Title: Investigation of gas flow through soils and granular fill materials for the optimisation of radon soil depressurisation systems

Marta Fuente(a,b,e), Eduardo Muñoz(c,d,*), Isabel Sicilia©, Jamie Goggins(b,e), Le Chi Hunga,(b,e),
Borja Frutos(c), Mark Foley(a)

a School of Physics, National University of Ireland Galway, Ireland

b Civil Engineering, College of Engineering & Informatics, National University of Ireland Galway, Ireland

c Eduardo Torroja Institute for Construction Science IETcc-CSIC, Madrid, Spain

d Superior Technical School of Architecture, Technical University of Madrid, UPM, Spain

e Centre for Marine and Renewable Energy (MaREI), Ryan Institute, National University of Ireland Galway, Ireland

Abstract

The purpose of this study is to investigate gas flow through different types of granular fill materials and soil by means of a series of experimental laboratory tests, in relation to soil depressurisation systems for radon reduction under buildings and the soil surrounding the foundation. Air permeability characterisation of materials used as granular fill material layer beneath the slab in buildings is a key parameter for optimum performance of soil depressurisation systems to mitigate radon. A test apparatus was developed, adapted from previous studies, to measure the gas permeability of the samples and Finite Element Method numerical simulations were validated to simulate the flow behaviour through them. Theoretical expressions for permeability were discussed based on the analysis of experimental results and numerical simulations, finding that Darcy-Forchheimer equation provides the best match to the experimental results. Darcy's law also proved to be suitable for low gas velocities, whereas Ergun's equation resulted in a poor fit of the experimental data. Benchmark analysis of the granular fill materials under study and other European standards (Spanish, Irish, British) are also presented.

Keywords: Granular fill materials; Permeability; Radon; Soil depressurisation system

1. Introduction

Radon (^{222}Rn) is a radioactive gas, product of the decay of ^{226}Ra , which belongs to the decay series of uranium (^{238}U), present in varying amounts across the Earth's crust. It is highly mobile, and its half-life is 3.8 days, emanated from rocks or soil, radon can permeate through the soil and release into the atmosphere. Outdoor radon concentration is not a health problem as it is diluted and dispersed in the atmosphere, but if radon gas enters the air space of a building it can accumulate causing elevated indoor radon concentration. According to the World Health Organization (WHO), radon is classified as the second leading cause of lung cancer in the general population after tobacco smoking (WHO, 2009). Inhaling radon has been shown to cause this disease through the decay of its short lived alpha decay products, such as alpha emitting ^{218}Po and ^{214}Po , which induce pulmonary cell DNA damage. Therefore, reduction of indoor radon levels in buildings is considered an important public health issue and since February 2018, with the implementation of the 2013/59/EURATOM Basic Safety Standards (BSS)

Directive, all European Union Member States are required to take action plans against radon in buildings exceeding the reference radon level (Council of the European Union, 2014).

Among the different existing techniques for radon prevention and mitigation, soil depressurisation is considered the most effective solution in radon reduction (Frutos et al., 2011; Long et al., 2013; Jiránek, 2014). It prevents the transfer of radon from the soil towards the building by decreasing the pressure in the granular fill material layer under the concrete slab and thus, reversing the pressure difference between the soil and the occupied space (DELG, 2002). Soil depressurisation systems can be active and passive and include three basic components: a suction point, an exhaust pipe connected to the suction point to draw the soil gas out from the building, and a means of extraction (mechanical or passive).

Several factors affect the performance of a soil depressurisation system, such as permeability of the granular fill material layer beneath the slab and the native soil surrounding the building foundation. Other factors include the thickness of the sub-slab layer, size of the suction point, any crack or gap in the floor, moisture content and atmospheric conditions (Jiránek and Svoboda, 2007; Diallo et al., 2015; Muñoz et al., 2017).

Previous studies have highlighted the importance of understanding the permeability degree of the compacted granular fill material layer beneath the slab related to radon mitigation by soil depressurisation (Hung et al., 2018a, b). Characterisation of Irish standardised granular fill materials specified as permeable granular layers beneath the concrete floors and foundations, used for soil depressurisation systems in Ireland was conducted, including grading, compaction, and air permeability tests.

