RADON, FUNGAL SPORES AND MVOCs REDUCTION IN CRAWL SPACE HOUSE: A CASE STUDY AND CRAWL SPACE DEVELOPMENT BY HYGROTHERMAL MODELLING

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ABSTRACT

In this case study was to investigate how ventilation of the crawl space will influence on concentrations of radon, fungal spores and MVOCs in the crawl space and indoors of detached house. The crawl space pressurisation by exhaust air from indoors was successful to prevent the convective flow of radon from the soil, but it increased microbial growth in the crawl space. After installation of the supply and exhaust ventilation in the crawl-space and in the living space, the concentrations of fungal spores in the crawl space and also entry of radon and MVOCs into a house decreased.

A microbiologically safe crawl space was determined with hygrothermal simulation utilizing the Finnish Mould Growth Model and a two year examination period. The optional structures of the crawl space being depressurised with exhaust ventilation included an open base uncovered ground and various air-sealed closed structures. When mould growth of building materials was at medium resistant sensitivity class, mould was not observed during different air change rates in any of the examined structures. Open base uncovered gravel ground is a functional solution of a crawl space, only when there are no organic materials. The air-sealed ground structure is recommended build with concrete + insulation and when air exchange rate (ach) varied from 0.2 to 1 h^{-1}. A concrete ground in the crawl space having ach from 0.2 to 0.6 h^{-1} is also very effective. XPS insulation and plastic sheet covered ground are not recommendable due to their high mould index.

Keywords: crawl space; modelling; radon; mould growth; ground covers; air change

1. INTRODUCTION

In the Nordic countries, crawl spaces are typically outdoor air-ventilated. In older buildings, ventilation is often natural, but mechanical ventilation is quite common in newer buildings.
If the crawl space less than 0.8 m height, which is typical nowadays, the operation of the natural ventilation is often unsatisfactory. The flow of radon-bearing soil gas and entry of mould-like odours (MVOCs) from the crawl space depend on the difference in crawl space-indoor pressure and the leakage area between the crawl space and the house. According to the studies, a significant fraction of infiltration air can enter into the house via the crawl space [1, 2, 3, 4], but the correlation between microbial concentrations in crawl space and indoors depends on the microbial species [3] and pressure difference across the structure [4]. Natural ventilation of crawl space has not been found to give greater than about 50 % reduction of indoor radon in most cases [1].

Infiltration of airborne particles such as fungal spores and microbial metabolites from the crawl space is a more complex and less known process than radon and MVOCs. Secondary metabolites are expected to be present in airborne spores, and may thus occur in airborne dust and bioaerosols. The penetration of fungal spores is expected by Liu and Nazaroff to be a function of particle diameter, crack geometry, and pressure difference across the crack [5]. They have modelled particle penetration through uncomplicated cracks. Further studies are needed in real buildings, where exist cracks having different kind of surface and geometry. In addition, the size of spores varies a lot according to the species being between 1μm – 100 μm and the mean size of microbial spores increases during the activities [6, 7].

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In buildings with mechanical ventilation the pressure difference between indoor and outdoor is often in a range of 0–10 Pa, but pressures of up to several tens of pascals are possible for building with mere exhaust ventilation [8,9,10,]. In general, the exhaust ventilation in crawl space with opening vents, maintains slight under pressure relative outdoor. Improving ventilation in the crawl space reduces the indoor radon concentration by less 60 % on average [11].

In mechanical crawl space depressurisation systems, a fan is installed to exhaust crawl space air and to reduce its entry into the house. However, crawl space depressurisation increases the convective flow of radon-bearing or other soil gas, moisture from the soil and outdoor air into the crawl space. In addition to avoid mould growth in the crawl space structures the efficient disturbance of fresh air in the whole sphere of crawl space is important and often defective. Crawl space depressurisation has been found to give reduction of indoor radon in the range of 70% to 96% [1].

In crawl space pressurisation systems, a fan is installed to blow outdoor air or indoor air into the crawl space. If pressurisation is successful, it prevents the most of the convective flow of radon-bearing and other gas from the soil. In addition, reduction of radon depends on the leakage area between the crawl space and the living space. If indoor air is used it raises the relative moisture and temperature of the crawl space and thus, promotes the microbial growth in structures of the crawl space. Crawl space pressurisation also increases air infiltration from the crawl space into the living space. Crawl space pressurisation has been found to give reduction of indoor radon in the range of 30% to 80% [1].

