Indoor Air 1993, 3: 376–381
Printed in Denmark · all rights reserved

#7551

Indoor Air
ISSN 0905-6947

Causes of Poor Sealant Performance in Soil-Gas-Resistant Foundations

Arthur Scott[1]

Abstract

Sealants for radon-resistant foundation construction must seal the gap between concrete sections. Modern sealants have such low permeability that seal performance depends only on the permeability of the material that contacts the sealant. The surface permeability of concrete walls and floors was measured by a specially designed permeameter, which measures the airflow induced by a pressure difference across a temporary test seal applied to the surface. The permeability of bulk concrete is about 10^{-16} m^2. Areas free of surface defects had surface permeability ranging from 10^{-14} to 10^{-16} m^2. However, surface defects are common on concrete wall surfaces, which increase the permeability to $>10^{-12}$ m^2, too high for standard seal designs to be adequate as the only method of soil gas and radon exclusion. Radon-resistant seals require either extended contact widths or mechanical removal of the surface layer and defects.

KEY WORDS:
Permeability, Radon, Concrete, Sealants, Field measurements.

[1] Arthur Scott and Associates, 2020 South Millway Drive, Unit 11, Mississauga, Ontario, Canada L5L 1K2, Telefax 416-828-2389

Introduction

A typical house has a ventilation rate of 200 m^3 h^{-1}, so a radon supply rate of 8×10^3 Bq h^{-1} is needed to cause a house air concentration of 40 Bq.m^{-3}. If the house is in a radon-prone area with a soil gas concentration of 200 kBq m^{-3} (5 400 pCi.L^{-1}), this corresponds to a soil gas entry rate of 0.04 m^3 h^{-1} (1.1×10^{-5} m^3 s^{-1}).

The flow of soil gas into a house is set by the pressure difference across the soil and foundations and the total resistance. The pressure difference across foundations and soil is about -4 Pa, so a flow of 1.1×10^{-5} m^3 s^{-1} is equivalent to a soil plus foundation resistance (=pressure/flow) of 4×10^5 Pa s m^{-3}. This suggests that a criterion for a radon-resistant foundation should be that the foundation resistance is high enough to limit the soil gas entry rate to less than 0.04 m^3 h^{-1}, or a foundation resistance, R_{min}, $\geq 4 \times 10^5$ Pa s m^{-3}. The radon supply rate from soil gas entry will be less than the supply by diffusion from and through the building materials. As the resistances of the foundation components are in parallel, to ensure a foundation resistance $>4 \times 10^5$ Pa s m^{-3}, the resistance of a single component such as the wall/floor joint seal should be ten times higher than R_{min} or 4×10^6 Pa s m^{-3}. This will be used as a criterion for a radon-resistant seal.

Air permeability of solid concrete is $\sim 10^{-16}$ m^2 (Grace; Bakker, 1983) which is so low that significant soil-gas and radon flows cannot take place *through* concrete. Soil-gas enters buildings through low-resistance openings and joints between concrete sections, and can be excluded if these are sealed. Modern sealants have an air permability of 10^{-22} m^2 (Grace; ASTM, 1984), much less than that of concrete, so the total resistance of a poured concrete basement with sealed joints should approach the resistance of the 200 m^2 of concrete itself (10^7 to 10^8 Pa s m^{-3}). This resistance is much higher than that needed for a radon-resistant foundation, so it should be a matter of course to transform ordinary foundations into radon-resistant ones by sealing the joints. Nevertheless, sealing as a passive preventive measure in new construction has had poor success. Possible explanations for this are:

- not all openings through the basement concrete were sealed during construction;
- the bulk permeability of the concrete used in the houses was much higher than 10^{-16} m^2;
- the effective resistance of the joints and openings was less than 4×10^5 Pa s m^{-3}, despite the application of sealants.

The presence of unsealed openings is a design or supervision failure, and can be overcome by improved foundation designs, training in sealant application techniques, inspection, and familiarity with the task requirements. However, if the permeability of the concrete used in houses is much higher than 10^{-15} m^2, or if sealants cannot bond effectively to the concrete surface, then passively radon-resistant housing cannot be produced by sealing openings, no matter how good the design or workmanship.

