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Characterisation of specified granular fill materials for radon mitigation by soil depressurisation systems

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HIGHLIGHTS

- A test apparatus was developed to measure air permeability of granular materials.
- Air permeability is strongly influenced by the compaction and the change of moisture.
- Poorly-graded granular material extracts air much better than well-graded granular material.
- Empirical equations have been proposed.

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ABSTRACT

A series of experimental laboratory tests were conducted to quantitatively investigate the characterisation of the *T1 Struc* and *T2 Perm* specified granular fill materials for soil depressurisation systems for radon reduction under buildings. The characterisation included determination of grading curves, measurement of air permeability, porosity, and the effective particle diameter of the stone. A test apparatus was developed to measure the air permeability of the granular fill materials under different compaction degrees. Test results showed that the *T1 Struc* and *T2 Perm* specified granular fill materials could be classified as well-graded and poorly-graded granular materials, respectively. The air permeability and porosity of *T1 Struc* decrease with the increase in compaction degree and are strongly affected by the change of moisture content. However, the air permeability of *T2 Perm* was found to be independent of the compaction degree and variation of moisture content. Computational Fluid Dynamic (CFD) simulations were validated to simulate the flow behaviour of the *T1 Struc* and *T2 Perm* granular fill materials. The primary parameters for simulating the flow behaviour of the materials were confirmed to be the air permeability, porosity, and effective particle diameter. Based on the CFD simulation results, the effective particle diameter was found to vary with the compaction degree for *T1 Struc*, whereas that of *T2 Perm* was constant at 16.2 mm.

1. Introduction

Radon (^{222}Rn) is a product from the decay chain of uranium (^{238}U) present in soils and rocks. It is a colourless, odourless, tasteless gas which has been identified as a human carcinogen by the World Health Organisation (WHO), the International Agency for Research on Cancer (IARC) and the U.S. Environmental Protection Agency (EPA) [1]. Studies have shown that the outdoor radon concentration globally is between 5 Bq/m^3–15 Bq/m^3, and does not pose a health risk [2,3]. However, indoor concentrations can be significantly higher, which has been shown to cause lung cancer through the decay of its short-lived daughter products resulting pulmonary cell DNA damage. It is estimated that indoor radon levels account for 9% of deaths from lung cancer and about 2% of all deaths from cancer in Europe [4].

Reduction of the indoor radon concentration is an important issue for buildings [5]. There are several methods for radon prevention and mitigation, such as the active and passive soil depressurisation (SD), sealing of surfaces, barriers and membranes, ventilation of unoccupied spaces, and ventilation of occupied

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ΔP	Pressure drop [Pa]
A	Cross section area of air flow [m^2]
c	Forchheimer constant
CFD	Computational fluid dynamics
$d_{ef,}$ $d_{ef\ (Erg)}$	Effective particle size of the granular fill material [mm, m]
D−F	Darcy-Forchheimer
G	Mass flow rate [kg/m^2.s]
G_s	Specific gravity of material
k	Turbulent kinetic energy [m^2/s^2]
k_{ah}	Air permeability of the granular fill material [m^2]
$k_{ah(ASTM)}$	Air permeability obtained from ASTM (2013) equation [m^2]
$k_{ah(wn)}$	Air permeability of the granular fill material at varying moisture content [m^2]
$k_{ah(wnc)}$	Air permeability of the granular fill material at compaction moisture content [m^2]
$k_{ah(D-F)}$	Air permeability obtained from Forchheimer (1901) equation [m^2]
$k_{ah(Ergun)}$	Air permeability obtained from Ergun (1952) equation [m^2]
k_{as}	Air permeability of soil [m^2]
k_p	Darcy air permeability [Darcy]
L	Length of the compacted granular fill material (m)
m	Correction factor
n_h	Porosity of the granular fill material
N_k	Normalised air permeability
N_w	Normalised moisture content
P_1	Pressure recorded by pressure sensor P$_1$ of the test apparatus [Pa]
P_2	Pressure recorded by pressure sensor P$_2$ of the test apparatus [Pa]
P_{2CFD}	Absolute pressure at outlet chamber in CFD [Pa]
P_{CFD}	Absolute pressure in CFD [Pa]
P_B	Atmospheric pressure [Pa]
P_I	Inlet gas pressure [Pa]
$P_{reading}$	Pressure sensor reading [Pa]
P_s	Standard reference pressure[Pa]
$P_{theoretical}$	Theoretical pressure with the water column height [Pa]
Q_{CFD}	Inlet air flow rate in CFD simulations [m^3/s]
Q_{in}	Inlet air flow rate in CFD [m^3/s]
Q_m	Measured air flow rate [m^3/s]
Q_{av}	Average air flow rate [m^3/s]
SD	Soil depressurisation
T	Kelvin room temperature [K]
T_S	Reference Kelvin temperature [K]
R^2	Correlation coefficient
v	Air flow velocity (m/s)
V_{solid}	Volume of the solid phase [m^3]
V_{total}	Total volume of material [m^3]
w_{nc}	Compaction moisture content [%]
$w_{nc(opt)}$	Optimal compaction moisture content [%]
w_n	Test sample moisture content [%]
Greek letters	
$\gamma_{dry\ (95\%)}$	95% maximum dry unit weight [kN/m^3]
γ_{dry}	Dry unit weight [kN/m^3]
γ_w	Unit weight of water [kN/m^3]
μ	Dynamic viscosity [Pa.s]
ω	Specific dissipation rate [1/s]