There is no standard technique for gas permeability testing of granular fill materials. Characterisation of granular fill materials' gas permeability can be addressed through different techniques, either experimental or using theoretical calculations. The results obtained from different procedures are not always in agreement and the direct transfer of those results to models for the calculation of depressurisation techniques effectiveness can lead to inaccurate predictive outcomes (Bonnefous et al., 1992).

In terms of soil gas permeability, there is an extended technique for in situ measurements to assess transport through soil using the RADON JOK equipment (Radon v.o.s., www.radon-vos.cz). The principle of this equipment consists of air withdrawal by means of negative pressure. However, this technique is limited to soil field measurements in a range of gas permeability from 10^{-11} m^2 to 10^{-14} m^2 (Castelluccio et al., 2015) and, thus, it is not useful to test granular fill materials and some types of soils.

This paper presents permeability characterisation of different types of granular fill materials commonly used in Spanish building practices. The work includes modelling of gas flow behaviour through soil and granular fill materials to assess permeability and discussion of the equations to calculate gas permeability. Furthermore, benchmarking analysis of European standard granular fill materials is presented.

2. Materials and methods

2.1 Design of the test apparatus

The test apparatus developed for this study was based on the laboratory experimental set-up by Hung et al. (2018a), which, in turn, was based on the operating principle from the standard ASTM-D6539 (2013) and previous works of Gadgil et al. (1991) and BRE (1998). The design consists of three different

parts: an inlet chamber, a testing sample chamber, and an outlet chamber. Gas is pressurised from a source into the inlet, it goes through the sample and then flows out the outlet chamber. Pressure difference across the sample is measured to obtain permeability.

The apparatus was made of Perspex and PVC pipes with 125 mm diameter, 4 mm thick walls and total length of 3050 mm (see Figure 1). It was divided into different segments to facilitate filling and testing: an inlet segment 1000 mm long, four sample segments of 250 mm length each and an outlet segment 1050 mm long. The segments were joined by flexible couplings to prevent gas leakage. The diameter of the pipe was chosen to suit samples with particle size not bigger than 30 mm in any case.

Several differential pressure sensors were placed at different points along the sample chamber, as well as at the inlet and outlet chambers, to measure pressure drop along the sample and the inlet-outlet pressure difference. The pressure sensors used were DG-700 Pressure & Flow Gauge (measuring range -1250 Pa to 1250 Pa; accuracy $\pm 1\%$) and Honeywell model HSCDRRD006MDSA3 (operating pressure ± 6 mbar, accuracy 0.25%). A pitot tube (model Testo 0635 2145; measuring range +1 to +100 m/s) for measuring flow velocity and a hot wire anemometer (model Testo 425; measuring range 0 to +20 m/s; accuracy $\pm(0.03 \text{ m/s} + 5\% \text{ of mv})$ and resolution 0.01 m/s) were used to measure flow rate in the inlet chamber. The gas source chosen was a compressed air generator and a needle valve was used to regulate the inlet air.

Figure 1. Diagram of the test apparatus (left), picture of the test apparatus setup (right).

The procedure to conduct the experimental test was as follows:

- 1) Air leakage was tested prior to any tests.
- 2) The sample chamber was filled with the uncompact material under study and all the sensors set up.
- 3) Controlled air flow rate was pressurised into the gas inlet chamber and measurements from pressure sensors and velocity meter recorded.
- 4) Pressure at the inlet was increased gradually with each sample being tested for a range of pressures from 20 to 600 Pa.

2.2 Gas permeability expressions

Permeability is a property of a porous material, defined as the ability of a fluid or gas to transmit through the porous medium. For gas flow through a porous material, transportation is governed by the gas permeability. In this section, different expressions to determine gas permeability are presented and discussed.