Concrete surfaces differ in composition and texture from bulk concrete. The vertical surface layer in contact with the form is composed almost entirely of cement paste and the smallest aggregate particles. The thickness of this layer is 3 to 5 mm, depending on the mix and concrete placement practices. Water released from setting concrete bleeds to the surface, and drains down between the form and the concrete, producing small vertical channels and sometimes "honeycombing" of this cement surface layer.

When concrete is poured, large air bubbles are trapped in the mix, and lodge against the forms, pitting the surface cement layer. Most concrete mixtures have 1–2% volume of air incorporated in the cement paste as ~0.5 to 1 mm diameter bubbles to increase the fluidity and these bubbles are present throughout the surface layer. They may link to make interconnected pores that increase the effective permeability of the vertical surface layer to much higher values than bulk concrete. In contrast, horizontal surfaces are trowelled or "floated" for appearance. The trowelling eliminates air bubbles, pores and pits from the horizontal surface cement layer.

A common sealing detail uses a formed slot to hold the sealant between concrete sections. The width is typically 12 to 25 mm. The sealant thickness is limited to about half the width of the joint so that relative movement of the units can stretch the sealant material without generating high stresses that might break the adhesive bond to concrete. Sealant contact widths of 5 to 10 mm are implied. This is illustrated in Figure 1, together with an indication of the potential soil gas entry routes bypassing the seal via porous surface layers.

The joint between two surfaces that meet at right angles with small relative movement can be closed by caulking. A bead of sealant is placed in the corner between the surfaces and tooled into contact with both surfaces. Sealant contact widths of 5 mm are implied. This is illustrated for a wall/floor joint in Figure 1, together with the potential soil gas entry routes bypassing the seal via porous surface layers.

The permeability of the concrete in contact with the sealant bead limits the achievable seal resistance. To illustrate: if the resistance of a 40 m sealed basement perimeter joint is 4×10^6 Pa s m^{-3}, the resistance of each metre of seal must be 1.6×10^8 Pa s m^{-2} (resistances in parallel). A seal as shown in Figure 1 has two parallel contact surfaces, so the linear resistance of each contact surface must be 3.2×10^8 Pa s m^{-2}.

If the sealant makes a perfect bond with the con-

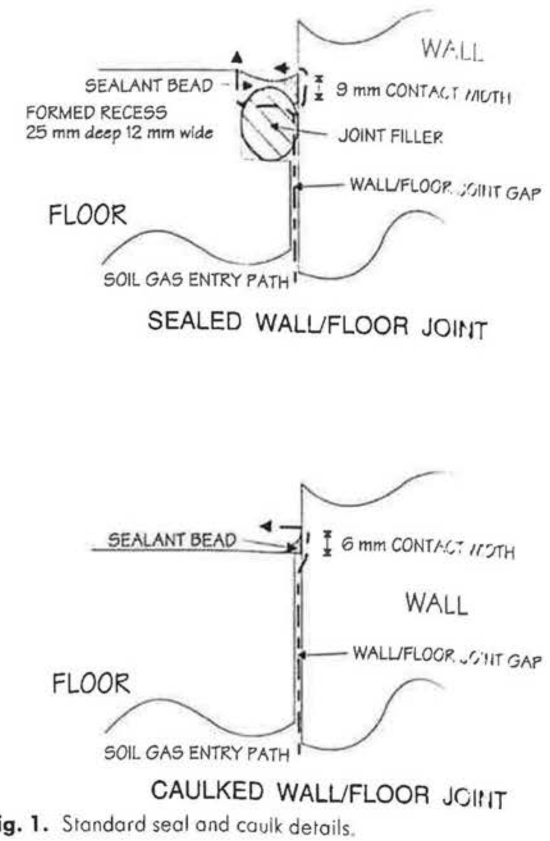

Fig. 1. Standard seal and caulk details.

crete surface, air can only move past the seal through the concrete itself. The linear resistance of the concrete section beneath the seal, R_L, is related to permeability by Darcy's law:

