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AIRTIGHTNESS OF CONCRETE BASEMENT SLABS

REPORT FOR
CANADA MORTGAGE AND HOUSING CORPORATION

Airtightness of Concrete Basement Slabs

FILE: M91001

Prepared by:

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December 19, 1991

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December 18, 1991

Mr. Peter Russell
Research Division
Canada Mortgage and Housing Corporation
682 Montreal Road
Ottawa, Ontario
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Dear Peter:

Attached is our final report on the study of the airtightness of concrete basement slabs that we performed for CMHC. This report includes a detailed presentation of the results achieved in the test of the airtightness of a full basement floor. The other tasks, which have been reported on in detail already, are only briefly summarized. I also enclose the report provided to us by SRC.

We enjoyed working on this very interesting project. We feel that the results obtained are significant, and will be useful to code officials and to builders.

Yours truly,

for Gren Yuill, Ph.D., P.Eng.

GY:kc
Encl.

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ABSTRACT

The purpose of this project was to develop and evaluate means of making basement floors airtight, with the objective of keeping out radon bearing soil air. The main elements of this project were laboratory tests of the airtightness of several floor assemblies, and a field test of the airtightness of a floor in a real house.

In the laboratory tests, several arrangements of polyethylene films were tested, as seals of the floor-wall joint, and as crack seals. Also tested were concrete slabs without polyethylene films, and a concrete slab with a crack created and sealed with a waterstop strip.

The results of the laboratory tests showed that a lapped and caulked polyethylene film can be used successfully to make cracked concrete airtight. They also indicated that the use of a waterstop could be a successful technique.

In the field test, a lapped and caulked polyethylene air barrier was installed in the basement of a house, using techniques that could be applied by a house builder. A concrete floor was poured on top of it. Airtightness testing showed that this air barrier was very successful in sealing the basement from the soil, and would reduce radon contamination by almost two orders of magnitude.

EXECUTIVE SUMMARY

This project had the objective of developing and evaluating means of making basement floors airtight. Airtight basements are desirable to prevent the infiltration of air from the soil surrounding the basement. This sub-soil air can carry with it undesirable contaminants. The worst of these is radon, a radioactive gas produced in varying quantities in most mineral materials, which is known to be a major cause of lung cancer. In addition to radon, sub-soil air can carry with it moisture, organic pollutants such as bacteria and fungal spores, and chemical substances with which the soil may be contaminated.

Air leaks into basements by flowing down through the soil, then into the house through cracks and holes in the concrete walls and floor. The driving force is the buoyancy force on the warm air within the house. In most houses, the major resistance to this flow is not the walls and floor, but the soil itself. Thus a substantial improvement in floor airtightness would be required to have a significant effect on flow. It has been found in the past that this improvement can not be achieved at reasonable cost by caulking and sealing the basement floor from the inside, so it is desirable to develop economical means of achieving it at the time of construction. The present project had that objective.

This project was composed of six tasks. They were:

A. the development of a detailed outline for the project,

B. a review of the present technology of concrete slabs and plastic films,

C. a field test of the performance of several concrete floor slabs with and without polyethylene sheet under them,

D. a series of tests of the airtightness of concrete slabs in a test cell. These slabs used several arrangements of polyethylene sheets under the slab and at the floor-wall joint,

E. a forum to discuss with industry representatives the work already completed and the practicality of the approaches being taken,

F. and a field trial to test the procedures that had been developed in the lab, both for airtightness and for practicality.

In the first task, the project outline, it was concluded that the questions to be answered were:

1) Are floors poured on polyethylene film air barriers actually more airtight when cracked than those without air barriers?

2) Are lapped joints adequate or is caulking needed?

3) Is installation damage critical? Can air leak through holes in the air barrier, then between the air barrier and the concrete to a crack or does the concrete adhere or conform to the air barrier well enough to seal this?

4) If the answer to Question 3 is "No", it is feasible to deliberately perforate the air barrier, to allow water to drainage, so that the present wet-mix approach can continue to be used?

5) Can an air barrier caulked to the walls effectively seal the floor-wall crack?

6) What are the costs of the techniques proposed?

7) Are there other approaches to keeping out radon that will be more cost effective?

8) Can a double layer of polyethylene film under the concrete floor slab reduce the coefficient of friction enough to eliminate shrinkage cracking?

The details of the remaining project steps were planned to answer these questions.

In the second task the technology of concrete slabs, plastic films and caulking materials was reviewed, with the help of several experts on these topics and on the problem of keeping radon out of houses. It was tentatively concluded that:

1) Properly made concrete is effectively impermeable to air. Only openings are significant sources of air leakage. Therefore, surface sealants are of no interest.

2) The deliberate openings in and around the concrete floor slab are isolation joints to allow for movement. It is not feasible to caulk these joints with a material that will allow the movement required between the floor and the wall and will maintain its properties over the life of the house.

3) Concrete floors could be made much stronger and more resistant to shrinkage by the use of proper water/cement ratios and improved curing practices. However, it is unlikely that this could completely eliminate cracking unless control joints were used. Sealants are not

available at reasonable cost that will accommodate the movement of a control joint and have the required durability. A feasible approach is to imbed a waterstop in the concrete, to induce a control joint and at the same time to seal it.

4) A polyethylene film under the floor slab is technically feasible. However, its cost and performance must be determined. A major problem in the use of a polyethylene film is the added cost of concrete additives and curing. This cost must also be determined.

5) It is possible that the changes in the procedure for making a floor slab could be avoided if a perforated polyethylene film were used. It may be that a grid of perforations in the film would allow enough water to drain out that the present "wet-mix" technique could continue to be used. It is also possible that the draining cement paste would ultimately plug these holes well enough that the film would still be effective in making the slab airtight, even when cracked.

The remaining tasks of the project were planned to test these tentative conclusions and explore further the issues raised.

The third task of the project was a field study, which was carried out by the Saskatchewan Research Council (SRC). The details of the field study are provided in SRC report, "Concrete Foundation Air Leakage Study".

This field study was not successful. SRC was unable to get homeowners to agree to the drillings of pressure taps through their floors, so they used the foundation drainage system as a pressure reference. This can cause a significant distortion of the apparent foundation air flow. A second problem with the SRC test procedure was that only local measurements of specific cracks were made. This meant that the variability of conditions within a house, as well as between houses, added to the uncertainty about the significance of the results obtained. SRC concluded that a valid assessment of the relative air leakage performance of the foundation types could not be made on the basis of the field testing.

The fourth task of this project was a series of laboratory tests. The primary objective of these tests was to determine the effect of polyethylene substrates on the airtightness of cracked concrete slabs and of floor wall joints.

A second objective was to determine the effect of a second layer of polyethylene on the coefficient of friction under the slab. An additional objective that was added during the testing was to determine the effect of a waterstop on the airtightness of a crack in a concrete slab.

The airtightness tests were carried out using an airtight box approximately 1 m square, within which a floor section consisting of gravel, polyethylene and concrete slab could be constructed. The airflow to the gravel bed and the pressure in the bed could be measured. The concrete could be cracked and the width of the crack could be adjusted.

Each of the specimens to be tested was treated as follows. First, the concrete slab was cracked and a pair of dial gauges installed on the crack. The crack was adjusted to the first width to be tested. Then a flow was supplied to the sub-slab gravel and the resulting pressure differential across the slab was measured. This was repeated for several different flow rates and for several different crack widths.

Tests of this kind were carried out for concrete slabs with:

a. no polyethylene,
b. lapped, uncaulked polyethylene,
c. lapped and caulked polyethylene (with two different thicknesses of caulk),
d. perforated polyethylene.

Tests a, b, and c were repeated for floor-wall joints.

An additional test was carried out on a concrete slab with the crack sealed by a metal waterstop, but without a polyethylene substrate.

The results of these tests are presented in Tables 1 to 3.

Table 1 summarizes the values of the flow resistance, R, and the flow coefficient, C, at one particular crack width. As this table shows, the effect of polyethylene under the slab is very significant, reducing the airflow by almost 96%. Caulking the polyethylene causes a further major reduction, to approximately three order of magnitude less than the flow through the bare slab. It is also interesting to note that the perforated polyethylene was very tight. This was because the cement paste leaked through the perforations, sealing them.

Table 1 Flow Resistance (R) and Flow Coefficient (C) for the Slab
Crack Width = 1.5 mm:

Poly Configuration	R (Pa s/l)	C (l/Pa s)
No Poly	25	4.0E-02
Lapped and Uncaulked Poly	610	1.6E-03
Lapped and Caulked Poly	9200	1.1E-04
Perforated Poly	11000	9.1E-05
#2 with Lapped Caulked Poly	42000	2.4E-05

To test the airtightness of the apparatus, a test was done on a concrete slab with the crack well sealed. The flow coefficient was 3×10^{-7} l/Pa s, indicating that both the test apparatus and the concrete slab were very airtight. This latter result is very significant, not only in assessing the accuracy of the present experiment. It has often been suggested that the radon-laden air enters houses through uncracked concrete slabs. However, the present tests show that properly mixed concrete is effectively impermeable to air when uncracked.

The conclusions that can be drawn from this first series of tests are:

a. perforations are not a serious problem,
b. polyethylene has a very significant effect, and
c. caulking of the polyethylene is necessary.

The results of the tests of the floor-wall joints were less conclusive. Table 2 presents these results. As can be seen, the flow resistance of the joint without polyethylene was much higher than that of a crack of the same width. This was probably because of the flow resistance of the floor-footing joint. In real houses, floors get lifted off footings, but in the present tests there was no means of doing so. Therefore, little weight should be given to the results of these tests.

Table 2 Flow Resistance (R) and Flow Coefficient (C) for Floor-Wall Joint Specimens at a Crack Width of 1.5 mm:

Poly Configuration	R (Pa s/l)	C (l/Pa s)
No Poly	3100	3.2E-04
Lapped and Uncaulked Poly	870	1.2E-03
Lapped and Caulked Poly	4300	2.3E-04

Some concrete placement contractors object to the use of polyethylene under concrete floors because of its effect on drying and curing of the concrete. An alternative approach would be the use of a waterstop, a strip of material that produces a control joint and seals it. If the control joint prevents cracks elsewhere, this will make the concrete airtight. This approach was tested and it was found that the control joint provides a much tighter seal than lapped and caulked polyethylene. The flow resistance of the waterstopped control joint was 400,000 Pa s/l for a 1.5 mm crack. This approach deserves further study if waterstop suitable for use in residential basement floors can be produced at reasonable cost.

It was thought that the friction between concrete and sub-slab gravel could provide the force necessary to crack concrete during shrinkage. Therefore, tests were carried out to measure the coefficient of friction under a concrete slab, by pulling the slab with a calibrated spring. Slabs with one and two layers of polyethylene were tested. The results are presented in Table 3. These results show that the second layer of polyethylene does reduce the coefficient of friction significantly, but they also show that the stress caused by the friction is not high enough to crack the concrete. This indicates that shrinkage cracking is caused by differential shrinkage or by shrinkage of the slab constrained by slab penetrations such as pipes or columns, not by whole-slab shrinkage with tension caused by friction.

Table 3 Results from the Friction Test:

Number of Layers of Poly	Coefficient of Friction	Maximum Stress (30'x40')
1	0.65	13.5 psi
2	0.40	8.3 psi

To understand the significance of the results of the airtightness tests it is necessary to compare the overall airtightness of a floor with the airtightness of the soil around a house. Using measured air permeability data for soils, the resistance of a well compacted soil around a house will vary from 20 to 600 Pa s/l, with a typical silty soil having a resistance of 33 Pa s/l. A concrete floor with 25 m of 1.5 mm crack would have a resistance of 1 Pa s/l. This resistance is insignificant compared to that of the soil, and tightening the basement by sealing 50% of the total leaks would have no effect on the inflow of soil gas. On the other hand, a floor with 25 m of 1.5 mm crack and with an underlay of lapped and caulked polyethylene would have a resistance of 1680 Pa s/l. Now the floor is the major resistance, much greater than the soil. The inflow of soil gas is reduced 98% compared to the floor without polyethylene.

The value of these test results depends on the cost of implementing their results. It has been estimated that the material and labor costs of the installation of lapped and caulked polyethylene sheet is \$2.92 to \$3.75 per m^2. This includes a cost of \$1.08 per m^2 for the additional work of finishing the concrete, caused by the lack of drainage. On the other hand, this extra work can be avoided by the use of a superplasticizer instead of water to make the concrete fluid. This costs about \$1.00 per m^2 of floor, but it results in a far stronger concrete with less shrinkage cracks and a lower air permeability than would be produced by a wet mix.

Considering these factors, an estimate of additional cost of about \$400 to \$800 for houses from 100 m^2 to 230 m^2 appears reasonable. That is a significant expense, approaching the cost of installing a sub-slab depressurization system in a new house. However, the sub-slab air barrier approach has the advantage that it is passive, probably more long-lasting and it does not use electricity or increase infiltration.

The fifth task of this project was the forum held on June 27, 1991, at CMHC in Ottawa to present the results of the laboratory research described above, and to obtain input from the construction industry and from other radon researchers about the direction the project should take. A list of attendees is attached.

A key issue raised at the meeting was whether or not it was feasible to concrete placement contractors to pour floors on top of an impermeable substrate such as polyethylene. It was agreed that this was a feasible approach, provided that a superplasticizer was used instead of excess water to achieve high slump. In particular, this was the view of Lyle Hamre of the Canadian Portland Cement Association and of John Broniak of the Canadian Home Builders Association.

Based on this view, and on the results of the laboratory tests that showed lapped and caulked polyethylene to be very airtight, it was decided to continue the project in its original direction. Therefore, the field demonstration was set up to test this concept. It was agreed that the basement floor would be sealed using techniques that would be available to a housebuilder (that is, using polyethylene sheet caulked at the footings, at seams, and at penetrations with acoustical sealant.) However, greater than normal care would be taken to make the installation the best possible using that technology. The air flow through the polyethylene was to be measured as a function of the pressure differential.

Several other approaches to sealing the floor were discussed, including the use of perforated polyethylene and the use of a waterstop system to control and seal cracks, but it was agreed that a caulked polyethylene air barrier showed better promise than any of these.

