacuum bag sealant tape. Richmond Aircraft Products RS200.

A.2 PROCEDURES

A nondestructive test has been developed to measure the interconnected porosity of concrete samples. Figure A-1 illustrates the test apparatus. To perform this test, the concrete sample is mounted in a diffusion tube using an impermeable epoxy. The sample is then sealed on one edge and evacuated using a vacuum pump. The sample is then allowed to re-equilibrate, and the volume of air necessary to re-establish equilibrium is measured using a bubble in a graduated burette. The detailed procedure is as follows:

(*) 1 CFM = 0.00047 m^3/s; 1 micron = $1 \mu m$; 1HP=746W; and 1 in. = 0.025m

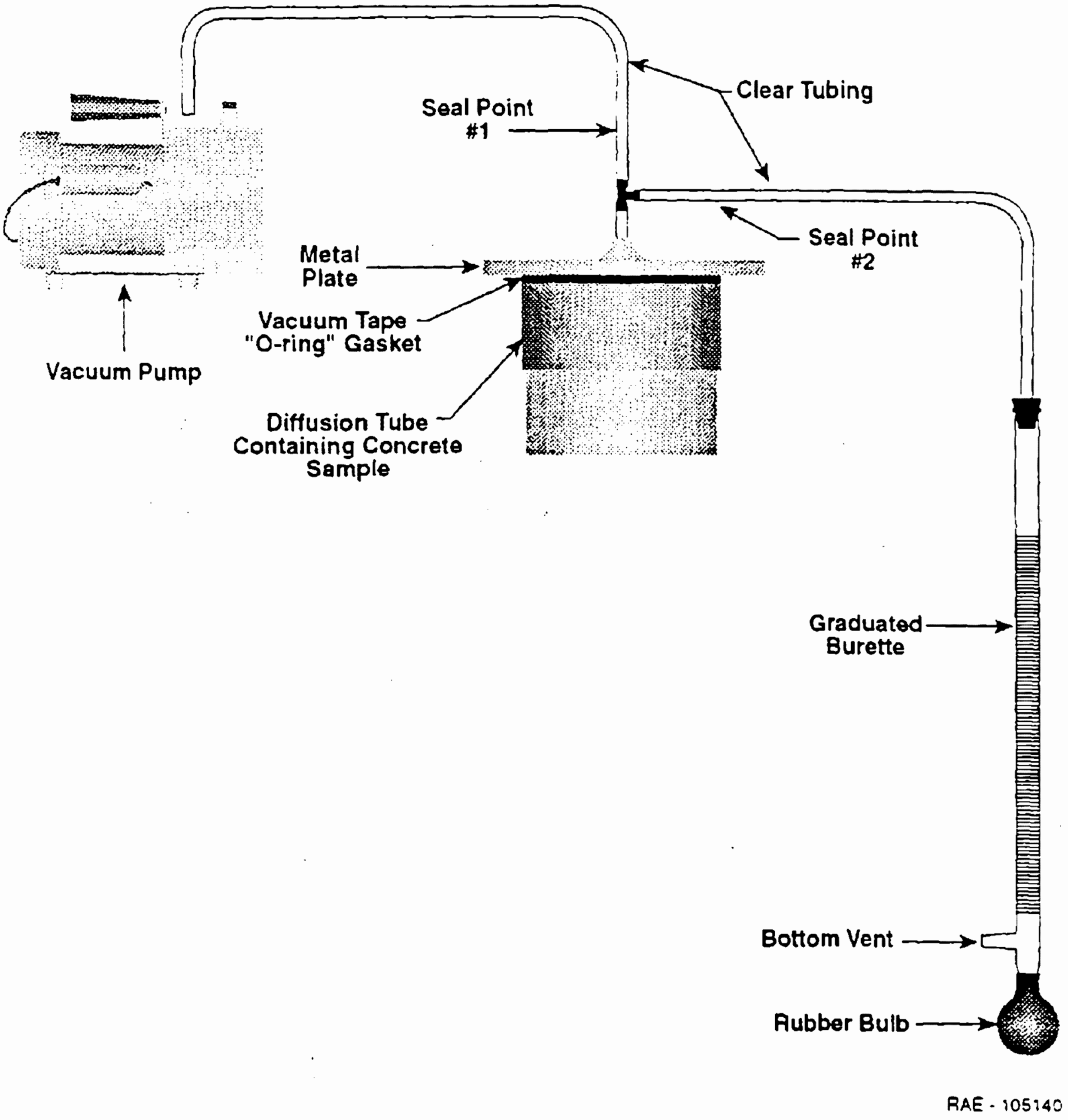

Figure A-1. Apparatus for measuring the interconnected porosity of concrete samples.

Appendix B

QUALITY ASSURANCE FOR CONCRETE ANALYSIS

The quality assurance of all analyses is determined by three data quality parameters: precision, accuracy, and completeness. The following sections present the summary statistics of the analytical results in terms of these data quality parameters for radium assays, radon emanation, radon diffusion, and permeability coefficients. Completeness of the laboratory tests is estimated from the total number of measurements compared to the total number of samples available for testing. According to this basis, the completeness percentage for all analyses was 100 percent.

B.1 RADIUM CONCENTRATION MEASUREMENTS

There are no numerical data quality indicators for radium concentration measurements in concrete due to the lack of prior testing and of radium levels and variability in concrete. However, comparisons between the data quality indicators for soils (Nielson and Rogers, 1991) and concrete illustrate the precision of the sealed-can, gamma counting method. The precision of the radium determinations is defined as the relative measurement uncertainty.

All the uncertainties in the radium determinations are less than ±20 percent at >2 pCi g^{-1}. As expected, numerous measurements are associated with higher uncertainties, but these are all in a radium range low enough to approach the detection limit.

A second estimate of the precision of the radium determinations is based on comparing the results of duplicate assays for a selected number of samples. Three duplicates were counted in the radium and emanation determinations. Table B-1 summarizes the results for radium concentrations. The final column lists the differences between the duplicate assay results and those given in the report. The average absolute difference is -0.2 pCi g^{-1}. The relative standard deviation between the duplicate measurements is 14.6 percent. The relative standard deviation is computer as (Rogers, et al., 1994).

$$RSD_{dup} = \sqrt{2n \, \Sigma \, (x_1 - x_2)^2} \; / \; \Sigma \, (x_1 + x_2) \qquad \textbf{(B-1)}$$

where

RSD_{dup} = relative standard deviation among duplicates

x_1 = first observation

x_2 = second observation

n = number of pairs being compared.

TABLE B-1. COMPARISON OF DUPLICATE RADIUM ASSAYS TO ESTIMATE ANALYTICAL PRECISION

Sample No.	Duplicate Radium ($pCi\ g^{-1}$)	Original Radium ($pCi\ g^{-1}$)	Difference ($pCi\ g^{-1}$)
A-1	1.6	1.7	-0.1
C-1	0.8	0.9	-0.1
D-1	1.6	2.1	-0.5
Average absolute difference ($pCi\ g^{-1}$)			0.2
Relative standard deviation (all detected)			14.6 percent

The agreement of similar analyses with standard reference material demonstrates the accuracy of the radium concentration measurements. An Isotope Products Laboratory (IPL) reference material was spiked into several powdered quartz sand aliquots to prepare the standard at 1014 ± 16 $pCi\ g^{-1}$. The material was sealed in a can similar to those used for the concrete samples and was analyzed regularly at the beginning and end of each batch of samples. Table B-2 presents the results of these analyses.

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