Darcy's law

$$Q = \frac{kA}{\eta}\frac{P}{L} \text{ Resistance} = \text{pressure/flow} = \frac{P}{Q} = \frac{L\eta}{kA}$$

$$R_L = \frac{(C + 1.4\,T)\,\eta}{k_s\,T}\,\mathrm{Pa\,s\,m^{-2}} \tag{1}$$

where C = sealant contact width (m), T = thickness of surface layer (m), η = air viscosity (1.8×10^{-5} Pa.s), k_s = permeability of surface layer (m^2). The average path length beneath the seal was estimated at 1.4 T longer than the seal contact width C by numerical analysis of the flow pattern.

For a seal contact width of 6 mm, and a 3 mm thick surface layer, Equation 1 implies that a surface layer permeability of 2×10^{-13} m^2 is needed to achieve the linear seal resistance of $R_L = 3.2 \times 10^8$ Pa s m^{-2} needed for a radon-resistant seal. The permeability of cement paste is $\sim 10^{-15}$ m^2 (Powers et al., 1955), so we expect that joints between "floated" concrete surfaces can be sealed effectively. However, vertical surfaces or concrete masonry units may contain interconnected pores that increase the effective permeability of the surface layer to much higher values.

Standard seal designs will be satisfactory for radon-resistant foundations only if the surface permeability is consistently much lower than 2×10^{-13} m^2. A surface permeameter suitable for field measurements was developed to measure the surface layer permeability of concrete produced by current house building practices.

Method

A temporary 6 mm wide seal (comparable to the width of a standard seal detail) is placed on the surface to be tested. A chamber is sealed to the surface on one side of the seal, and a second chamber is sealed to the surface on the other side of the seal. There is no direct connection between these chambers except that both touch the same concrete surface. One chamber is depressurised to a constant pressure with a variable speed pump, and leakage through the concrete beneath the seal draws air out of the second chamber. The airflow from the second chamber is measured by displacement of an oil slug in a capillary tube attached to the second chamber.

A cross-section sketch of the permeameter is shown in Figure 2. Each chamber is semicircular; 35 cm long, 8 cm wide, and 4 cm high. The length of concrete surface under test is 30 cm. At a linear seal resistance of 1×10^{10} Pa s m^{-4} (100 times higher than the required value for an effective radon-resistant seal), an under-pressure of 1000 Pa in the first chamber will give a flow of 3×10^{-8} m^3 s^{-1} (3 cm^3 min^{-1}) out of the second chamber. This is equivalent to a 0.2 m min^{-1} displacement rate in a 3 mm diameter tube, which is easily measured.

The feasibility of the field test procedure depends on producing a very good seal between the surface under test and the measurement chamber edge to ensure that all air drawn past the test seal is replaced by air drawn solely through the measurement tube. A rope caulk was tested as the chamber edge sealant by sealing a chamber to a metal sheet, depressurizing the chamber, and estimating the very low leakage rate from the rate of pressure rise in the chamber. The resistance of the perimeter seal and all the rest of the apparatus, including connectors, hoses, manometer, pump shut-off valve, and joints in the chamber itself was 2×10^{12} Pa.s.m^{-3}.

A good seal against concrete cannot be produced reliably with just rope caulk alone because of surface dusting. A two-stage seal is used. The surface is coated with rubber cement, which bonds to both the concrete and the rope caulk. This two-stage seal was tested by sealing a closed chamber to a solid concrete slab, and estimating the leakage flow from the rate of pressure change as the pressure rose from −8 000 Pa to −500 Pa. The resistance from all flow paths, including flow though the 50 mm thick slab,