The sixth task in this project was the field trial of the sub-slab polyethylene air barrier. An air barrier was placed on the sub-slab gravel of a new house in Winnipeg and a concrete slab was poured over it. The polyethylene was caulked to the footings and to the jack-post pads with acoustical sealant. All laps in the polyethylene were caulked and the polyethylene was caulked to the plumbing pipe penetrations.

The airtightness of the polyethylene was tested before the concrete floor was poured, and again after the concrete had been poured and had cured for 14 days. The tests were done by depressurizing the sub-slab gravel through a flow meter and variable speed fan. At the same time the house pressure was controlled with a blower door so that the house pressure equalled the sub-slab pressure, or so that the ambient pressure equalled the sub-slab pressure. In the former case, the equivalent leakage area (ELA) from outdoors through the soil to the sub-slab gravel was measured. In the latter case the ELA of the polyethylene was measured.

The ELA of the polyethylene was found to be 0.6 cm^2 before the floor was poured. This was about four times higher per unit area than had been found in the laboratory tests. The ELA of the soil was measured to be 6.1 cm^2, ten times higher than that of the polyethylene. Thus the tight polyethylene was now the major barrier to air movement into the house, and would be expected to reduce the soil gas inflow by about 90%.

That the polyethylene was more leaky than in the lab tests was not surprising, for two reasons. First, there was no concrete on top of it, and second, the pipe penetrations provided additional leakage sites.

The airtightness tests were repeated two weeks after the concrete was poured. The ELA of the soil dropped to 2.7 cm^2 during this time. This change was probably caused by a combination of compaction of the soil as it settled into the backfill zone, and saturation due to heavy rain during the test period. The ELA of the concrete slab and polyethylene were so low that no flow whatsoever could be detected with a 50 Pa pressure difference. By considering the accuracy of the instruments, it was estimated that the ELA must be less than .05 cm^2. Even at this upper limit the soil gas inflow would be reduced to less than 2% of that with a leaky floor.

These tests of floor slab airtightness were highly successful. However, a second objective of the field trial was not met as successfully. This was the evaluation of the practicability of using a superplasticizer to make the concrete spreadable instead of using excess water. Unfortunately, some error was made in the preparation of the concrete mix, and after it was spread the surface was covered with water. The concrete could not be finished for almost 24 hours. This was the problem that was expected to be avoided by the use of the superplasticizer. The reason for this problem could not be determined, but all the concrete experts consulted agreed that it was not caused by the presence of the sub-slab polyethylene.

The additional cost of using a polyethylene substrate was estimated at \$2.92 to \$3.75 per m^2 of basement floor area. This estimate was not based on measurements made in the test house, but on an assessment of the time that would be taken when this procedure became better understood.

RÉSUMÉ

Cette étude a pour objectif la mise au point et l'évaluation de moyens permettant de rendre les planchers de sous-sol étanches à l'air. Il est souhaitable d'assurer leur étanchéité pour prévenir l'infiltration d'air provenant du sol environnant, car cet air souterrain risque de transporter des contaminants indésirables, le plus dangereux étant le radon, gaz radioactif produit en quantités variables dans la plupart des matières minérales et reconnu comme l'une des principales causes du cancer du poumon. Outre le radon, l'air souterrain peut transporter de l'humidité, des polluants organiques comme des bactéries ou des spores fongiques de même que des substances chimiques amenant une contamination du sol.

L'air chemine dans le sol et finit par s'introduire dans la maison par les fissures et les orifices des murs et du plancher de béton. La force motrice de ce phénomène est la poussée aérostatique de l'air chaud à l'intérieur de la maison. Dans la plupart des maisons, la principale résistance à ce mouvement ne vient pas des murs ou du plancher, mais bien du sol même. C'est pourquoi il faut améliorer considérablement l'étanchéité à l'air du plancher pour agir suffisamment sur ce mouvement. On a découvert dans le passé que cette amélioration ne peut être réalisée à un coût raisonnable en calfeutrant et en étanchéifiant de l'intérieur le plancher du sous-sol. Il est donc souhaitable de concevoir une façon économique d'y parvenir au moment de la construction. Tel est le but de cette étude divisée en six tâches :

A. Élaborer un plan détaillé du projet;

B. Examiner la technologie actuelle en matière de dalles de béton et de membranes de plastique;

C. Évaluer sur le terrain le comportement de plusieurs dalles de plancher en béton avec et sans membrane de polyéthylène sous-jacente;

D. Procéder à une série de tests d'étanchéité des dalles de béton dans une cellule d'essai, tout en disposant de plusieurs façons les feuilles de polyéthylène sous la dalle et à la jonction du mur et du plancher;

E. Organiser un forum afin de discuter, avec des représentants de l'industrie, des travaux déjà réalisés et de la praticabilité des méthodes envisagées;

F. Éprouver sur le terrain les méthodes mises au point en laboratoire tant pour en connaître l'étanchéité que la praticabilité.

Pour la première tâche, consistant à élaborer le plan de travail, il s'agit de répondre aux questions suivantes :

1) Les planchers coulés sur des pare-air en polyéthylène sont-ils vraiment plus étanches à l'air, quand ils sont fissurés, que ceux qui sont exempts de pare-air?

2) Les joints à recouvrement sont-ils appropriés ou faut-il aussi les calfeutrer?

3) Les dommages à l'installation sont-ils cruciaux? L'air peut-il s'infiltrer par les trous du pare-air, puis entre le pare-air et le béton jusqu'à une fissure, ou le béton suit-il suffisamment la membrane ou y adhère-t-il assez pour colmater ces brèches?

4) Si la réponse à la question 3 est «non», est-il possible de perforer délibérément le pare-air pour permettre à l'eau de s'écouler, de sorte que l'actuelle méthode du dosage humide puisse continuer de s'employer?

5) Le pare-air correctement calfeutré aux murs peut-il faire efficacement échec aux fissures chevauchant le plancher et le mur?

6) Combien coûtent les techniques proposées?

7) Existe-t-il d'autres façons plus efficientes de faire obstacle à l'infiltration du radon?

8) Est-ce qu'une double membrane de polyéthylène placée sous la dalle de béton peut réduire suffisamment le coefficient de friction pour éliminer les fissures causées par le retrait?

Les autres étapes visent à répondre à ces questions.

À la deuxième étape, la technologie des dalles de béton, des membranes de plastique et des matériaux de calfeutrage est passée en revue, avec l'aide de plusieurs experts dans ces domaines, dans l'optique du problème d'infiltration du radon à l'intérieur des habitations dont voici les conclusions provisoires :

1) Le béton bien constitué est vraiment étanche à l'air. Seules les ouvertures constituent d'importantes sources d'infiltration d'air. C'est pourquoi le calfeutrage en surface ne présente pas d'intérêt.

2) Les ouvertures intentionnellement aménagées dans la dalle de plancher en béton et à sa périphérie servent de joints de rupture. Il est impossible de calfeutrer ces joints avec un matériau donnant libre cours au mouvement requis entre le plancher et le mur tout en conservant ses propriétés durant la durée utile de l'habitation.

3) Les planchers de béton pourraient être beaucoup plus solides et résistants si le dosage tout indiqué en eau et ciment était respecté et si les méthodes de cure étaient améliorées. Cependant, il est peu probable que ces mesures permettent d'éliminer complètement les fissures à moins d'avoir recours à des joints de retrait. Il est impossible de se procurer à un coût raisonnable des produits de scellement qui permettent le mouvement d'un joint de retrait tout en offrant la durabilité requise. Il serait faisable de noyer une lame d'étanchéité dans le béton, de produire un joint de retrait et, en même temps, de le sceller.

4) Il est techniquement possible de poser une membrane de polyéthylène sous la dalle de plancher, mais le coût et l'exécution de la manoeuvre restent à déterminer. Le problème important qu'entraîne l'utilisation d'une membrane de polyéthylène est le coût additionnel que représentent les additifs et la cure du béton. Il faut donc aussi en déterminer le coût.

5) Les changements apportés à la réalisation d'une dalle de plancher pourraient être évités en ayant recours à une membrane de polyéthylène perforée. Une grille de perforations dans la membrane pourrait favoriser l'écoulement de suffisamment d'eau pour que la technique actuelle du mélange humide soit maintenue. En outre, il se pourrait que les résidus de ciment finissent par obstruer suffisamment ces perforations pour que la membrane permette tout de même à la dalle de plancher de demeurer étanche à l'air, même en cas de fissuration.

Les autres tâches sont consacrées à la vérification de ces conclusions provisoires et à l'exploration des autres interrogations soulevées.

La troisième tâche consiste en une étude sur le terrain menée par le Saskatchewan Research Council (SRC), d'ailleurs exposée en détail dans le rapport du SRC intitulé «Concrete Foundation Air Leakage Study».

Cette étude n'a pas remporté le succès escompté. En effet, le SRC n'a pas pu convaincre les propriétaires-occupants de lui laisser percer des prises de pression dans le plancher de leur maison et a donc dû se résoudre à utiliser le réseau d'évacuation des fondations comme référence pour la pression. Ce procédé peut fausser énormément les données du mouvement d'air apparent des fondations. Le second problème, qu'entraîne la méthode d'essai du SRC, est le fait que seules des mesures ponctuelles de fissures particulières ont été faites. La variabilité des conditions à l'intérieur d'une maison, et entre les maisons, s'est donc ajoutée à l'incertitude entourant la pertinence des résultats obtenus. Le SRC conclut que les essais menés sur le terrain n'ont pas permis d'effectuer une évaluation valable de l'étanchéité à l'air des types de fondation étudiés.

La quatrième tâche est constituée d'une série d'essais en laboratoire. Ces essais visent principalement à déterminer l'effet de substrats en polyéthylène sur l'étanchéité à l'air des dalles de béton et de la jonction du plancher et du mur fissurés.

Le second objectif consiste à établir l'effet, sur le coefficient de friction sous la dalle, d'une seconde membrane de polyéthylène. Les chercheurs en ont ajouté un autre durant les essais, dans le but de déterminer quel effet aurait une lame d'étanchéité sur la perméabilité à l'air d'une fissure dans la dalle de béton.

Les essais d'étanchéité à l'air sont menés au moyen d'un caisson étanche d'environ 1 m^2 à l'intérieur duquel est aménagée une section de plancher composée de gravier, de polyéthylène et d'une dalle de béton. Le mouvement d'air du lit de gravier et la pression à laquelle le lit est soumis peuvent se mesurer. Le béton y est fissuré et la largeur de la fissure peut être modifiée.

Chacun des spécimens à l'essai est traité comme suit. D'abord, on fissure la dalle de béton et on installe des comparateurs à cadran sur la fissure. La fissure est réglée à la première largeur à analyser. Ensuite, un mouvement d'air est insufflé au gravier sous la dalle et on mesure la différence de pression résultante s'exerçant sur la dalle. Cette opération est répétée pour divers mouvements d'air et pour diverses largeurs de fissure.

Voici les types de dalles de béton mis à l'essai :

a. dépourvues de polyéthylène;

b. pourvues de polyéthylène à joints recouverts non scellés;

c. pourvues de polyéthylène à joints recouverts scellés (comprenant deux couches de calfeutrage différentes);

d. munies de polyéthylène perforé.

Les essais a, b et c sont répétés à la jonction du plancher et du mur.

Un essai additionnel est effectué sur une dalle de béton dont la fissure est scellée par une lame d'étanchéité en métal, mais sans substrat de polyéthylène.

Les résultats de ces essais paraissent aux Tableaux 1 à 3.

Le Tableau 1 résume les valeurs de la résistance au mouvement d'air, R, et du coefficient de mouvement, C, à une largeur de fissure donnée. Comme l'illustre ce tableau, l'effet du polyéthylène posé sous la dalle est très significatif puisqu'il permet de réduire le mouvement d'air de près de 96 p. 100. Le scellement du polyéthylène permet de réduire le mouvement encore davantage, soit d'un ordre de grandeur d'environ 3 par rapport au mouvement d'air passant à travers une dalle nue. Il est également intéressant de noter que le polyéthylène perforé est très étanche, car la pâte de ciment coule par les perforations, les scellant du même coup.

Tableau 1
Résistance au mouvement d'air (R) et coefficient de mouvement (C) de la dalle
Largeur de la fissure = 1,5 mm

Configuration du polyéthylène	R (Pa s/L)	C (L/Pa s)
Pas de polyéthylène	25	4,0E-02
Polyéthylène à joints recouverts non scellés	610	1,6E-03
Polyéthylène à joints recouverts scellés	9 200	1,1E-04
Polyéthylène perforé	11 000	9,1E-05
Polyéthylène de type 2 à joints recouverts scellés	42 000	2,4E-05

Pour éprouver l'étanchéité à l'air de l'appareil d'essai, on effectue un essai sur la dalle de béton, la fissure bien scellée. Le coefficient de mouvement d'air est de 3 x 10^{-7} L/Pa s, indiquant que l'appareil et la dalle de béton sont très étanches à l'air. Ce dernier résultat est très significatif, et pas seulement pour évaluer la précision de l'expérience actuelle. On a souvent évoqué que l'air chargé de radon s'infiltre dans les maisons en passant à travers les dalles de béton non fissurées. Cependant, les présents essais montrent que le béton bien malaxé dénué de fissures est vraiment étanche à l'air.

Cette série d'essais permet de conclure que :

a. les perforations ne posent pas de sérieux problèmes;
b. le polyéthylène revêt une importance considérable;
c. le scellement du polyéthylène est nécessaire.

Les essais de la jonction du plancher et du mur sont moins concluants. Le Tableau 2 en présente les résultats. Comme on peut le constater, la résistance au mouvement d'air de la jonction exempte de polyéthylène est beaucoup plus élevée que celle d'une fissure de même largeur. Cette différence est probablement attribuable à la résistance au mouvement d'air de la jonction du plancher et de la semelle. Dans une maison, le plancher se soulève par rapport à la semelle, alors que dans nos essais, il est impossible de reproduire cette situation. Il faut donc accorder peu d'importance aux résultats de ces essais.