The first equation considered to obtain gas permeability of a porous material is Darcy's law, which is a linear relationship between the fluid flow rate that goes through the porous medium, Q (m³/s), the cross section, A (m²), and the hydraulic gradient $\Delta h/\Delta l$ (Lambe and Whitman, 1969).

$$Q = -k \frac{\Delta h}{\Delta l} A \quad (1)$$

where k (m/s) is a constant known as Darcy's permeability coefficient, which depends both on the porous medium and the fluid. Absolute or specific permeability, K_D (m²), which only depends on the porous medium, can be obtained as:

$$K_D = k \frac{\mu}{\gamma} \quad (2)$$

where μ (Pa.s) is the dynamic viscosity of the fluid, and γ (Pa/m) is the specific weight of the fluid. Combining equations (1) and (2) the following formula is derived,

$$K_D = -\frac{\mu}{\gamma} \frac{Q}{A} \frac{\Delta h}{\Delta l} \quad (3)$$

Finally, knowing that $Q = v \cdot A$ and $\Delta h = \Delta P/\gamma$, Darcy's permeability equation can be written as follows:

$$K_D = -\frac{\mu v}{\Delta P/\Delta l} \quad (4)$$

where v (m/s) is the fluid velocity through the porous medium, and ΔP (Pa), is the pressure differential between two points of the sample porous material at a distance Δl (m).

Darcy's law has limitations for liquids at high velocities and for gases at very high or very low velocities. In such cases, the relationship between the pressure gradient and gas velocity is not linear. Darcy's law validity is related to the Reynolds' number (Scheidegger, 1958):

$$Re = \frac{\rho v D}{\mu} \quad (5)$$

where ρ (kg/m³) is the fluid density and D (m) is a diameter related with the porous medium. Scheidegger attributes D the changes in the validity of Darcy's law regarding Reynolds' number.

Darcy's law is valid for models considering low permeability, such as low velocities of the gas through the porous medium (laminar flow). However, in order to develop a suitable model for a larger range of velocities, considering turbulent flow, the Darcy-Forchheimer equation is presented (Forchheimer, 1901).

$$\frac{\Delta P}{\Delta l} = -\frac{\mu}{K_{DF}}v - c\frac{\mu}{K_{DF}}v^2 \quad (6)$$

where K_{DF} (m^2) is Darcy-Forchheimer specific permeability and c (s/m) is a constant called the Forchheimer factor (Gadgil et al., 1991). From equation (6), the following expression for the permeability is obtained:

$$K_{DF} = -\frac{\mu}{\Delta P/\Delta l}v - c\frac{\mu}{\Delta P/\Delta l}v^2 \quad (7)$$

On another note, Ergun (1952) studied fluid flow through beds of granular materials, considering that pressure losses were caused by kinetic and viscous energy losses, as it is shown in equation (8).

$$\frac{\Delta P}{\Delta l} = -150\frac{(1-n)^2\mu}{n^3d_p^2}v - 1.75\frac{(1-n)\rho}{n^3d_p}v^2 \quad (8)$$

where n is the porosity of the granular material and d_p (m) is the effective diameter of the granular particles. If velocity tends to the zero, the first term of equation (8), which is the viscous term, dominates and therefore the fluid is considered viscous. At high fluid velocities, kinetic term prevails and the fluid is considered turbulent.

By relating equations (6) and (8), Ergun's permeability expression is obtained as follows:

$$K_E = \frac{n^3d_p^2}{150(1-n)^2} \quad (9)$$

Unlike previous expressions discussed, equation (9) doesn't require an experimental test to relate fluid velocity to the pressure drop through a granular material sample, but it requires knowledge of the porous material characteristics such as the porosity and the effective diameter of the particles.

2.3 Materials under study

To study the behaviour of gas flow through different porous media, four different materials were tested (see Figure 2). Two samples were types of gravel, composed of crushed stone with different particle size distribution, sample A: garbancillo 4/12 and sample B: gravel 4/20. Third sample tested, sample C: debris, was composed of loose natural material consisted of broken pieces of demolition waste, normally obtained as a result of building demolitions and commonly used as filler. Last material selected for the study was a type of soil, sample D: soil, which can be classified as coarse grained soil (ASTM-D2487, 2017). The materials were selected in order to cover a wide range of gas permeability.

All samples were tested uncompacted, but sample D was also tested under manual compaction to reproduce field conditions of the soil. Soil was compacted manually using a metal rammer weighing 7.5 kg, by applying 10 blows of the rammer dropping from the controlled height of 200 mm.

Figure 2. Pictures of a) sample A: garbancillo 4/12, b) sample B: gravel 4/20, c) sample C: debris and d) sample D: coarse grained soil.