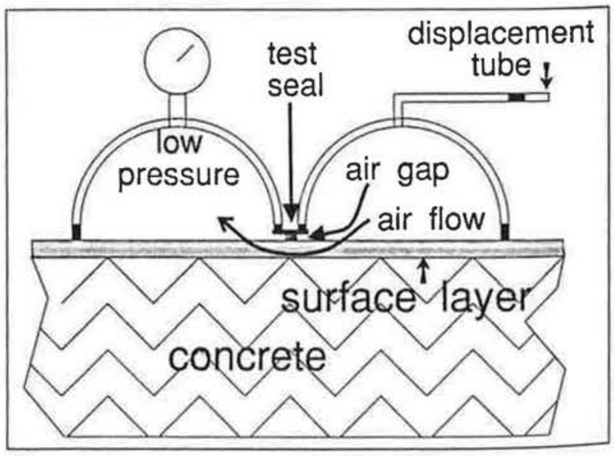

Fig. 2. Surface permeability measurement apparatus.

was $> 1 \times 10^{11}$ Pa.s.m^{-3}. If the measured leakage took place entirely through the concrete slab, the bulk permeability of the slab was $\sim 10^{-16}$ m^2.

The seal resistance estimates given by this test did not vary systemically with pressure. This suggests that estimates (of high resistance at least) do not depend on the pressure difference across the seal. The resistance of this perimeter seal is 100 times higher than the resistance of a 300 mm section of a satisfactory test seal (10^9 Pa s m^{-3}), so leakage past the non-test seal will not significantly affect estimates of test seal resistance.

If tests were carried out in the laboratory alone, the test seal material would be a polyurethane caulk, but the setting time is ~ 24 hours, which is too long to use in a field test. Rubber cement will set in a minute, and was tested as a surrogate seal material. Polyurethane caulk[1] and rubber cement seals 6 mm wide were applied to the same concrete slab, and tested with the permeameter. The polyurethane seal had an apparent linear resistance of 10^{11} Pa.s.m^{-2}, while the rubber cement seal had an apparent linear resistance of 2×10^{11} Pa.s.m^{-2}. This shows that rubber cement and polyurethane can produce comparable test seals. Both these resistances are much higher than the linear resistance criterion of 3×10^8 Pa.s.m^{-2} suggested for a radon-resistant seal.

A temporary test seal is produced in the field by placing two 300×25 mm strips of non-adhesive plastic tape on the surface with a 6 mm gap between their inner edges. A 50 mm wide band of rubber cement is painted (three coats) over the tapes and the 6 mm strip of exposed concrete. This forms a continuous airtight film between the permeameter chamber edge seals and a 6 mm wide sealant contact zone. The plastic tape provides a low resistance path from chamber to edge of the test seal beneath the chamber edge seals. A 20 mm band of rubber cement is painted (two coats) onto the concrete where the chamber edge seal (non-test seal) will land. This is illustrated in Figure 3.

Rope caulk is placed on the chamber edges, and the chambers forced into contact with the rubber cement. Both chambers are connected and depressurised together by a variable speed electric pump. If a pressure of $-8\,000$ Pa is not achieved, each chamber is depressurised in turn with the pump. If a pressure of $-4\,000$ Pa is achieved in a chamber, it is selected as the test chamber, and held depressurised for at least a minute to allow atmospheric pressure to compress and force the rope caulk seal into good contact with the surface to produce an airtight seal. The oil slug in the capillary tube needs a pressure difference of 1 to 2 Pa to move along the tube, so this procedure was adopted to ensure that all the air drawn out of the chamber past the test seal is replaced by air drawn through the capillary tube.