Tableau 2
Résistance au mouvement d'air (R) et coefficient de mouvement (C) des spécimens de joint plancher-mur
Largeur de la fissure = 1,5 mm

Configuration du polyéthylène	R (Pa s/L)	C (L/Pa s)
Pas de polyéthylène	3 100	3,2E-04
Polyéthylène à joints recouverts non scellés	870	1,2E-03
Polyéthylène à joints recouverts scellés	4 300	2,3E-04

Certains entrepreneurs de mise en place du béton s'opposent à l'emploi de polyéthylène sous les dalles de plancher à cause de son effet sur l'assèchement et la cure du béton. On pourrait alors le remplacer par une lame d'étanchéité, une bande de matériau qui agit comme joint de retrait étanche. Si le joint de retrait prévient les fissures ailleurs, il permettra au béton de demeurer étanche à l'air. Après essai, il s'avère que ce joint de retrait est beaucoup plus étanche qu'une membrane de polyéthylène dont les joints à recouvrement sont scellés. La résistance au mouvement d'air du joint de retrait étanche est de 400 000 Pa s/L pour une fissure de 1,5 mm. Cette méthode mérite de plus amples études pour déterminer si le joint de retrait étanche utilisé pour le plancher du sous-sol de bâtiments résidentiels peut être produit à un coût raisonnable.

On croit que la friction entre le béton et le gravier sous la dalle suffit à faire fissurer le béton durant le retrait. C'est pourquoi on tente de mesurer le coefficient de friction sous une dalle de béton en tirant sur la dalle au moyen d'un ressort calibré. Des dalles dotées d'une et de deux membranes de polyéthylène sont mises à l'essai. Les résultats figurent au Tableau 3. Ceux-ci montrent effectivement que la seconde membrane réduit considérablement le coefficient de friction, mais aussi que la contrainte qu'exerce la friction ne peut pas faire fissurer le béton. La fissuration due au retrait survient donc en cas de retrait différentiel, ou lorsque la dalle subit une contrainte en raison des tuyaux ou des colonnes qui la traversent, et non du retrait de toute la dalle quand la tension est causée par la friction.

Tableau 3
Résultats des essais de friction

Nombre de membranes de polyéthylène	Coefficient de friction	Contrainte maximale (30 pi x 40 pi)
1	0,65	13,5 lb/po²
2	0,40	8,3 lb/po²

Pour comprendre la portée des résultats des essais d'étanchéité à l'air, il est nécessaire de comparer l'étanchéité à l'air globale d'un plancher avec celle du sol entourant la maison. Grâce à la mesure de la perméabilité à l'air des sols, on sait que la résistance d'un sol bien compacté autour d'une maison varie de 20 à 600 Pa s/L, un sol particulièrement limoneux ayant une résistance de 33 Pa s/L. Le plancher de béton parcouru par 25 m de fissures de 1,5 mm aurait une résistance de 1 Pa s/L. Cette résistance est insignifiante comparativement à celle du sol, et le fait de rendre le sous-sol étanche en scellant 50 p. 100 du total des infiltrations n'aurait aucun effet sur l'infiltration des gaz souterrains. Par contre, un plancher parcouru par 25 m de fissures de 1,5 mm et reposant sur une membrane de polyéthylène dont les joints sont recouverts et scellés offrirait une résistance de 1 680 Pa s/L. C'est le plancher, plus que le sol, qui oppose la meilleure résistance. L'infiltration des gaz souterrains est réduite de 98 p. 100 par rapport au plancher dépourvu de polyéthylène.

La valeur de ces résultats dépend du coût de leur mise en application. On estime que le coût des matériaux et de la main-d'oeuvre liés à l'installation de membranes de polyéthylène aux joints recouverts et scellés est de 2,92 \$ à 3,75 \$ le m^2. Cette estimation comprend le coût de 1,08 \$ le m^2 pour réaliser le travail additionnel de finition du béton requis à cause de l'évacuation déficiente. Par ailleurs, ce travail additionnel peut être évité en ayant recours à un superplastifiant à la place de l'eau pour liquéfier le béton. Ce procédé coûte 1,00 \$ le m^2 de plancher, mais le béton en ressort beaucoup plus résistant et présente moins de fissures dues au retrait. En outre, il est plus étanche à l'air que le béton réalisé par dosage humide.

Tout compte fait, il en coûterait environ 400 à 800 \$ de plus pour réaliser les fondations de maisons de 100 à 230 m^2. C'est là une dépense importante qui correspond à peu près à ce qu'il en coûte pour doter une maison neuve d'un système de dépressurisation sous la dalle. Néanmoins, cette mesure offre l'avantage d'être probablement très durable, ne consomme pas d'électricité et n'accroît pas l'infiltration.

La cinquième tâche de cette étude consistait à tenir un forum, le 27 juin 1991, aux bureaux de la SCHL à Ottawa afin de présenter les résultats de la recherche en laboratoire décrite plus haut et d'obtenir l'avis de l'industrie de la construction et de chercheurs oeuvrant dans le secteur du radon quant aux orientations que cette recherche doit prendre. Une liste des participants est annexée au présent rapport.

L'une des questions clés soulevées lors de ce forum était de savoir s'il est possible pour les entrepreneurs de mise en place du béton de couler un plancher sur un substrat imperméable comme le polyéthylène. Il semble que ce procédé soit réalisable à condition d'employer un superplastifiant au lieu de l'eau pour obtenir un degré d'affaissement élevé. Telle est, entre autres, l'opinion de Lyle Hamre, de l'Association canadienne du ciment Portland, et de John Broniak, représentant l'Association canadienne des constructeurs d'habitations.

Selon ces avis et compte tenu des résultats des essais en laboratoire qui confirment l'excellente étanchéité à l'air du polyéthylène lorsque ses joints sont recouverts et scellés, on décide de poursuivre les objectifs initiaux de l'étude. Par conséquent, la démonstration sur le terrain visant à étayer ce concept est préparée. Il est convenu de sceller le plancher du sous-sol selon les techniques à la disposition des constructeurs d'habitations (c'est-à-dire le scellement des membranes de polyéthylène à la semelle, aux joints et aux points de pénétration à l'aide d'un matériau d'isolement acoustique). Cependant, il faut redoubler d'attention afin que l'installation selon ce procédé soit la plus parfaite possible. La quantité d'air traversant le polyéthylène doit se mesurer en fonction de la différence de pression.

Plusieurs autres méthodes de scellement du plancher sont envisagées, dont l'emploi de polyéthylène perforé et l'utilisation d'une lame d'étanchéité permettant d'enrayer et de sceller les fissures, mais l'on s'entend sur le fait qu'une membrane de polyéthylène scellée est plus prometteuse que les autres procédés.

La sixième tâche est consacrée à l'essai en service du pare-air de polyéthylène. Le pare-air se place sous la dalle, sur le gravier, d'une maison neuve à Winnipeg et la dalle de béton est coulée dessus. Le polyéthylène est scellé avec un matériau d'isolement acoustique aux semelles et aux assises des poteaux télescopiques. Tous les joints à recouvrement des membranes de polyéthylène sont scellés. Enfin, le polyéthylène est calfeutré à la hauteur où pénètrent les canalisations de plomberie.

L'étanchéité à l'air du polyéthylène est vérifiée avant de mettre en place le plancher de béton. La vérification est répétée après une cure de 14 jours suivant la mise en place. Les essais sont menés par dépressurisation du gravier sous la dalle au moyen d'un ventilateur à vitesse variable et d'un débitmètre. Au même moment, la pression de la maison est contrôlée à l'aide d'une porte dotée d'un ventilateur afin que cette pression, ou la pression ambiante, soit égale à la pression sous la dalle. Dans le premier cas, on mesure la surface de fuite équivalente (SFE) de l'espace compris entre l'extérieur, le sol et le gravier sous la dalle. Dans le second cas, c'est la SFE du polyéthylène qui est mesurée.

La SFE du polyéthylène est évaluée à 0,6 cm^2 avant la mise en place du béton, soit environ quatre fois plus par unité de surface que les résultats des essais en laboratoire. La SFE du sol est établie à 6,1 cm^2, c'est-à-dire 10 fois plus que celle du polyéthylène. Le polyéthylène étanche devient donc le principal obstacle au mouvement de l'air à l'intérieur de la maison et peut sans doute réduire l'infiltration des gaz souterrains d'environ 90 p. 100.

Le fait que le polyéthylène soit moins étanche que lors des essais en laboratoire ne surprend pas les chercheurs, et ce pour deux raisons. La première, c'est qu'il n'est pas recouvert de béton, la seconde étant que les points de pénétration constituent des zones d'infiltration additionnelles.

Les essais d'étanchéité à l'air sont répétés deux semaines après la mise en place du béton. La SFE du sol est descendue à 2,7 cm^2 pendant ce temps. Ce changement est probablement occasionné par le compactage du sol pendant qu'il se tasse dans la zone de remblayage et par la saturation résultant des fortes précipitations observées durant la période d'essai. Les SFE de la dalle de béton et du polyéthylène sont tellement minimes qu'aucun mouvement d'air ne peut être détecté à une différence de pression de 50 Pa. Compte tenu de la précision des instruments, on estime que la SFE est inférieure à 0,05 cm^2. Même à cette extrême limite, l'infiltration de gaz souterrain serait réduite à moins de 2 p. 100 par rapport à ce que représenterait un plancher peu étanche.

Les essais d'étanchéité à l'air de la dalle de plancher sont très fructueux. Cependant, ce n'est pas le cas du second objectif de l'étude. Il s'agit de l'évaluation de la faisabilité de l'emploi d'un superplastifiant en remplacement de l'eau en vue de faciliter la mise en place du béton. Malheureusement, une erreur a été commise au moment du dosage du béton, de sorte qu'après sa mise en place, le béton s'est trouvé recouvert d'eau. Il a été impossible pendant près de 24 heures de finir le béton. Or, c'est ce problème que l'on prévoyait éviter en ayant recours au superplastifiant. La cause du problème n'a pu être déterminée, mais tous les experts en béton consultés s'entendent pour dire que le polyéthylène sous la dalle n'en est pas la cause.

On estime qu'il en coûterait entre 2,92 $ et 3,75 $ le m^2 pour mettre en oeuvre une membrane de polyéthylène sous la dalle de plancher du sous-sol. Cette estimation ne repose pas sur des mesures prises dans la maison d'essai, mais sur une évaluation du temps nécessaire une fois le procédé maîtrisé.

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1.0 INTRODUCTION

This is the final report for the project entitled "The Airtightness of Concrete Basement Slabs" that was carried out by G. K. Yuill and Associates (Man.) Ltd. for CMHC. The fundamental objective of the project was to develop, test and try out an economic means of reducing the flow of radon into houses. The approach taken was to introduce different configurations of a substrate of polyethylene into both the slab and floor-wall joint and evaluate its effectiveness on increasing airtightness.

The project involved several different tasks. Task A involved a review of the radon issue and present building technology in order to clearly define the outline of the project. Task B was a review of concrete and film technology to decide whether or not the approach proposed would be both technically and economically feasible. Task C was an air leakage study on existing basement floors, some of which had polyethylene installed and the others without. Task D involved extensive laboratory tests to evaluate the technical feasibility of the approach. This part of the project involved the construction and testing of typical sections of basement floor slabs and of the floor-wall joint. Task E was a meeting with CMHC and other representatives to review the results up to the date of the meeting. From the meeting, it was to be decided which direction should be taken on the project, more particularly, Task F. Task F was a field trial. It involved the implementation of the decided approach, in a real basement, and an evaluation of its performance with respect to airtightness.

Two progress reports were submitted during the course of the project. The various phases of the project that were completed earlier, and included as final discussions in one of the progress reports, are only summarized in this report. In those cases, reference is made to the appropriate progress report.

2.0 TASK A: PROJECT OUTLINE

Task A was carried out at the beginning of the project. The objective of this part of the project was to review all of the presently available information on the issue of radon exposure, radon entry control, energy conservation and building practices to determine which issues had to be addressed and to refine the details of the test procedures. The review included discussions between Dr. Yuill and personnel from the Portland Cement Association of Canada, U.S. Environmental Protection Agency, ASTM committee, the Florida Department of Community Affairs, and also concrete experts at the National Research Council and Penn State University. Details of the review are included in Chapter 2 of the April 2, 1991 progress report. A brief summary is presented in this section.

Radon is a chemically inert gas that is produced in the soil. It causes lung cancer. Radon enters houses primarily through cracks in basement floors and walls and pipe penetrations. To reduce the level of radon in a house, two approaches can be taken. The first is to depressurize the sub-slab volume, with a sub-slab suction system, and the second is to make the floor more airtight. The goal of this project focused on the development and testing of the latter approach. More specifically, it focussed on the evaluation of the effectiveness of using a substrate of polyethylene in the floor system. Although this method is beneficial because it reduces the heating load of a house by lowering the infiltration rate through the floor, because it reduces the sub-slab suction system fan electrical energy use (if such a system still required) and because it is a relatively inexpensive alternative for obtaining a tighter floor, it introduces a problem with respect to the concrete.

If a polyethylene substrate is used, the wet mix concrete normally used for basement floors would require more work to finish because bleed water can't escape through the bottom. For this main reason, it was decided to introduce superplasticizers into the concrete to reduce the water-to-cement ratio while maintaining the workability of the mix, to recommend proper curing practices and, as a result, to increase the strength of the floor.

The main focus of the project was directed at the use of the polyethylene substrate and at the required tests to address all the concerns that were raised.

3.0 TASK B: CONCRETE AND FILM TECHNOLOGY REVIEW

The objectives of this task were to review the possible materials and practices that could enhance the long-term airtightness of slab and determine the most cost effective approach. Details of this part of the project are included in Chapter 3 of the April 2, 1991 progress report and in the Executive Summary of the July 30, 1991 progress report.

This review confirmed that the approach of using a substrate of polyethylene has a good prospect of being technically feasible and economical.

It has been estimated (Proskiw#, 1991) that introducing the polyethylene substrate approach to the basement floor system would increase the cost of the basement by between \$2.92 and \$3.75 per m^2 of floor.

Three types of tests were conducted to assess the technical feasibility of the polyethylene approach.

4.0 TASK C: FIELD TESTS

The field tests involved investigating the foundation air leakage in a group of ten houses in Saskatoon, Saskatchewan. This part of the project was carried out by the Building Science Division of the Saskatchewan Research Council. The purpose of this phase was to determine if polyethylene affected the airtightness of concrete slabs by testing existing basement floors for airtightness. Ten basement floors were tested, five with an underlay of polyethylene and five without.