Particle size distribution and porosity are relevant characteristics for the study of porous materials' gas permeability and therefore they were considered for the study. Grading curves of the materials under study were obtained following standard UNE EN-933-1 (UNE-EN 933-1:2012).

Porosity was determined experimentally for all granular fill material samples as the ratio of total volume of pore space within the media divided by the total volume of material (Hung et al., 2018a) using the following expression:

$$n = \frac{V_{total} - V_{solid}}{V_{total}} = \frac{V_{fluid}}{V_{total}} \quad (10)$$

A known volume tank, $V_{total} = 7051 \text{ cm}^3$, was filled with the sample material and then water added until the volume was full. Before that, the sample was saturated during 24 hours to fill internal porosity. Water mass, Δm , was measured and then fluid volume obtained as $V_{fluid} = \Delta m / \rho_{fluid}$, where ρ_{fluid} is the density of the fluid.

2.4 FEM simulations

Finite Element Model (FEM) simulations were performed to assess gas permeability of the samples and to benchmark the different expressions for permeability calculation. The finite element software COMSOL Multiphysics V5.3 (COMSOL, 2017) was used in this study.

Due to the test apparatus geometry, the axisymmetric analysis was selected for modelling because it uses rotational symmetry to optimise numerical simulation calculations. The Laminar Flow interface, based on the Navier-Stokes equations for conservation of momentum and the continuity equation for conservation of mass, was used for modelling. The simplified equation is

$$\nabla P \mathbf{i} = -\frac{\mu}{K} \mathbf{v} - \beta \mathbf{v} |\mathbf{v}| \quad (11)$$

From equation (11), by changing K and β parameters, equations (4), (6) and (8) can be obtained. For Darcy's law $K = K_D$ and $\beta = 0$; for Darcy-Forchheimer equation, $K = K_{DF}$ and $\beta = c/K_{DF}$; and for Ergun $K = K_E$ and $\beta = 1.75(1 - n)\rho/n^3 d_p$.

Boundary conditions were specified based on the test apparatus setup, with inlet velocity condition at the bottom of the test apparatus. The type of mesh selected was rectangular, with maximum element size of 8.13×10^{-4} m and minimum element size of 9.37×10^{-6} m. All simulations were performed under stationary analysis, with parametric sweep study and using the direct solver MUMPS (MULTifrontal Massively Parallel sparse direct Solver).

3. Results and discussion

3.1 Particle size distribution and porosity of the samples

Figure 3 shows the grading curves for each sample under study. Based on the particle size distribution, debris can be classified as well-graded material, while garbancillo 4/12, gravel 4/20 and the soil under study are classified as poorly-graded materials.

Figure 3. Particle size distribution of the different materials under study, a) sample A: garbancillo 4/12 and B: gravel 4/20, b) sample C: debris and c) sample D: soil. Particle diameter d_{50} is indicated for all samples.

The effective particle diameter for poorly-graded materials can be taken directly as d_{50} from the grading curve (Hung et al., 2018a). Thus, the effective particle diameter is 9.1 mm for garbancillo 4/12 and 13.8 mm for sample gravel 4/20. For sample C: debris, d_{50} obtained from the grading curve is 10.7 mm and for sample D: soil, d_{50} is 0.64 mm.

Porosity for the granular fill materials samples was obtained experimentally, resulting in $n = 0.46$ for sample A: garbancillo 4/12, $n = 0.40$ for sample B: gravel 4/20 and $n = 0.42$ for sample C: debris. The values obtained are very similar, which can be related to the nature of the materials composition.

3.2 Experimental test results and permeability calculation

Table 1 shows an example of the experimental results obtained for the different materials tested, in this case for sample B: gravel 4/20. Pressure at different points along the test apparatus (see Figure 1) and the gas velocity were recorded. Then, pressure gradient over the sample length was calculated.

Table 1. Experimental results for sample B: Gravel 4/20. P_i is the pressure recorded at each i -detector position, v gas velocity and $\Delta P/\Delta l$ the pressure gradient over the sample length. The uncertainty in pressure is $u(P_i) = \pm 5$ Pa and for the gas velocity $u(v) = \pm 0.02$ m/s.