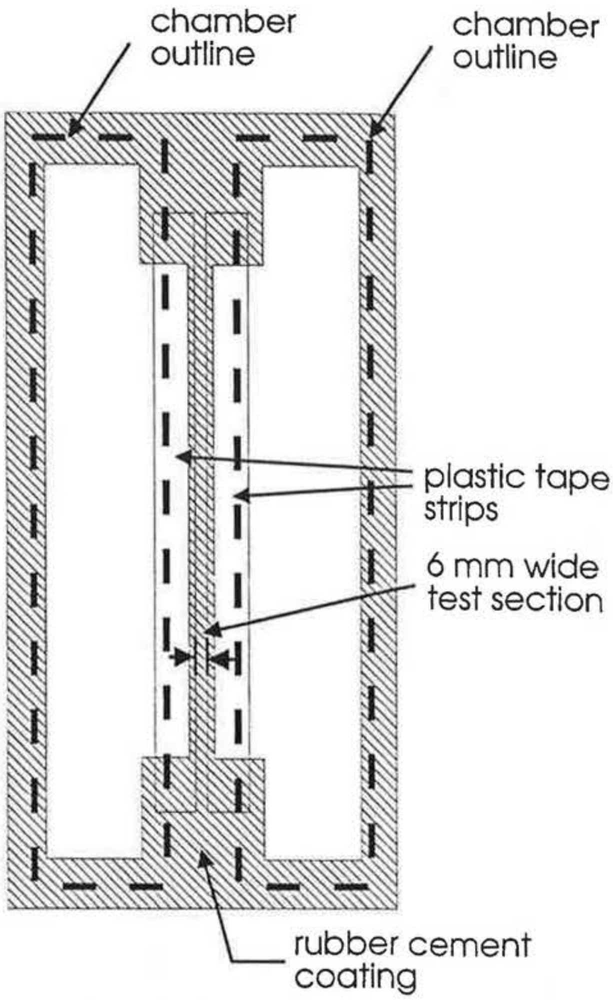

Fig. 3. Test seal application detail.

If a pressure lower than -300 Pa could be obtained in the other chamber, it is used as the depressurization chamber; if not, another location is selected for the test seal.

Results

Concrete walls and floors of new basement houses built by different contractors were tested to measure the surface permeability of concrete produced and finished with current practices. Table 1 summarizes

[1] Tremco DyMonic caulk, Tremco Inc.

Table 1 Surface permeability of basement concretes.

Effective permeability of concrete surfaces (m^2) (nominal concrete permeability 1×10^{-16} m^2)		
Floor	Wall without surface pores	Wall with surface pore
8.8×10^{-16}	7.7×10^{-15}	1.8×10^{-12}
1.3×10^{-15}	3.6×10^{-17}	1.0×10^{-12}
1.0×10^{-16}	6.2×10^{-12}	1.0×10^{-11}
9.2×10^{-14}	3.5×10^{-16}	6.8×10^{-12}
7.0×10^{-15}	1.8×10^{-14}	–

the effective surface permeability of concrete surfaces. Table 2 lists the test sites and the measured pressure, flow, calculated R_L of a 6 mm wide seal and surface permeability. Sections of the concrete surface layer were chiselled away at each test location to estimate the layer thickness. The thickness varied from spot to spot on the same wall, most values being between 2 and 4 mm. The average thickness was 3 mm.

In general, the permeability of smooth defect-free surfaces on both concrete walls and floors averages 10^{-15} m^2, 10 times higher than the nominal bulk permeability of 10^{-16} m^2. Values were highly variable, ranging from a low of 3.6×10^{-17} m^2 on a wall, to a high of 9.2×10^{-14} m^2 on a poor quality concrete floor surface.

However, the testing found that concealed and connected sub-surface pores long enough (>20 mm) to bridge the chamber perimeter seal are common in vertical surfaces. They are large enough to increase the apparent permeability to $>1 \times 10^{-12}$ m^2. This is greater than the maximum acceptable permeability of $\sim 10^{-13}$ m^2 suggested for "radon-resistant" seals. One wall permeability measurement was as high as 6.2×10^{-12} m^2, comparable to effective permeability measured when bypass pores are present. Perhaps a concealed pore bypassed the test seal in this measurement. These frequent sub-surface bypasses will limit resistance achievable by any long seal, no matter how well the sealant bonds to the surface.

Discussion

The vertical concrete faces examined had cement surface layers 2 to 5 mm thick, containing many 0.5 to 1 mm diameter air bubbles, plus large pits, depressions and "wormtracks" caused by connected strings of larger air bubbles trapped in the surface layer between concrete and form. These surface features depended on form preparation, not the concrete mix, for different surface textures were found on adjacent form sections of the same wall.

Wall areas tested with the permeameter were selected to be as smooth, level and as free from pits as possible, for it is very difficult to seal the permeameter chambers to an uneven, pitted surface. Despite this careful selection, in each wall test one of the chambers had a high leak rate, caused by connected pores in the surface layer bypassing the 15 to 25 mm wide rubber cement perimeter seal area. This suggests that pores large

Table 2 Permeameter measurement data.