Results and details from this study are included in SRC's August, 1991 report entitled "Concrete Foundation Air Leakage Study". This report is presented in Appendix A.

Proskiw, G., Personal Communication, July 24, 1991.

This field study involved the air leakage tests, a concrete permeance test and a floor slab crack inventory.

Due to variations in foundation construction and condition, and in house types/ages that were obtained, no conclusions could be made from the airtightness tests on the floors.

The concrete permeance test was conducted using a Schupack air permeance meter. This test gave an indication of the surface quality of the floors and the permeability of the concrete.

5.0 TASK D: LABORATORY TESTS

Task D comprised the largest part of the project. This task involved a series of laboratory tests to determine the effect that different configurations of polyethylene substrates had on the airtightness of cracked concrete slabs and of floor-wall joints.

A second objective was to determine the effect a second layer of polyethylene had on the coefficient of friction under the slab. An additional objective, that was added during the testing, was to determine the effect of a waterstop on the airtightness of a crack in a concrete slab.

A detailed description of the laboratory equipment, tests and results are presented in Part A of the July 30, 1991 progress report.

The airtightness tests were carried out using an airtight test cell approximately 1 m square, which was assembled around a laboratory built floor specimen consisting of gravel, polyethylene and a concrete slab. The airflow through the test cell and the pressure in the gravel bed could be measured. The concrete could be cracked and the width of the crack could be adjusted. Figs. 1 and 2 show the test configuration.

FIGURE 1

CROSS–SECTION OF THE TEST CELL AND SLAB SPECIMEN

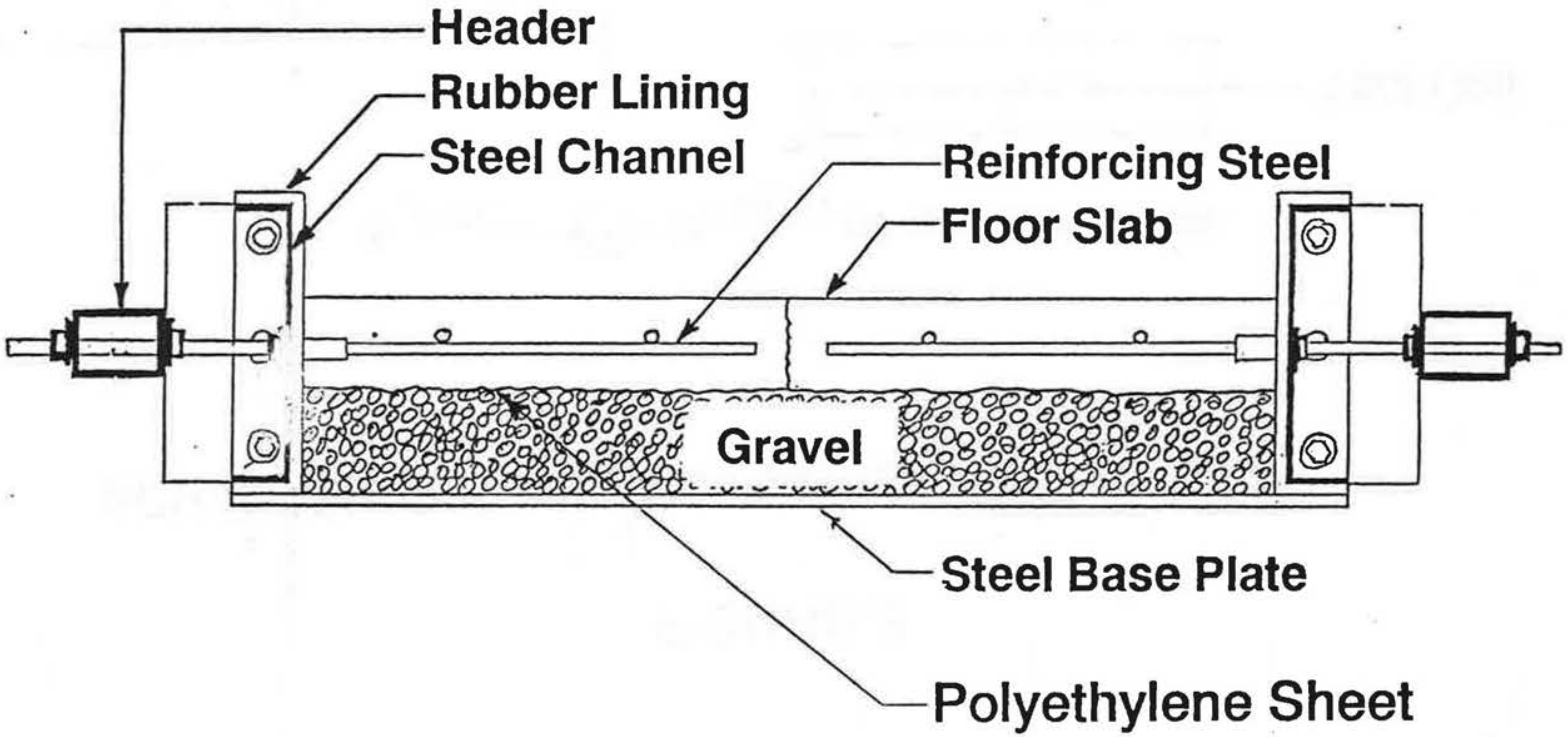
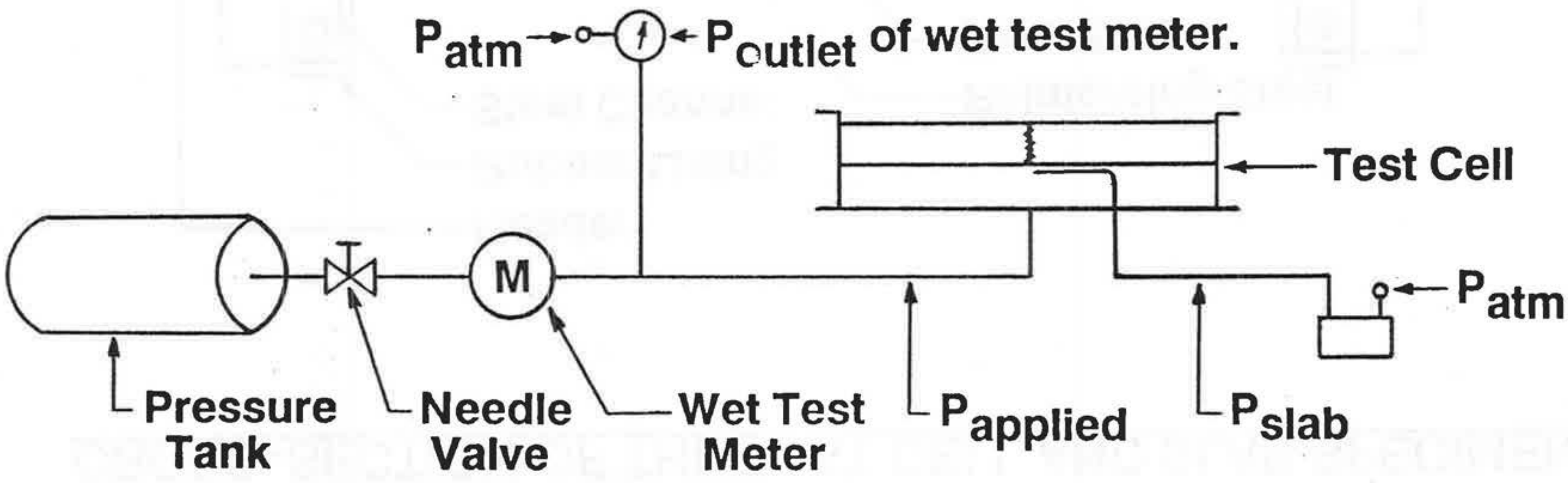


FIGURE 2

SCHEMATIC OF LEAKAGE TEST APPARATUS CIRCUIT



All tubing is 1/4" ID with 1/4" OD copper tube used as couplings.

Each of the specimens to be tested was treated as follows. First, the concrete slab was cracked and a pair of dial gauges installed on the crack. The crack was adjusted to the first width to be tested. Then a flow was supplied to the sub-slab gravel and the resulting pressure differential across the slab was measured. This was repeated for several different flow rates. The resulting data was then correlated by an equation of the form:

$$Q = C \Delta P$$

where Q = the flow rate [l/s],
C = a coefficient [l/s Pa],
ΔP = the pressure difference across the slab [Pa].

This series of tests, and the correlation, were repeated for several different crack widths.

Tests of this kind were carried out for concrete slabs with:

a. no polyethylene,

b. lapped, uncaulked polyethylene,

c. lapped and caulked polyethylene (with two different thicknesses of caulk),

d. perforated polyethylene.

Tests a, b, and c were repeated for the floor-wall joint specimens.

An additional test was carried out on a concrete slab with the crack sealed by a metal waterstop, but without a polyethylene substrate.

The results of these tests are summarized in Figs. 3 to 8 and Tables 1 to 3.

Fig. 3 shows a typical set of flow versus pressure curves for a test specimen, the slab with no polyethylene. As the lower curves on this graph indicate, the relationship was usually linear. The top two curves of Fig. 3 were the only ones of the entire project that required an exponent other than 1.0 on the pressure differential. This indicates that for all but these two leakiest cases, laminar flow dominated.

Fig. 4 shows the flow coefficient, C, as a function of crack width, for all the cases tested. As can be seen, the slab without polyethylene was much leakier than the other cracked slabs, followed by the slab with uncaulked polyethylene.

Because the flow-pressure relationship is linear, a flow resistance,

$$R = 1/C$$

can be introduced. Fig. 5 shows the variation of R with crack width.

Table 1 summarizes the values of the flow resistance, R, and the flow coefficient, C, at one particular crack width. As this table shows, the effect of polyethylene under the slab is very significant, reducing the airflow by almost 96%. Caulking the polyethylene causes a further major reduction, to approximately three orders of magnitude less than the flow through the bare slab. It is also interesting to note that the perforated polyethylene was very tight. This was because the cement paste leaked through the perforations, sealing them.