spaces. However, the active and passive SD methods have proven to be the best options for indoor radon prevention and mitigation [5–9]. The principle of a SD system is to decrease the pressure in the granular fill material layer beneath the floor, thus reversing entry path of radon from soil into the building, as well as extracting gas trapped in the granular fill material layer (Fig. 1).

There are several different factors which can influence the effectiveness of the SD system. These factors include the air permeability (k_{ah}) of granular fill material and native soil (k_{as}) beneath the floor, cracks in the floor, radon sump size, sealing, moisture content, fan speed, and atmospheric conditions [10–16]. Studies have shown that the k_{ah} of the granular fill material layer significantly affects the effectiveness of the SD system [7,8,11,13,18,19]. In addition, the granular fill material layer beneath the floor should satisfy the bearing capacity and serviceability criteria and should be permeable to ensure the effectiveness of the SD system.

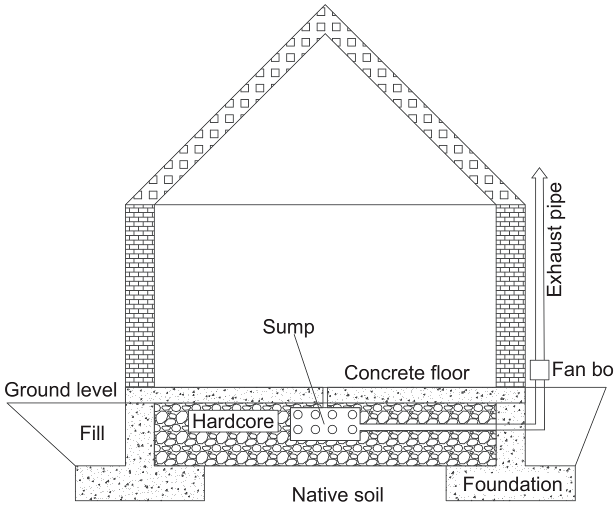

Fig. 1. A schematic diagram of a house with an SD system.

Since July 1998, all new buildings constructed in the Republic of Ireland have been required to include a radon mitigation system, regardless of the level of the radon concentration [20]. The T1 Struc and T2 Perm granular fill materials are specified as permeable granular layers beneath the concrete floors and foundations of buildings in Ireland [21]. These materials are used to increase the bearing capacity of the foundation, as well as to avoid the expansion of the underfloor caused by the existence of pyrite bearing material. However, a comprehensive characterisation of these materials has not been published.

In buildings, the bearing layer beneath the foundation and floor should be compacted before any superstructure is built. This process is to increase the density of the bearing layer, thus, ensuring the bearing capacity and serviceability criteria. Therefore, understanding the degree of permeability of compacted granular fill material layers beneath the floor and foundation is fundamental. The degree of permeability of a granular fill material layer is primarily influenced by its k_{ah} and porosity (n_h) values [7,11,13,17,18,19]. In addition, the granular fill material might experience a range of moisture contents (w_n) after compaction during its service life. The moisture content of the granular fill material could be dry, partially saturated or fully saturated depending on the environmental conditions, water table, and geological conditions.

This paper presents results of characterisation of the Irish T1 Struc and T2 Perm granular fill materials. The characterisation