Test No.	$P_1 \pm 5$ (Pa)	$P_2 \pm 5$ (Pa)	$P_3 \pm 5$ (Pa)	$P_4 \pm 5$ (Pa)	$P_5 \pm 5$ (Pa)	$v \pm 0.02$ (m/s)	$\Delta P/\Delta l$ (Pa/m)
1	20	25	14	7	4	0.08	28 ± 19
2	40	42	27	13	6	0.12	49 ± 21
3	60	60	41	22	8	0.14	69 ± 20
4	80	77	54	28	10	0.17	90 ± 22
5	100	95	67	35	12	0.21	111 ± 22
6	120	113	80	43	14	0.25	132 ± 23
7	300	268	199	107	32	0.38	314 ± 26
8	415	368	276	149	45	0.48	431 ± 27
9	500	438	331	180	53	0.50	513 ± 28
10	510	448	336	181	55	0.50	524 ± 28

Figure 4 shows test results for samples A and B, where pressure gradient over the sample length is plotted against gas velocity along with trend lines. It can be seen that test results are in good agreement with the Darcy-Forchheimer equation (6), inducing a coefficient of determination $R^2 = 0.987$ and 0.996 , for samples A and B, respectively. However, there is very poor agreement between the experimental results and Ergun equation (9).

Figure 4. Pressure difference over length versus gas velocity for a) sample A: garbancillo 4/12 and b) sample B: gravel 4/20.

Figure 5 shows test results for sample C: debris, similar to the previous granular fill material samples A and B, and sample D: soil. It can be noted that the Darcy-Forchheimer trend line for sample C is in good agreement with experimental results, inducing a coefficient of determination $R^2 = 0.994$, while

Ergun trend line doesn't match the experimental data. For sample D, only Darcy-Forchheimer trend line is presented as the porosity value to obtain Ergun trend line was not determined experimentally.

Figure 5. Pressure difference over length versus gas velocity for a) sample C: debris and b) sample D: soil.

Permeability was determined using the different expressions in section 2.1, where gas permeability values for all samples tested are summarised in Table 2. For each test number of every sample, a value of Darcy's permeability is obtained according to equation (4). Then, average Darcy's permeability is presented in Table 2 for each sample. Darcy-Forchheimer permeability is obtained from the quadratic trend line that fits the experimental data in Figures 4 and 5, by comparing fitted parameters with equation (6). Ergun permeability is calculated from equation (9), once porosity and effective particle size of the sample are known.

Table 2. Summary of permeability values obtained for granular fill material samples with Darcy's law (4), Darcy-Forchheimer (7) and Ergun (9).

Sample	K_D (m ²)	K_{DF} (m ²)	K_E (m ²)
A: Garbancillo 4/12	$(2.5 \pm 0.8) \times 10^{-8}$	$(9.7 \pm 6.3) \times 10^{-8}$	$(1.8 \pm 0.2) \times 10^{-7}$
B: Gravel 4/20	$(3.1 \pm 1.1) \times 10^{-8}$	$(9.0 \pm 3.5) \times 10^{-8}$	$(2.4 \pm 0.3) \times 10^{-7}$
C: Debris	$(2.0 \pm 0.6) \times 10^{-8}$	$(7.3 \pm 2.6) \times 10^{-8}$	$(1.7 \pm 0.2) \times 10^{-7}$
D: Soil	$(1.2 \pm 0.4) \times 10^{-8}$	$(2.1 \pm 0.4) \times 10^{-8}$	-

Darcy's permeability values indicate that all samples present a similar gas permeability. From Darcy-Forchheimer permeability values, gravel samples A and B present a similar permeability approximately $9 \times 10^{-8} \text{ m}^2$, and for sample C, it is slightly lower. Ergun permeability obtained for samples A, B and C is similar in all three cases. However, the order of magnitude found for Ergun permeability is 10^{-7} m^2 .

, and sample C present a similar permeability on the order of magnitude of 10^{-8} m^2 . Also, Ergun permeability obtained for samples A, B and C is similar in all three cases. However, the order of magnitude found for Ergun permeability is 10^{-7} m^2 .