FIGURE 3

AIRFLOW CURVES FOR THE SLAB WITH NO POLYETHYLENE

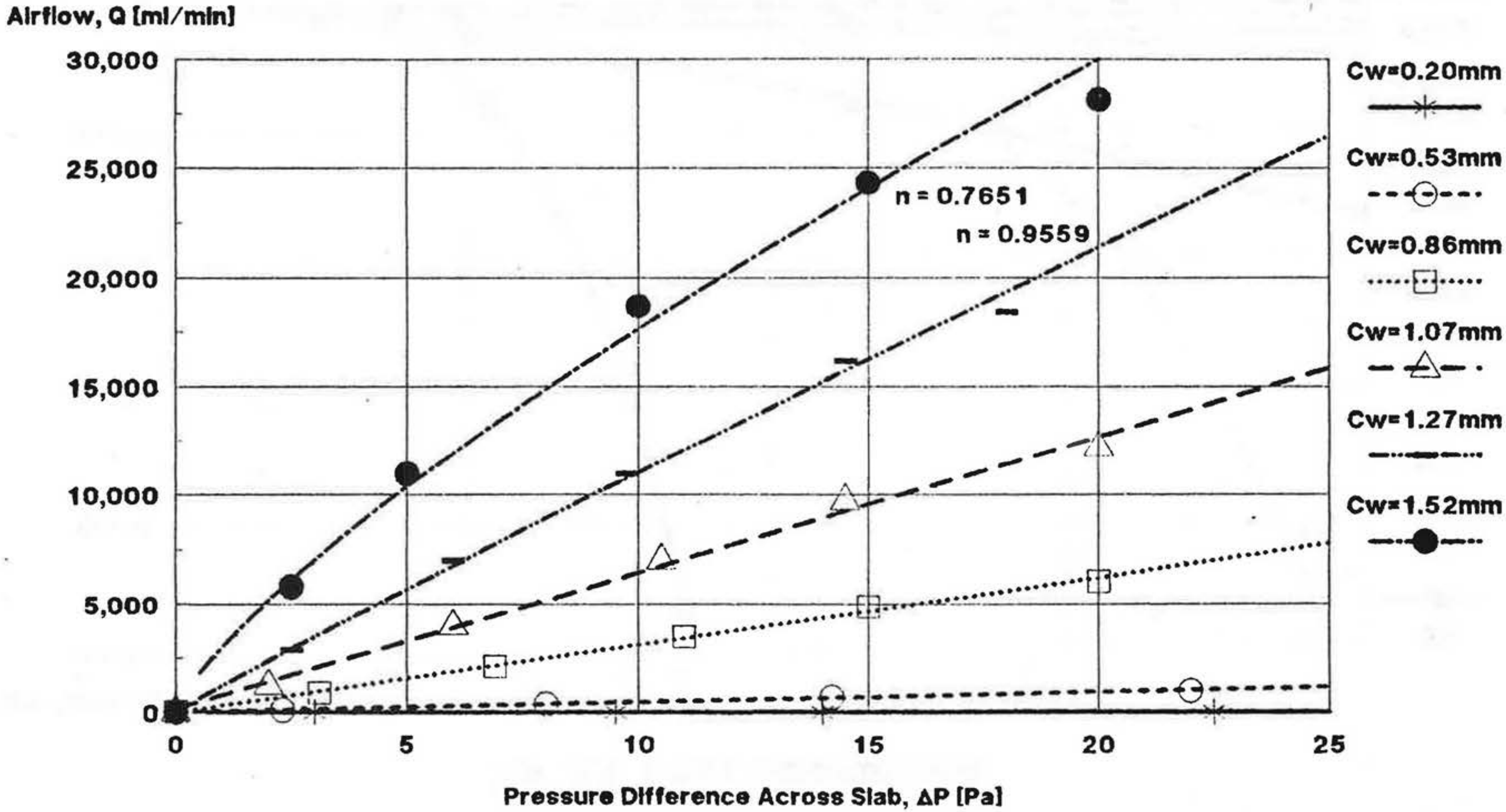


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FIGURE 4

Flow Constant vs Crack Width for All Test Specimens

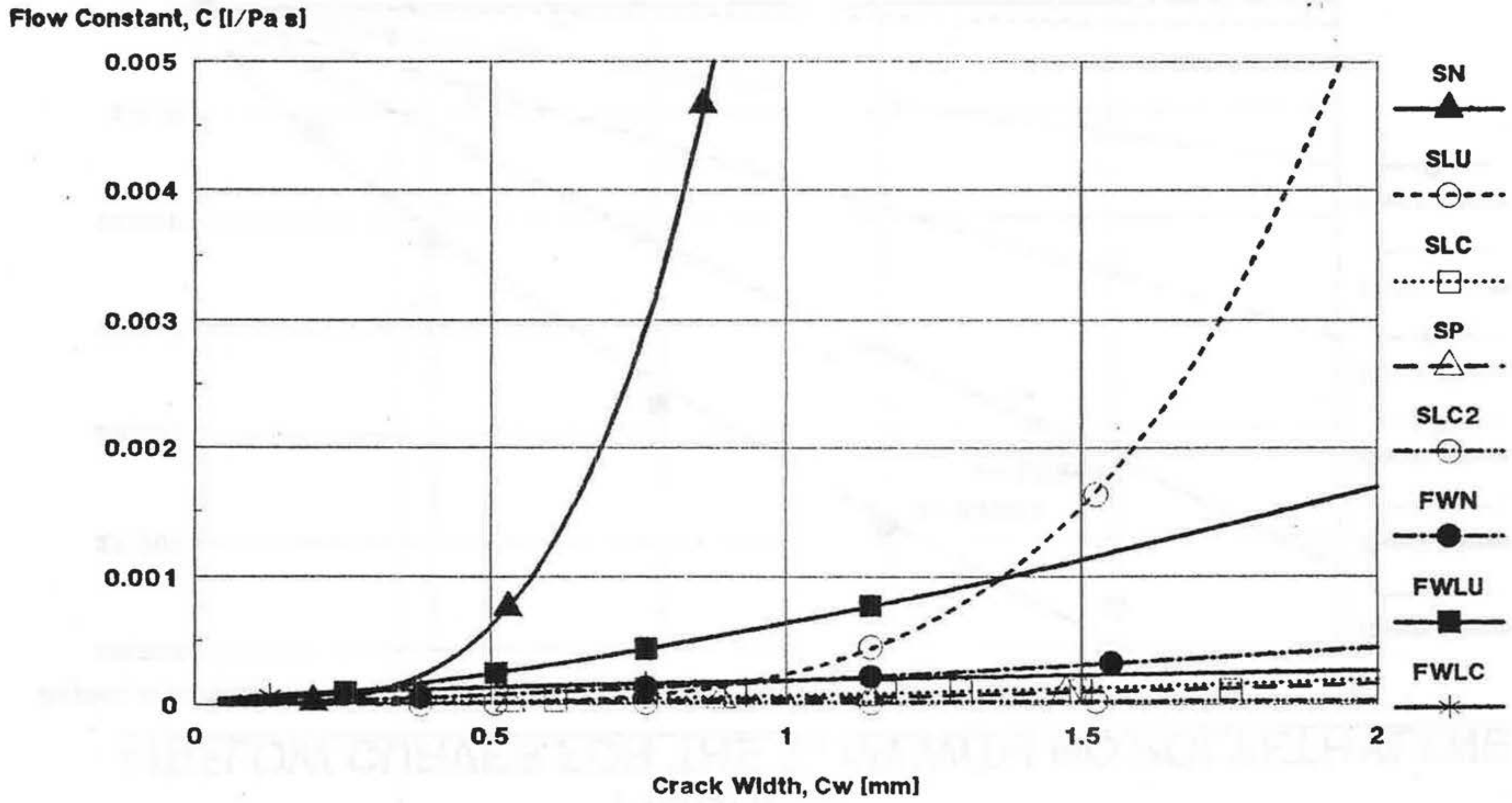

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FIGURE 5

Total Resistance to Airflow vs Crack Width for All Test Specimens

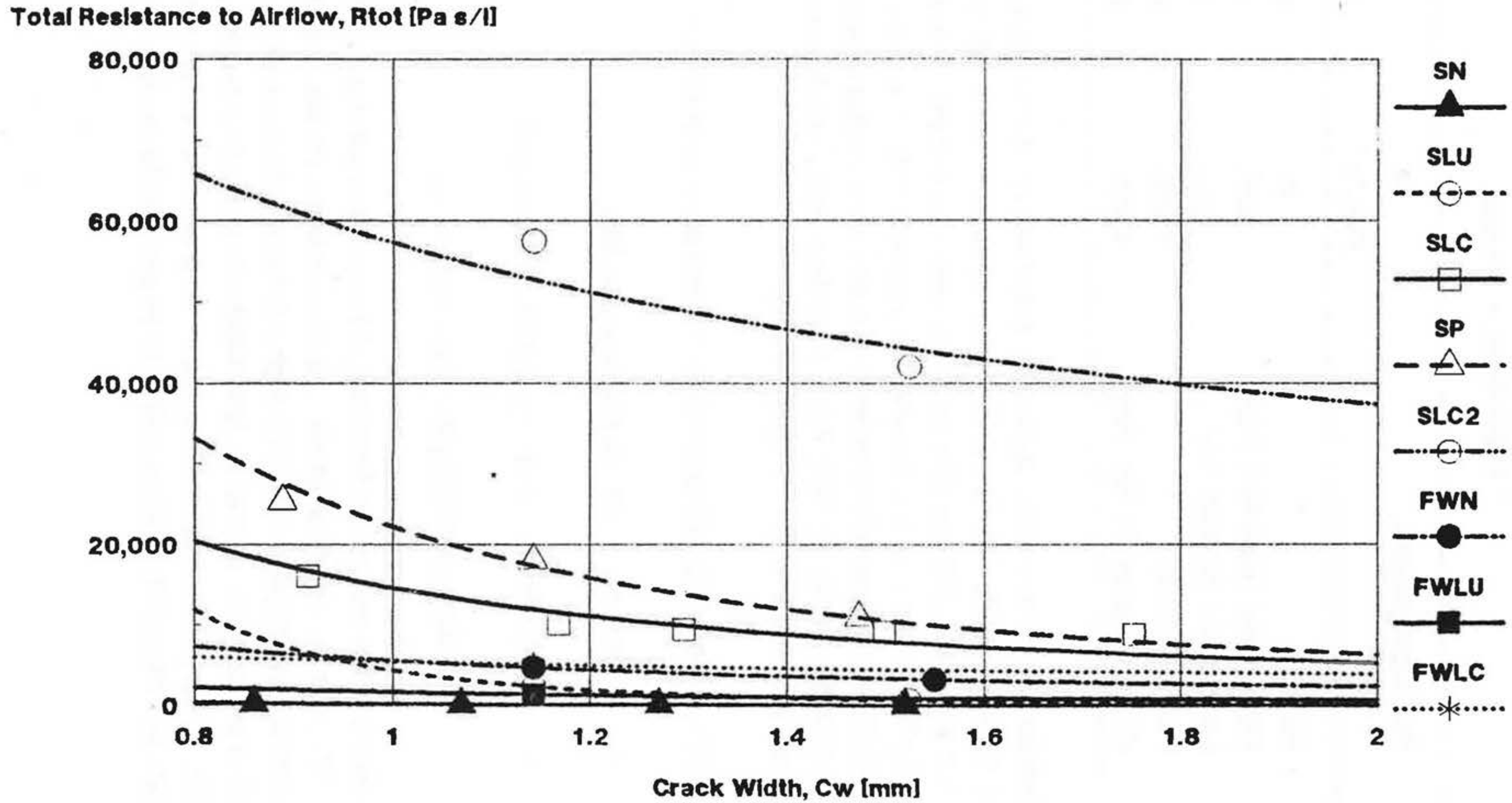

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Table 1 Flow Resistance (R) and Flow Coefficient (C) for the Slab
Crack Width = 1.5 mm:

Poly Configuration	R (Pa s/l)	C (l/Pa s)
No Poly	25	4.0E-02
Lapped and Uncaulked Poly	610	1.6E-03
Lapped and Caulked Poly	9200	1.1E-04
Perforated Poly	11000	9.1E-05
#2 with Lapped Caulked Poly	42000	2.4E-05

To test the airtightness of the apparatus, a test was done on a concrete slab with the crack well sealed. The flow coefficient was 3×10^{-7} l/Pa s, indicating that both the test apparatus and the concrete slab were very airtight. This latter result is very significant, not only in assessing the accuracy of the present experiment. It has often been suggested that radon-laden air enters houses through uncracked concrete slabs. However, the present tests show that properly mixed concrete is effectively impermeable to air when uncracked.

The conclusions that can be drawn from this first series of tests are:

a. perforations are not a serious problem,

b. polyethylene has a very significant effect, and

c. caulking of the polyethylene is necessary.

The results of the tests of the floor-wall joints were less conclusive. Figs. 6 and 7, and Table 2, present these results. As can be seen, the flow resistance of the joint without polyethylene was much higher than that of a crack of the same width. This was probably because of the flow resistance of the floor-footing joint. In real houses, floors get lifted off footings, but in the present tests there was no means of doing so. Therefore, little weight should be given to the results of these tests.

FIGURE 6 Flow Constant vs Crack Width for the Floor-Wall Joint Specimens

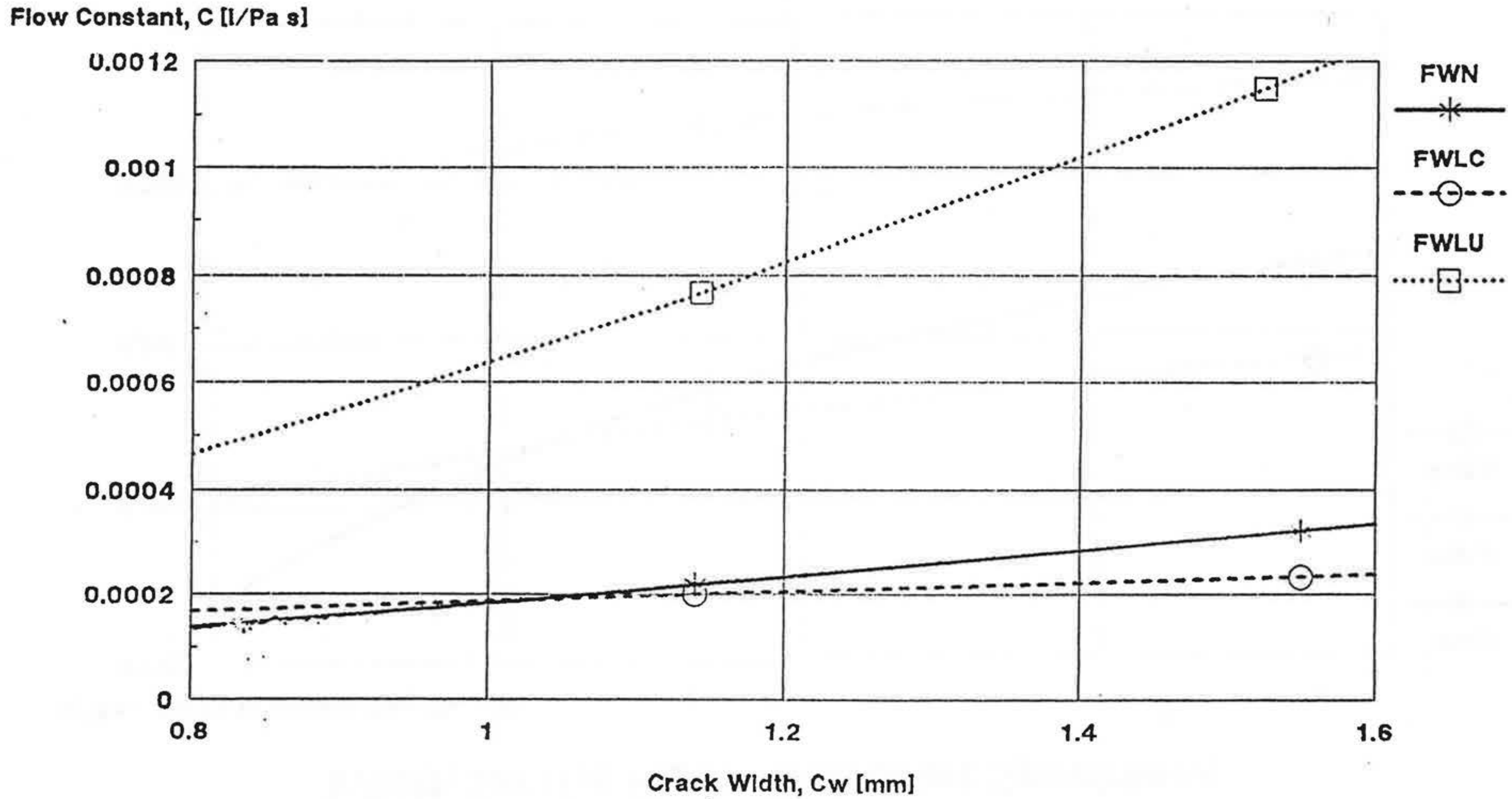

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FIGURE 7 Total Resistance to Airflow vs Crack Width for the Floor-Wall Joint Specimens