Site	Pressure (-kPa)	Flow (m^3/s)	Linear resistance[1] ($Pa.s.m^{-2}$)	Surface permeability[1] (m^2)
A 11 garage floor	2.50	8.0×10^{-9}	9.2×10^{10}	8.8×10^{-16}
M 51 wall pore*	1.10	1.0×10^{-5}	7.7×10^{7}*	1.8×10^{-12}*
M 51 wall	1.10	3.1×10^{-8}	1.0×10^{10}	7.7×10^{-15}
M 51 floor	2.80	1.3×10^{-8}	6.4×10^{10}	1.3×10^{-15}
P 43 wall pore*	1.45	7.5×10^{-6}	1.4×10^{8}*	1.0×10^{-12}*
P 43 wall	1.45	1.9×10^{-10}	2.3×10^{12}	3.6×10^{-17}
P 43 floor	0.71	2.6×10^{-10}	8.1×10^{11}	1.0×10^{-16}
E 21 wall	0.31	7.0×10^{-6}	1.3×10^{7}	6.2×10^{-12}
E 21 floor	2.50	8.4×10^{-7}	8.8×10^{8}	9.2×10^{-14}
E 147 wall pore*	0.33	1.8×10^{-5}	1.3×10^{7}*	1.0×10^{-11}*
E 47 wall	0.33	4.2×10^{-10}	2.3×10^{11}	3.5×10^{-16}
E 151 wall pore*	0.51	1.8×10^{-5}	2.8×10^{7}*	6.8×10^{-12}*
E 151 wall	0.51	3.4×10^{-8}	4.4×10^{9}	1.8×10^{-14}
E 151 floor	0.09	2.3×10^{-9}	1.2×10^{10}	7×10^{-15}

[1] Permeability and resistance values are calculated using Equation 1 on the basis of 2 mm average surface layer thickness for all sites.
* The pore bypasses the chamber perimeter seal which is 0.7 m long. The equivalent resistance and permeability are calculated using 0.7 m as the test seal length.

enough to be a significant seal by-pass occur as frequently as once per metre even in "good" concrete surfaces. The resistance of a 40 m floor/wall joint seal will be set by the parallel resistance of the $\sim$40 concealed pores that bypass it, not by the permeability of the concrete surface itself. Expected soil gas entry rates past a perfect 40 m seal with 40 bypasses are $>0.2\ m^3.h^{-1}$, equivalent to 200 Bq m^{-3} in radon-prone areas.

Other obstacles to production of low leakage seals besides concealed sub-surface pores were identified by visual inspection. They are:

- protruding and uneven forming near corners and at form junctions
- large air bubbles and pits in the concrete surface
- connected lines of bubbles (wormtracks)
- patches of loosely attached surface layer
- concrete splash and spatter layers.

The first two obstacles prevent placing sealant into continuous contact with both floor and wall. The last three are causes of bypass routes. "Radon-resistant" seals between concrete sections cannot be guaranteed unless these obstacles and bypasses are prevented or removed before the seal is applied. Mechanical removal of the concrete surface layer is a necessary first step to produce radon-resistant seals with conventional sealing details.

Acknowledgement

This work was supported in part by the United States Environmental Protection Agency under Contract 68-DO-0097, Work Assignment 13.

References

ASTM D1434-84; *Test Method of Determining Gas Permeability Characteristics of Plastic Film and Sheeting to Gases*, Philadelphia, PA, American Society for Testing and Materials.

Bakker, R.F.M. (1983) *Permeability of Blended Cement Concretes*, American Concrete Institute SP-79, Vol. 1, pp. 589–605.

Grace, W.R. & Company. *Determination of the Permeability of Portland Cement Concrete* (private communication).

Powers, T.C., Copeland, L.E., Hayes, J.C. and Mann, H.M. (1955) "Permeability of portland cement paste", *ACI Journal*, **51**, 285–298.