In the case of the soil sample, the Darcy-Forchheimer permeability value is approximately 4 times lower than for the granular fill materials, but still is in the same order of magnitude. Soil permeability values reported in other publications are in the range of 10^{-15} to 10^{-9} m^2 (Nielson et al., 1994). A possible explanation for this result is that the sample was taken and then placed in the experimental device, modifying the natural conditions in which is encountered when tested under other type soil permeability tests performed in situ. Sample D was tested again under manual compaction to

reproduce field conditions of the soil. Results for this experimental tests are presented in Figure 6, where permeability values obtained for the compacted soil sample following Darcy equation (4) was $(9.6 \pm 2.8) \times 10^{-9} \text{ m}^2$ and from Darcy-Forchheimer equation (7) was $(3.8 \pm 2.2) \times 10^{-8} \text{ m}^2$.

Figure 6. Pressure difference over length versus gas velocity for sample D, uncompacted and under manual compaction. Dots represent experimental data and dashed line the Darcy-Forchheimer equation trendline.

Figure 6 shows that both the uncompacted and compacted soil samples present very similar permeability; taking into account the uncertainty the data are not significantly different. The value obtained for the Darcy permeability of the compacted soil sample, $9.6 \times 10^{-9} \text{ m}^2$, does reflect a lower permeability than the uncompacted soil and it is more sensible for a soil sample according to the literature (Friske et al., 2010). However, the numerical values for the Darcy-Forchheimer permeability indicate a lower permeability for the uncompacted soil, although considering uncertainty values for both samples are not significantly different.

Figure 7 shows experimental results for all samples. It is clear from the figure that the soil sample has lower permeability than the granular fill materials. Within the granular fill materials, it is observed that debris has the lowest permeability, followed by garbancillo 4/12, and then gravel 4/20, which is directly related to the size of the materials and the fact that debris is a well-graded material in contrast with gravel and garbancillo.

Figure 7. Comparison of pressure difference over length versus gas velocity experimental results for all samples under study, sample A: garbancillo 4/12, sample B: gravel 4/20, sample C: debris and sample D: soil, tested uncompacted and under manual compaction.

3.3 FEM simulations

Simulations were performed using a geometry of the domain based on the test setup, specifying boundary conditions according to Figure 1. The inlet velocity condition was set at the bottom, the wall condition was defined along the external wall of the apparatus and the outlet pressure condition (0 Pa) was set at the top end. The type of mesh selected was rectangular, with maximum element size of 8.13×10^{-4} m and minimum element size of 9.37×10^{-6} m.

The physical model implementation for all simulations was the following: laminar flow along porous media domain. Input parameters required for simulations were density and viscosity of the fluid, and the permeability of the sample. Values of the density and viscosity of the gas used for all simulations are $\rho = 1.2 \text{ kg/m}^3$ and $\mu = 1.8 \times 10^{-5} \text{ Pa s}$.

In the case of the model based on Ergun's equation, the effective particle size and porosity were also required as input parameters. The effective particle diameter was determined from the particle size distribution and the porosity was determined experimentally.

Data from previous works (Gadgil et al., 1991; BRE, 1998) was used to validate numerical simulations (see Figure 8).

Figure 8. Experimental data from the literature a) Gadgil et al. (1991), b) BRE (1998) and simulations.

Permeability and Forchheimer factor values used for this purpose are as follows: $k = 1 \times 10^{-7} \text{ m}^2$ and $c = 9.5$ for the 3/4" round hardcore sample (Gadgil et al., 1991); $k = 9.9 \times 10^{-8} \text{ m}^2$ and $c = 7.2$ for the 20 mm single sized sample (BRE, 1998).

The results obtained from the simulations are presented in Figure 9 for the different samples under study. It is observed in all cases that Darcy's simulation only matches experimental data for low gas velocities, and in all cases Darcy-Forchheimer's simulation provides the best match to the experimental data.

Figure 9. Comparison of FEM simulations and experimental results for all samples under study, a) garbancillo a/12, b) gravel 4/20, c) debris and d) soil (u and c in the legend indicate uncompacted and compacted, respectively).

Ergun's simulation performed using experimental values of porosity and the effective diameter of the granular particles doesn't match experimental tests, with lower permeability than Darcy-Forchheimer simulation results for all granular fill materials. This finding is in agreement with previous works that state Ergun's equation is not suited for non-uniform particles having non-spherical shape (Olatunde and Fasina, 2018).