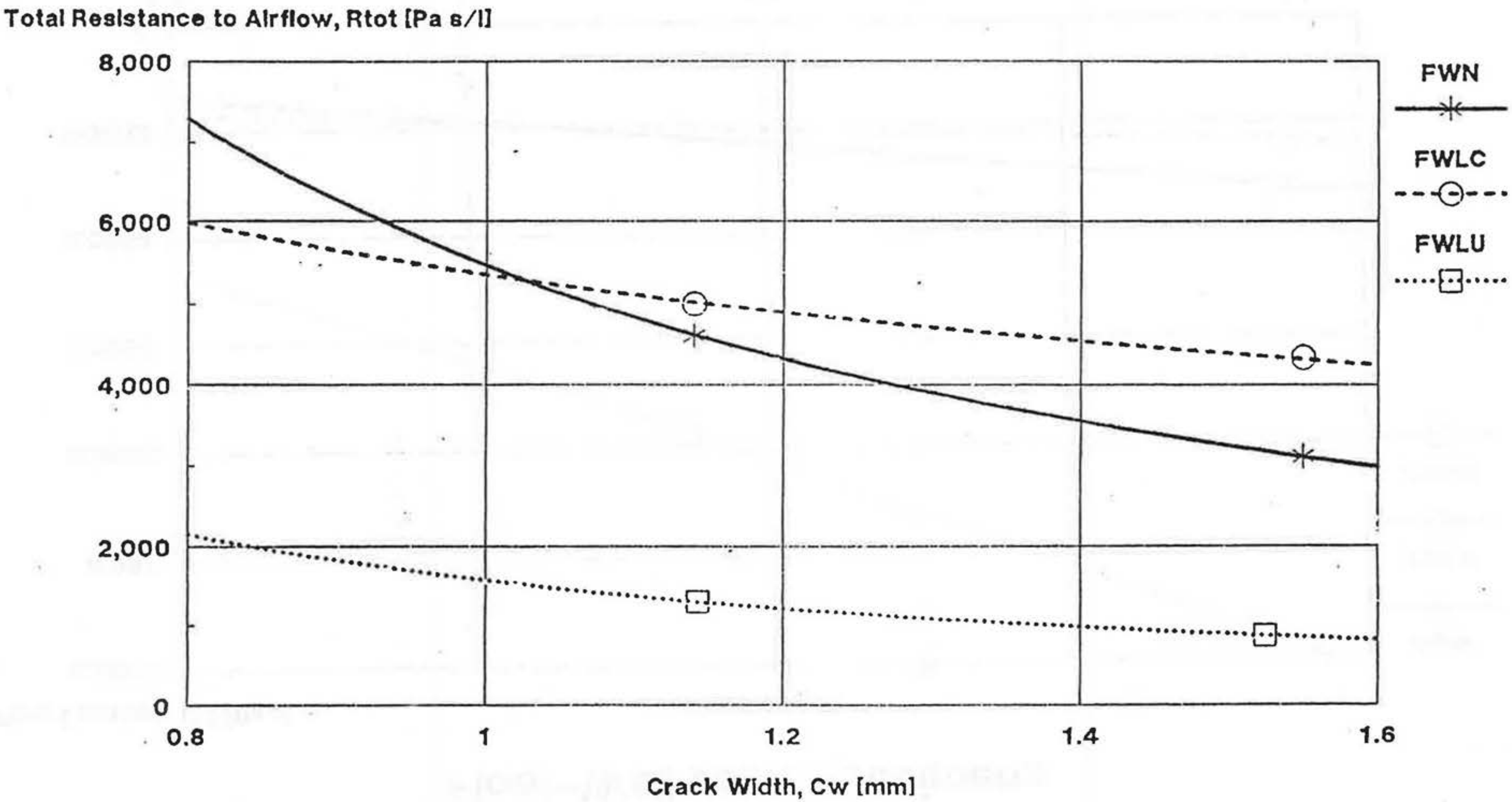

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Table 2 Flow Resistance (R) and Flow Coefficient (C) for Floor-Wall Joint Specimens at a Crack Width of 1.5 mm:

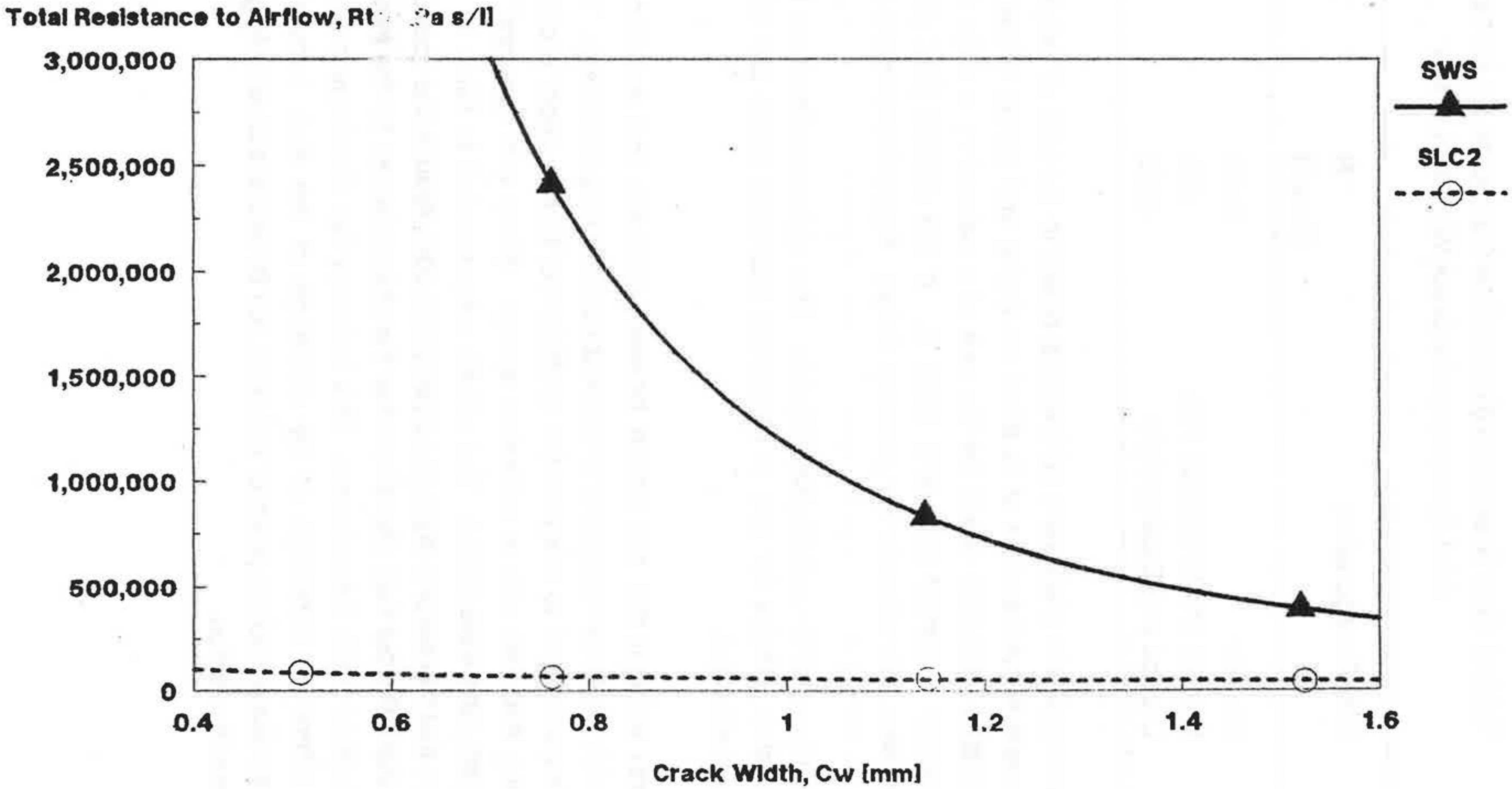
Poly Configuration	R (Pa s/l)	C (l/Pa s)
No Poly	3100	3.2E-04
Lapped and Uncaulked Poly	870	1.2E-03
Lapped and Caulked Poly	4300	2.3E-04

Some concrete placement contractors object to the use of polyethylene under concrete floors because of its effect on drying and curing of the concrete. An alternative approach would be the use of a waterstop, a strip of material that produces a control joint and seals it. If the control joint prevents cracks elsewhere, this will make the concrete airtight. Figure 8 shows the results of a test of this approach. As can be seen, the control joint provides a much tighter seal than lapped and caulked polyethylene. This approach deserves further study if waterstop suitable for use in residential basement floors can be produced at reasonable cost.

It was thought that the friction between concrete and sub-slab gravel could provide the force necessary to crack concrete during shrinkage. Therefore, tests were carried out to measure the coefficient of friction under a concrete slab, by pulling the slab with a calibrated spring. Slabs with one and two layers of polyethylene were tested. The results are presented in Table 3. These results show that the second layer of polyethylene does reduce the coefficient of friction substantially, but they also show that the stress caused by the friction is not high enough to crack the concrete. This indicates that shrinkage cracking is caused by differential shrinkage or by shrinkage of the slab constrained by slab penetrations such as pipes or columns, not by whole-slab shrinkage with tension caused by friction.

FIGURE 8

Total Resistance to Airflow vs Crack Width for the Slabs with Waterstop and the Second with Lapped and Caulked Poly



SWSRTOT.CHT

Table 3 Results from the Friction Test:

Number of Layers of Poly	Coefficient of Friction	Maximum Stress (30'x40')
1	0.65	13.5 psi
2	0.40	8.3 psi

To understand the significance of the results of the airtightness tests it is necessary to compare the overall airtightness of a floor with the airtightness of the soil around a house. Using measured air permeability data for soils, the resistance of a well compacted soil around a house will vary from 20 to 600 Pa s/l, with a typical silty soil having a resistance of 33 Pa s/l. A concrete floor with 25 m of 1.5 mm crack would have a resistance of 1 Pa s/l. This resistance is insignificant compared to that of the soil, and tightening the basement by sealing 50% of the total leaks would have no effect on the inflow of soil gas. On the other hand, a floor with 25 m of 1.5 mm crack and with an underlay of lapped and caulked polyethylene would have a resistance of 1680 Pa s/l. Now the floor is the major resistance, much greater than the soil. The inflow of soil gas is reduced 98% compared to the floor without polyethylene.

The results of the laboratory tests generated the need for further laboratory studies, particularly on the floor-wall joint. It is recommended that more testing be conducted on the floor-wall joint specimens with the test cell having the additional capability of altering the floor-footing gap. It is also recommended that further study by done to determine the effectiveness and suitability of using waterstop across the floor-wall interface to increase the airtightness. This would apply to both laboratory and field work.

6.0 TASK E: FORUM

On June 27, a forum was held at CMHC in Ottawa to present the results of the laboratory research described above, and to obtain input from the construction industry and from other radon researchers about the direction the project should take. Table 4 lists the attendees.

A key issue raised at the meeting was whether or not it was feasible for concrete placement contractors to pour floors on top of an impermeable substrate such as polyethylene. It was agreed that this was a feasible approach, provided that a superplasticizer was used instead of excess water to achieve high slump. In particular, this was the view of Lyle Hamre of the Canadian Portland Cement Association and of John Broniak of the Canadian Home Builders Association.

Based on this view, and on the results of the laboratory tests that showed lapped and caulked polyethylene to be very airtight, it was decided to continue the project in its original direction. Therefore, the field demonstration was set up to test this concept. It was agreed that the basement floor would be sealed using techniques that would be available to a housebuilder (that is, using polyethylene sheet caulked at the footings, at seams, and at penetrations with acoustical sealant.) However, greater than normal care would be taken to make the installation the best possible using that technology. The air flow through the polyethylene was to be measured as a function of the pressure differential.

Several other approaches to sealing the floor were discussed, including the use of perforated polyethylene and the use of a waterstop system to control and seal cracks, but it was agreed that the caulked polyethylene approach showed better promise than any of these.

Appendix A of the July 30, 1991 progress report contains copies of the material presented on slides at the meeting.

TABLE 4

ATTENDEES AT CMHC WORKSHOP ON CONCRETE FLOOR AIRTIGHTNESS
AT CMHC ON JUNE 27, 1991

Lyle Hamre	CPCA
John Broniak	CHBA
Adair Chown	NRC
Dick McGregor	HWC
Arthur Scott	
Brian Gent	CHBA
Terry Marshall	CMHC
Peter Russell	CMHC
Craig Wray	Yuill and Associates
Gren Yuill	Yuill and Associates

7.0 TASK F: FIELD TRIALS

7.1 Introduction

The field trials were the last task in this project. The following material is the first report on this task.

The field trials involved the construction of a test basement floor in a new house using the system of lapped and caulked polyethylene as a substrate. The purpose of this phase of the project was to demonstrate a practical field procedure for obtaining a slab that will maintain a designed degree of airtightness without incurring a significant increase in cost.

Preparations for this phase of the project began by searching for contractors to collaborate with. Hilton Homes in Winnipeg agreed to cooperate, offering a house at 98 Dobrinsky Drive. The test house is approximately 72 m^2 (780 ft^2) and has an L shaped footprint. Work started in the house at the beginning of July and the last airtightness test was conducted in mid-August.

The objectives of the house trial were:

1. to evaluate the performance of the continuous sheet of lapped and caulked polyethylene, both before and after the pouring of the concrete floor,

2. to evaluate the practicality of using the chosen installation practices,

3. to assess the amount of labour involved in installing and sealing the substrate,

4. to investigate the suitability of using superplasticizers in reducing the water-to-cement ratio while still maintaining the workability,

5. to assess the amount of labour involved in pouring and finishing the concrete floor with superplasticizers added to the concrete, and

6. to learn the attitudes of the concrete placement contractors with respect to pouring concrete onto a polyethylene sheet.

The steps involved in the house trial include, in chronological order:

1. installing a sub-slab suction system,

2. isolating the sub-slab volume from the outside of the basement by sealing all weeping pipe entries with expandable foam,

3. installing four pressure tubes for sub-slab pressure measurement,

4. handcrafting polyethylene skirts around all pipe penetrations,

5. laying the polyethylene sheet over the gravel bed and sealing it to the skirts, footing and telepost pads,

6. conducting an airtightness test on the polyethylene sheet alone,

7. pouring the concrete floor,

8. applying a curing compound to permit proper curing of the slab,

9. conducting an airtightness test on the floor, and

10. plotting and analyzing the test results.

7.2 Assessment of the Labour Requirements

The practices applied in the trial basement proved to be too labour intensive to be fulfilled by the construction industry. Therefore, some improvements are required.

First and foremost, an alternate method for sealing around pipe penetrations is necessary. The use of some type of neoprene sleeve/skirt seal that slips either over or around a pipe would significantly cut down the labour time.

A second required improvement relates to sealing the polyethylene to the footing and telepost pads. During the sub-slab plumbing pipe installation and spreading of the gravel, both concrete surfaces get covered in water or mud, neither of which adhere to acoustical sealant. One of three alternatives may be used. First, instead of caulking the polyethylene to the footing, the bead could be run along the wall/footing corner where it is usually quite clean. This would eliminate the need to wash the surface of the footing. In this case only the telepost pads would require washing. Second, install a plastic "T" strip into the top of the footing and telepost pads to caulk the polyethylene sheet to. The strip would be easily installed and easy to wipe clean just before caulking. Third, use a waterstop that is cast into the bottom of the wall and either caulk the polyethylene to the waterstop or use the waterstop as a floor-wall joint seal and replace the polyethylene sheet with a grid of waterstop in the floor. This presents a totally different floor configuration and it would require more study to determine its effectiveness and suitability.

7.3 The Use of Concrete with Superplasticizers

The concrete used for the test basement floor was unsuccessful. Immediately after raking the mix, water began separating from the top and forming puddles up to 1/2" in depth. This bleeding continued for hours. It was not until 23 hours later that the floor was finished. A normal basement floor, with a wet mix poured directly onto the gravel, should take between six and eight hours to finish completely.

The cause for the water separation has not been established. Several experts were questioned, but none blamed the polyethylene sheet. Possible reasons include dirty sand used in the aggregate, the concrete sat too long in the truck, too much plasticizer being added, and some water being added on site. In spite of this failure, it is still believed by many of the people contacted that concrete with superplasticizers is a promising application.

7.4 The Airtightness Tests and Results

Two airtightness tests were conducted. One test was done on the polyethylene sheet alone to evaluate the performance of the air barrier and a second test was carried out after the concrete had cured for 14 days to determine how much tighter the floor became.

The airtightness tests involved regulating the sub-slab pressure and the house pressure with a sub-slab suction system and blower door assembly, respectively. Both fans were connected through rheostats to control the respective pressures. Airflow measurements were made by means of an orifice meter in the sub-slab suction system pipe. All pressures were measured with a set of magnehelic gauges.

The airtightness test included three airflow cases. The first was the total airflow, through both the floor and the soil together. In this case, the house pressure was kept equal to the outdoor pressure, and the sub-slab pressure was varied. The second case involved equalizing the outdoor and sub-slab pressures to obtain data on the flow through the floor only. The third case produced flows through the soil only by equalizing the sub-slab and house pressure. This test wasn't appropriate for the first airtightness test (without concrete) because the polyethylene sheet floated, so that equilibrium could not be reached.

The results of the airtightness tests are presented in Table 5. These results show that the floor system worked very well. The test on the polyethylene sheet alone showed that this air barrier was about four times leakier than determined from the test done on the specimen with the same configuration of polyethylene and with concrete in the lab. This ratio was not surprising, considering the pipe penetrations present in the field test, and considering that the polyethylene had no concrete on top of it. The test also showed that only 10% of the withdrawn air leaked through the sheet. The remaining 90% came through the soil. The flow through the polyethylene at a 10 Pa pressure differential was 0.15 l/s, and the equivalent leakage area (ELA) was 0.60 cm^2. This membrane alone is tight enough to keep out radon.

Table 5

Results from Airtightness Test on Concrete Basement Floor at 98 Dobrinsky Drive

Case 1: Total Flow: Pin=Pout
Pss wrt Pout

DPori (Pa)	Q (l/s)	Pss (Pa)
25	1.2162	20
49	1.7026	40
90	2.3072	75
140	2.8771	110
165	3.1232	125
250	3.8435	175

Case 2: Flow from Soil: Pss=Pin
Pss wrt Pout

DPori (Pa)	Q (l/s)	Pss (Pa)
22	1.1409	25
50	1.7199	50
82	2.2023	75
125	2.7188	100
170	3.1702	125

Case 3: Total Flow: Pin=Pout
Pss wrt Pout

DPori (Pa)	Q (l/s)	Pss (Pa)
18	1.0320	25
45	1.6316	50
85	2.2422	75
125	2.7188	100
170	3.1702	125

Case 4: Flow Through Floor:
Pss = Pout: Large Orifice Plate
No Flow was measured due to floor airtightness
DPori = 0 Pa with Pin = 50 Pa

Case 5: Flow Through Floor:
Pss = Pout: Small Orifice Plate
No Flow was measured due to floor airtightness
DPori = 0 Pa with Pin = 50 Pa

DPori = orifice pressure difference
Pin = indoor pressure
Pout = outdoor pressure
Pss = sub-slab pressure
wrt = with respect to

Equivalent Leakage Area, ELA, for Each Case Tested

CASE	C (L/s.Pa^n)	n	ELA (m^2)	ELA (cm^2)
1	0.247113	0.525123	0.00033	3.3
2	0.146465	0.633200	0.00025	2.5
3	0.106579	0.702652	0.00022	2.2

The test conducted on the concrete floor showed that the total flow and the flow through the soil were equal. No flow was detectable for the test done to measure the flow through the floor.

Even if the accuracy of the flow measurements was ± 1 Pa, implying that at a 50 Pa pressure differential the measured pressure drop of 0 Pa could really have been a 1 Pa drop across the orifice plate, this would work out to approximately 13 ml/s and an ELA of 0.05 cm^2. This is a very small area relative to the size of the basement and confirms that the basement floor is tight enough to keep radon out.

7.5 Estimated Cost Increase of the Floor

It has been estimated (Proskiw, 1991) that the material and labor costs of the installation of lapped and caulked polyethylene sheet is $2.92 to $3.75 per m^2. This includes a cost of $1.08 per m^2 for the additional work of finishing the concrete, caused by the lack of drainage. (Some concrete contractors have estimated as high as $3.50 per m^2 for this additional work, but this may have been based on a lack of experience.) On the other hand, this extra work can be avoided by the use of a superplasticizer instead of water to make the concrete fluid. This costs about $1.00 per m^2 of floor, but it results in a far stronger concrete with less shrinkage cracks and a lower air permeability than would be produced by a wet mix.

Considering these factors, the additional cost is estimated to be about $400 to $800 for houses from 100 m^2 to 230 m^2. That is a significant expense, approaching the cost of installing a sub-slab depressurization system in a new house. However, the sub-slab air barrier approach has the advantage that it is passive, probably more long-lasting, and it does not use electricity or increase infiltration.

8.0 CONCLUSIONS

The major conclusion reached as a result of this project is that a sub-slab polyethylene air barrier can be a very effective means of making a basement floor airtight. A second conclusion is that a waterstop system may have the same capability. A third approach with some potential is the use of perforated polyethylene, but the present project showed only that it could be airtight, not that it could have the hoped-for effect of draining excess water from polyethylene.

The best estimate of the cost of a sub-slab polyethylene air barrier is that it is not so expensive as to be out of the question, but neither is it so cheap as to be accepted as the final solution to the problem.

9.0 RECOMMENDATIONS

1. Since the flow of soil gas into homes presents a very serious pollution problem, and since the 1990 National Building Code requires the use of a sub-slab air barrier to reduce this problem, it is recommended that CMHC develop a technology transfer program to teach building code officials and housebuilders what is now known about the construction of airtight basement floors.

2. It is recommended that a further series of laboratory tests be carried out on the airtightness of floor-wall joints. These tests should extend the results of the previous tests by the addition of the capability of raising and lowering the floor relative to the footing. These tests should include measurements of the airtightness of caulked polyethylene and of a floor-wall waterstop.

3. It is recommended that further series of field trials be carried out in new houses. These trials should focus on
   a) the concrete placement procedure and its cost; and
   b) the resulting airtightness of the slab.

In these field tests, caulked polyethylene sheet, perforated polyethylene sheet, and waterstop should be tested and compared.

APPENDIX A

Saskatchewan
Research Council

CONFIDENTIAL

CONFIDENTIAL REPORT

Concrete Foundation Air Leakage Study

for

G.K. Yuill and Associates Ltd.
1441 Pembina Hwy.
Winnipeg, MB.
R3T 2C4

by

Building Science Division

Technology Transfer and Business Development Branch

Publication I-4800-23-C-91 August 1991

CONFIDENTIAL REPORT

Concrete Foundation Air Leakage Study

for

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August 1991

OVERVIEW

G.K. Yuill and Associates Ltd. is conducting a study (funded by Canada Mortgage and Housing Corporation) on the influence on foundation air leakage of installing sheet polyethylene under cast-in-place concrete floor slabs. This document presents the results of a field investigation of foundation air leakage in a group of ten houses in Saskatoon, SK. The work was conducted on behalf of G.K. Yuill and Associates Ltd. under SRC contract no. I-4800-42.

The Building Science Division (BSD) conducted field measurements of the air leakage characteristics of existing residential cast-in-place concrete foundations. To provide comparative data, five house basements constructed using conventional technology and five constructed with polyethylene film installed under the floor slab were investigated.

Due to the lack of control with respect to the construction details and the variation in house types/ages that could be obtained, it is not possible to draw strong conclusions regarding the relative "in-situ" performance of the two foundation types. General observation of the data showed that the average floor/wall crack equivalent leakage area was three to four times higher in the houses with polyethylene under the floor slabs. House age and the resulting soil coupling affect are confounding variables in this analysis. Large spatial variations in specific component air leakage characteristics were noted, both within a single foundation and among all the foundations tested.

It is recommended that, in future, a prospective study design be undertaken to ensure that the design parameters and site quality control are adequate to support definitive conclusions regarding the foundation air leakage control system performance.

ACKNOWLEDGEMENT

The Building Science Division acknowledges the contribution of the National Research Council of Canada in supplying additional resources to this project.

INTRODUCTION

The infiltration of soil gases into buildings through their foundations has been identified as a potentially serious problem. One effective measure for minimizing the soil gas entry rate is to construct foundations with high levels of air tightness.

The BSD has extensive experience in the field measurement of foundation air leakage. Studies conducted to date have shown that large spatial variations in air leakage within a building can exist. Based on previous BSD experience, a single site measurement in each house would not yield data that was representative of the system's performance and could result in erroneous interpretation. Likewise, the range of potential site conditions and construction practices will result in additional systematic variations in foundation air leakage. To ensure that a reasonably accurate assessment of the overall relative performance of a foundation system was obtained, multiple measurements on a number of foundations were required.

This project represented an initial investigation into the air leakage characterization of a number of relatively new concrete foundations constructed with and without a polyethylene sheet membrane installed under the floor slab. The relatively small number of foundations and lack of control over experimental site parameters restricts the extrapolation of the study results to the general population.

METHODOLOGY

A moderate level of investigation in a restricted number of houses was chosen as the best application of the project resources. This approach yielded a small, but credible data base that can be expanded through further foundation studies and interfaced with existing data on foundation air leakage.

The study used a retrospective case/control design to examine the relative performance of the two foundation air leakage control systems. The study examined five case houses (polyethylene under the floor slab) and five control houses (traditional, no polyethylene) and provided data that can be used by the client to evaluate the relative air leakage characteristics of the two study groups. The retrospective nature of the study prevented detailed matching of the two study groups. Local contractors and homeowners were contacted to solicit their participation in the study.

The project was conducted using privately owned houses ranging from approximately one to five years in age. One year was considered the minimum age to ensure that the foundation was "mature" and had reached a state of quasi-equilibrium. To the extent possible, houses of similar age, location and general foundation construction were used to minimize uncontrolled experimental variables.

The general methodology, equipment and analysis used for measuring the foundation air leakage are described in reference 1. The differential pressure measurements across the foundation components were taken relative to outdoor air pressure and relative to the ambient pressure in the foundation drainage system with the floor drain sealed.

The field measurement protocol included three components:

1) <u>foundation component air leakage</u>

4 - floor/wall interface locations
2 - typical floor crack areas (where possible)
1 - plumbing penetration (eg. clean-out)
1 - floor drain

The differential pressure measurement originally specified by the client required drilling a 10 mm diameter hole through the floor slab and installing a pressure reference (to be removed and the floor repaired after the measurement was completed) adjacent to each component measurement site. None of the homeowners would agree to this procedure and as an alternative, a pressure tap was located in the foundation drainage system and the floor drain cover sealed.

2) <u>concrete air permeance measurement</u>

A measurement of the concrete floor slab air permeance at four selected locations in each house was obtained using a Schupack instrument. The Schupack air permeance meter has several modes of operation. The technique selected involved measurement of the decay of the vacuum pressure in the apparatus in a one minute time interval. The amount of pressure decay is an indication of the relative air permeance of the concrete. Replicate measurements were made at each location.

3) inventory of floor crackage

A visual inspection and estimate of the total crack length and range of crack width was conducted. A photographic record of colour slides was obtained from each foundation.

ANALYSIS and RESULTS

General information on the houses is given in Table 1.

Before analysis, all of the air flow data were corrected to a reference temperature of 20°C and a density, ρ_r of 1.204 kg/m^3.

Differential pressure, ΔP (Pa) and corrected air flow rate, Q_r standard litres per minutes (SLM), data were used to calculate flow coefficient, C_r (L/s·Pa^n) and exponent, n (dimensionless) values for each component using a least squares curve fit regression of the expression:

$$Q_r = C_r \cdot \Delta P^n \qquad (1)$$

The calculated values of C_r and n were used to calculate equivalent leakage areas for each component, ELA (cm^2) using:

$$ELA = 11.57\ (\rho_r)^{0.5} \cdot C_r \cdot 10^{n-0.5} \qquad (2)$$

Where most of the air flow rates for a test run were around or below the measurement limitation for the equipment (0.5 SLM), no calculations or data are presented and the component is noted as having no measurable air leakage.

All of the calculated values for the components are given in Table 2. Values are presented using differential pressures referenced to ambient pressure and referenced to the sealed foundation drainage system.

Results of the Schupack vacuum decay measurements are given in Table 3.

Table 4 contains the results of the floor crack inventory.

The photographic record of the project is given in Appendix 1.

SUMMARY

It is apparent from the results obtained that there is a wide variation in the air leakage characteristics of the foundations tested.

Ideally, the foundation component air leakage data should be taken without soil coupling to ensure that only the foundation air leakage resistance is measured. In this retrospective study of existing homes, this was not an option. Use of the foundation drainage system as a pressure reference was an attempt to approximate the pressure regime adjacent to the foundation components but could not eliminate the soil resistance to air flow being integrated into the overall component air leakage characteristic.

This effect can cause a significant distortion of the apparent foundation air flow characteristics due to pressure transients created by depletion of soil gas from the soil mass. As the test is conducted, soil gas is removed from the surrounding soil creating a non-uniform time varying pressure gradient radiating outward from the component site. Since the soil is not an infinite source with zero resistance (as would be the case in above grade air leakage testing) the effect on the apparent foundation resistance will be highly influenced by soil properties, geometry, length of test and soil gas flow rate. "Tight" soils (such as clay) will exhibit the most pronounced effect while sand and gravel may have a lesser effect. Site specific conditions such as clay layering and top soil cover will further complicate the analysis.