3.4 Benchmarking granular fill materials

Figure 10 shows the particle size distribution for the granular fill materials tested, together with the grading curves of the Irish standard T1 Struc and T2 Perm granular fill materials published in the work of Hung et al. (2018a) and the grading curves of 20 mm, 40 mm graded and MOT type 1 granular fill materials published in the work of BRE (1998).

a) b)

Figure 10. Particle size distribution of –a) poorly-graded and b) well-graded– granular fill material samples (A: garbancillo 4/12, B: gravel 4/20, C: debris) and Irish (T1 Struc and T2 Perm) and British standard granular fill materials, taken from Hung et al. (2018a) and BRE (1998).

It can be seen from Figure 10 that the particle size distribution of garbancillo 4/12 and gravel 4/20 is similar to Irish T2 Perm and British 20 mm and 40 mm graded materials, all of them classified as poorly-graded materials. Similarly, debris sample size distribution up from 1 mm is very similar to T1 Struc and MOT type 1 granular fill materials, both well-graded materials. Therefore, characterisation of the materials presented in this paper could apply to different standards within a European context, based on the tested Spanish materials and comparison with Irish and British granular fill materials.

Comparison of results from permeability tests is presented in Figure 11 for the samples tested in this study and the British standards (i.e., 20 mm graded, 40 mm graded and MOT type 1). Irish standard (i.e. T1 Struc and T2 Perm) cannot be presented here, as there is only gas permeability tests under compaction reported.

a) b)

Figure 11. Comparison of pressure difference versus gas velocity experimental results for samples under study (A: garbancillo 4/12, B: gravel 4/20, C: debris and D: soil) with British standards, taken from BRE (1998). a) Poorly-graded materials grouped together and b) well-graded materials.

From Figure 11 a) it can be noted that the poorly-graded granular fill materials analysed present very similar trends, which indicate similar gas permeability values of approximately $9 \times 10^{-8} \text{ m}^2$. Assuming here that the Irish T2 Perm standard would present similar results, and with the knowledge from Hung et al. (2018b), these materials would be suitable to be part of the permeable layer in radon soil depressurisation systems.

However, by looking at Figure 11 b), debris and MOT type1 material present trends very unlike; results for soil sample are also presented for comparison. The material MOT type 1 present a higher slope than the soil sample tested in the current study, which means that it presents a significantly lower gas permeability.

4. Conclusions

This paper presents permeability characterisation of different types of granular fill materials through the development of a test apparatus based on the work of Hung et al. (2018a), also based on the operating principle from the standard ASTM-D6539 (2013) and previous works of Gadgil et al. (1991) and BRE (1998).

This test is motivated by the need to establish a standard method for the gas permeability measurement in granular fill materials and soils, given their critical role in radon mitigation in buildings. **Characterisation of different granular fill materials is of interest, as well, in order to have a collection of different material characteristics related to the installation of effective soil depressurisation systems to mitigate radon.** The method proposed here ensures that reliable and numerically validated results are obtained. Also, through the use of simulations, the behaviour of the material can be extrapolated for higher velocities which can't be easily performed in the laboratory.

From the experimental results, granular fill materials present pressure gradient against gas velocity curves with lower slope, which indicates higher permeability than for the soil sample. Among the granular fill materials tested, a clear relation between permeability values and the size and of the materials is found.

The use of the Darcy-Forchheimer's equation in the numerical simulations provides the best match to the experimental results. In all cases it is observed that Darcy's simulation only matches experimental data for low gas velocities (< 0.1 m/s). For these ranges, experimental data present a linear trend and Darcy's law is correct. But, for higher gas flow velocities Darcy's law shouldn't be used when trying to simulate radon gas behaviour through a porous medium.

Ergun's equation doesn't provide a good fit for experimental results using porosity and effective diameter of granular fill materials as input parameters for the model. A possible explanation for this can be related to the sensitivity when obtaining the porosity values for the samples experimentally, as it is a key parameter on Ergun's equation.

Overall, this work gives an insight into the characterisation of granular fill materials' permeability, which can have applications within the European context. It contributes to the understanding of the specification for soil depressurisation systems performance, in line with the implementation of the 2013/59/EURATOM Basic Safety Standards (BSS) Directive on promoting national action plans for reduction of radon concentration in dwellings with concentrations over the reference level.

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