Analysis of the influence of these parameters is beyond the scope of this report and, in general, may present unworkable levels of experimental error. A prospective study which is designed to eliminate soil coupling and control experimental variables would prevent these problems.

In the field testing of the ten houses, foundation drainage system pressures were observed to range from up to +10 Pa to -70 Pa when referenced to outdoor pressure.

A valid assessment of the relative air leakage performance of the two foundation air leakage control systems cannot be made on the basis of the field testing (considering the effects of construction variations, soil coupling and other site-specific effects).

The Schupack air permeance measurement technique can not directly quantify the one dimensional air permeance through the floor slab since several other significant air leakage pathways existed. The surrounding house pressure was not compensated and therefore, air leakage could occur directly around the seal to the concrete surface and through cross-leakage through the permeable concrete surface.

Not

REFERENCE:

1. Figley, D.A., Dumont, R.S., "Techniques For Measuring The Air Leakage Characteristics For Below Grade Foundation Components", Proceedings of the 82nd Annual Meeting of the Air and Waste Management Association, Anaheim, California, June 25-30, 1989.

↑Not intended to - relative concrete permeance.

Table 1. Basic House Data

House Code	House Style	Age (yrs)	Poly	Comments
1	Bungalow	1.5	Y	uninsulated, full basement, house unoccupied
2	4 Level Split	1	N	lowest level uninsulated, house unoccupied
3	Bungalow	4	Y	insulated full basement, house unoccupied
4	4 Level Split	5	N	half of lowest level finished, house unoccupied
5	4 Level Split	5	N	lowest level insulated, house unoccupied
6	4 Level Split	5	N	lowest level insulated, house unoccupied
7	4 Level Split	4	N	lowest level insulated, house unoccupied
8	2 Storey	1.5	Y	uninsulated full basement, show home
9	Bungalow	0.75	Y	uninsulated full basement, unoccupied, show home
10	Bungalow	1.5	Y	uninsulated full basement, house unoccupied

Table 2. Foundation Component Air Leakage (AL) Data

House Code	Component Location	ΔP ref. to atmosphere Cr (L/s-Pa^n)	n	ELA (cm^2)	ΔP ref. to foundation drainage system Cr (L/s-Pa^n)	n	ELA (cm^2)
1	F/W - A	0.001147	0.55	0.0082	ΔP same as atmospheric since weeping tile vented to atmosphere via 2 - 125 mm ø pipes		
	F/W - B	0.000619	0.89	0.0097			
	F/W - C	0.001495	0.73	0.0163			
	F/W - D	0.000175	1.08	0.0042			
	FC - E	*	*	*			
	FC - F	*	*	*			
	PP - G	NA	NA	NA			
	FD -	3.883	0.50	50.0			
2	F/W - A	*	*	*	*	*	*
	F/W - B	*	*	*	*	*	*
	F/W - C	0.005984	0.99	0.2358	0.031362	0.81	0.8182
	F/W - D	0.002587	0.96	0.0956	0.009925	0.89	0.3082
	FC - E	*	*	*	*	*	*
	FC - F	*	*	*	*	*	*
	PP - G	0.03657	0.74	0.7990	0.102719	0.68	1.9923
	FD -	0.740	0.70	15.0			
3	F/W - A	*	*	*	*	*	*
	F/W - B	*	*	*	*	*	*
	F/W - C	0.002476	0.84	0.0682	0.015980	0.67	0.2979
	F/W - D	*	*	*	*	*	*
	FC - E	*	*	*	*	*	*
	FC - F	*	*	*	*	*	*
	PP - G	0.00057	0.80	0.0143	0.003046	0.67	0.0569
	FD -	1.082	0.60	17.2			
4	F/W - A	0.000154	1.36	0.014	0.00074	1.16	0.0425
	F/W - B	*	*	*	*	*	*
	F/W - C	*	*	*	*	*	*
	F/W - D	*	*	*	*	*	*
	FC - E	*	*	*	0.000026	1.16	0.0015
	FC - F	*	*	*	*	*	*
	PP - G	NA	NA	NA	NA	NA	NA
	FD -	0.415	0.78	9.98			
5	F/W - A	0.000708	0.93	0.0242	0.000734	0.94	0.0256
	F/W - B	0.0000141	1.06	0.0065	0.000050	1.32	0.0041
	F/W - C	*	*	*	*	*	*
	F/W - D	0.001109	0.88	0.0340	0.001281	0.86	0.0375
	FC - E	*	*	*	*	*	*
	FC - F	*	*	*	*	*	*
	PP - G	0.000489	1.00	0.0194	0.000661	0.95	0.0234
	FD -	0.430	0.69	8.49			

6	F/W - A	0.000285	0.88	0.0087	0.000422	0.79	0.0104
	F/W - B	0.000495	0.84	0.0137	0.000266	0.97	0.0100
	F/W - C	0.000211	1.05	0.0095	0.000094	1.22	0.0063
	F/W - D	0.006149	0.61	0.1017	0.007188	0.58	0.1093
	FC - E	*	*	*	*	*	*
	FC - F	*	*	*	*	*	*
	PP - G	0.00044	1.02	0.0184	0.000435	1.02	0.0183
	FD -	0.566	0.72	11.9			
7	F/W - A	0.002132	0.87	0.0639	0.002586	0.83	0.695
	F/W - B	*	*	*	*	*	*
	F/W - C	0.000195	1.14	0.0108	0.00014	1.20	0.0089
	F/W - D	0.000736	1.00	0.0295	0.000982	0.93	0.0339
	FC - E	*	*	*	*	*	*
	FC - F	*	*	*	*	*	*
	PP - G	0.000505	0.96	0.0184	0.000446	0.98	0.0172
	FD -	0.768	0.66	14.16			
8	F/W - A	0.000032	1.35	0.0029	0.000115	1.18	0.0070
	F/W - B	0.069616	0.71	1.4442	0.12754	0.64	2.2404
	F/W - C	*	*	*	*	*	*
	F/W - D	*	*	*	*	*	*
	FC - E	0.000239	0.63	0.0041	0.000342	0.60	0.0054
	FC - F	*	*	*	*	*	*
	PP - G	0.14623	0.76	0.3403	0.030479	0.66	0.5538
	FD -	0.641	0.67	12.01			
9	F/W - A	0.000369	0.97	0.0138	0.000511	0.88	0.0155
	F/W - B	0.000134	1.08	0.0065	0.000141	1.05	0.0063
	F/W - C	0.00109	0.75	0.0246	0.000983	0.75	0.0224
	F/W - D	0.000612	0.83	0.0165	0.000837	0.73	0.0179
	FC - E	*	*	*	*	*	*
	FC - F	*	*	*	*	*	*
	PP - G	0.00698	0.79	0.1729	0.007657	0.74	0.1707
	FD -	1.344	0.62	22.49			
10	F/W - A	0.000387	1.07	0.0182	0.000898	0.94	0.0316
	F/W - B	0.000139	1.14	0.9843	0.000299	1.04	0.0133
	F/W - C	*	*	*	*	*	*
	F/W - D	0.000814	1.00	0.0331	0.001230	0.97	0.0458
	FC - E	*	*	*	*	*	*
	FC - F	*	*	*	*	*	*
	PP - G	0.002624	1.01	0.1069	0.004466	0.94	0.1562
	FD -	4.561	0.31	37.69			

* No measurable flow over the ΔP range 0-100 Pa

Legend:
- F/W - perimeter floor slab/wall crack
- FC - floor crack
- PP - plumbing penetration
- FD - floor drain
- NA - not applicable

Table 3. Schupack Concrete Air Permeance Test

House Code	Location	Initial Vacuum	Vacuum after 1 min.	Comments
1	(N.W.) a.1	24.8	17.0	slightly rough surface - trowel marks
	a.2	24.8	17.7	
	a.3	24.8	17.8	
	(N.E.) b.1	24.8	18.8	as above
	b.2	24.8	18.7	
	b.3	24.8	18.9	
	(S.E.) c.1	25.0	21.5	smooth surface
	c.2	25.0	21.8	
	c.3	25.0	21.8	
	(S.W.) d.1	24.8	17.0	slightly rough surface - trowel marks
	d.2	24.8	17.8	
	d.3	24.8	18.0	
2	(N.W.) a.1	24.5	21.7	smooth surface
	a.2	24.5	22.3	
	a.3	24.5	22.5	
	(N.E.) b.1	24.5	21.1	as above
	b.2	24.5	21.8	
	b.3	24.5	21.8	
	(S.E.) c.1	24.5	18.7	as above
	c.2	24.5	19.3	
	c.3	24.5	19.5	
	(S.W.) d.1	24.5	21.4	as above
	d.2	24.5	21.8	
	d.3	24.5	22.0	
3	(N.W.) a.1	23.8	16.0	smooth surface with small holes
	a.2	24.0	16.7	
	a.3	24.0	16.9	
	(N.E.) b.1	24.0	15.0	as above
	b.2	24.0	15.8	
	b.3	24.0	16.2	
	(S.E.) c.1	24.0	14.3	as above
	c.2	24.0	15.5	
	c.3	24.0	16.1	
	(S.W.) d.1	24.0	14.4	as above
	d.2	24.0	15.5	
	d.3	24.0	15.7	

4	(N.W.) a.1 a.2 a.3	24.5 24.5 24.5	19.6 19.7 20.0	slightly rough
	(N.E.) b.1 b.2 b.3	24.5 24.5 24.5	18.5 18.9 19.1	rough
	(S.E.) c.1 c.2 c.3	24.5 24.5 24.5	19.3 19.4 19.5	slightly rough
	(S.W.) d.1 d.2 d.3	24.5 24.5 24.5	20.9 21.6 21.7	smooth
5	(N.W.) a.1 a.2 a.3	24.5 24.5 24.5	21.8 22.4 22.6	uniform surface
	(N.E.) b.1 b.2 b.3	24.5 24.5 24.5	21.9 22.5 22.6	as above
	(S.E.) c.1 c.2 c.3	24.5 24.5 24.5	20.4 21.2 21.4	as above
	(S.W.) d.1 d.2 d.3	24.5 24.5 24.5	21.7 22.0 22.2	as above
6	(N.W.) a.1 a.2 a.3	24.0 24.0 24.0	19.2 20.1 20.2	slighly rough
	(N.E.) b.1 b.2 b.3	24.0 24.0 24.0	18.5 19.5 19.7	as above
	(S.E.) c.1 c.2 c.3	24.0 24.0 24.0	19.6 20.6 20.7	as above
	(S.W.) d.1 d.2 d.3	24.0 24.2 24.0	19.4 20.3 20.0	as above

7	(N.W.) a.1 a.2 a.3	24.5 24.5 24.5	20.3 21.2 21.6	smooth
	(N.E.) b.1 b.2 b.3	24.5 24.5 24.5	18.9 20.1 20.6	as above
	(S.E.) c.1 c.2 c.3	24.5 24.5 24.5	20.2 21.3 21.7	as above
	(S.W.) d.1 d.2 d.3	24.5 24.5 24.5	20.8 21.0 21.3	as above
8	(N.W.) a.1 a.2 a.3	24.5 24.5 24.5	15.6 16.1 16.2	fairly smooth with trowel marks
	(N.E.) b.1 b.2 b.3	24.5 24.5 24.5	16.6 17.1 17.2	as above
	(S.E.) c.1 c.2 c.3	24.3 24.3 24.3	14.7 14.4 14.5	as above
	(S.W.) d.1 d.2 d.3	24.5 24.5 24.5	16.4 17.1 17.2	as above
9	(N.W.) a.1 a.2 a.3	24.3 24.4 24.2	18.2 18.1 18.6	smooth surface
	(N.E.) b.1 b.2 b.3	24.5 24.5 24.5	20.4 21.4 21.8	as above
	(S.E.) c.1 c.2 c.3	24.0 24.0 24.0	16.5 17.0 17.5	as above
	(S.W.) d.1 d.2 d.3	24.2 24.3 24.2	17.7 18.6 18.7	as above

10	(N.W.) a.1	24.5	19.2	visible trowel marks
	a.2	24.5	19.3	
	(N.E.) b.1	24.5	16.7	as above
	b.2	24.5	16.7	
	(S.E.) c.1	24.5	16.6	as above
	c.2	24.5	16.8	
	(S.W.) d.1	24.5	16.2	as above
	d.2	24.5	16.6	

Table 4. Floor Slab Crack Inventory

House Code	Total Crack Length (m)	Comments
1	0	
2	2.3	one crack <1 mm wide
3	0	
4	12.5	several, mostly hairline, only part of slab available
5	17.3	largest 1 mm wide, others <1 mm wide
6	10.8	<1 mm wide
7	11.0	<1 mm wide
8	3.2	3 mm wide, one only
9	3.6	2 mm wide, one only
10	2.5	5 mm → 0 mm wide, one only

Appendix 1 - Photograph Record of Testing

Table A1. Photographic Record

House Code	Slide	Comments
1	1-1	House
	1-2	F/W location A
	1-3	F/W location C
2	1-1	House
	1-2	F/W location A
	1-3	F/W location C
	1-4	Floor crack
	1-5	Sewer clean out location G
	1-6	Floor drain
3	1-1	House
	1-2	Insulated foundation wall
	1-3	Stud wall with insulation removed
	1-4	Stud wall cut off
	1-5	F/W location A
	1-6	F/W location B
4	1-1	House
	1-2	Floor drain
	1-3	F/W
	1-4	Floor drain ΔP
5	1-1	House
	1-2	F/W location C
	1-3	Floor crack
	1-4	Floor crack

6	1-1 1-2 1-3 1-4 1-5	House F/W location A F/W location B Floor crack Sewer clean out location G
7	1-1 1-2 1-3 1-4 1-5 1-6	House F/W location A F/W location B F/W location D Floor crack Sewer clean out location G
8	1-1 1-2 1-3 1-4 1-5 1-6 1-7	House (rear view) F/W location A F/W location B Floor drain Sewer clean out location G Wall crack Wall crack
9	1-1 1-2	House F/W location C
10	1-1 1-2 1-3 1-4 1-5	House F/W location A F/W location B F/W location C Schupack test