Concentrations of the fungal spores and identifying genus level of fungal colonies are used to confirm or exclude the presence of possible mould growth and damages inside building structure and on a surface of the structure. Air sampling, building material or surface sampling methods have been used for the microbial analyses. However, the result of the microbiological analyse depends on the activity of the mould growth and on ambient conditions (nutrients, pH, humidity and temperature) [12].

The moisture output in the crawl space comes mostly from ground moisture evaporation and high moisture contents of ventilation air brought in from outside. Outdoor air-ventilated crawl spaces can prove problematic in the Nordic countries during summer, when outdoor air is warm and humid, and thus the absolute humidity of outdoor air is higher than that of the crawl space. In numerous studies of crawl spaces, long-term 70-90% relative humidity has been observed [13,14,15,16,17]. Different countries and region vary in climate, which should consider in design of the crawl space. The temperature in the crawl space is considerably lower than that of outdoor air due to cool earth and massive foundations cooling the crawl space. Thus, the warm and humid air from outside used for ventilation is cooled in the crawl space and the relative humidity increases. According to Matilainen and Kurnitski [22,13], humidity problems in crawl spaces can be reduced by heat insulation the cold ground in the crawl space and by arranging basic ventilation 0.5-1 h-1. In cases where the bottom of the crawl space is covered by a layer of crushed gravel as a form of evaporation insulation, it is recommended that in summer ventilation should increase to the value of (2-5 h-1) [13]. Because there is always enough organic material in a crawl space for mould to feed on, the conditions are favorable for the start of mould growth [18,19]. Of used construction materials only freshly made concrete has a high pH level that makes it less likely to mould, but as it ages its resistance to mould reduces. Moulds are able to grow in broad temperature ranges, and only the relative humidity in crawl space conditions is the limiting factor for mould growth. At low temperature (5 ^{o}C) mould growth is limited and mould does not growth at temperature below 0 ^{o}C [21].

Generally, 75 to 80 % can be considered a safe limit value for relative humidity in crawl spaces [14,20]. Some moulds can tolerate very low humidity, which from a microbiology perspective means that it is not possible to build a completely microbial clean crawl space. Mould growth on and the risk of moulding for structures in a crawl space can be assessed with a calculation by observing the building materials' temperature and humidity data over the examination period and using a developed calculation models that includes a classification that describes the mould growth sensitivity of typical building materials [19,20]. For the purpose of this calculation, materials have been divided into classes on the basis of their mould growth sensitivity. The models are a tool to simulate the progress of mould and decline development under different conditions on the surfaces of structures.

The microbial volatile organic compounds (MVOCs) are formed due to the primary and secondary metabolism of fungi and bacteria [23]. More than 200 compounds have been considered to be released by the microbes according to the literature [23]. However, those compounds can be released from the other sources as well. For example from the building and decoration materials, plants, chemicals and detergents. Nonetheless, many alcohols and ketones have a mould-like odour and are considered to be release from the microbes [24,25,26]. MVOCs can be analysed accurately, but the result of the analysis also depends on the activity variation of the mould growth and on availability of nutrients in a substrate. Furthermore, it is proposed that the different microbial species produce specific MVOCs, which could be used as an indicator of the microbial growth [24,26]. Korpi et al. [27] recently reported that some alcohols, ketones, and terpenes can be regarded as MVOC. On the other hand, the various VOCs accompany microbial activity but no single VOC is reliable indicator of biocontamination in building materials. Pasanen et al. [28] calculated theoretically indoor air concentration of selected VOCs for rooms with and without microbial contamination. The results revealed that microbial growth in construction seems to have only a marginal effect on the total VOC load in indoor air.

Aim of this case study was to investigate how ventilation parameters of the crawl space will influence on concentrations of radon, fungal spores and MVOCs in the crawl space and indoors. In addition to this, simulations were used to study the temperature and humidity conditions and mould growth sensitivity of crawl spaces. The open and closed ground structures were modelled during period consisting of consecutive building physically critical test years. The optimal ventilation rate of mechanical exhaust was determined in the crawl space for different structural options. The goal of mechanical ventilation is to maintain a sufficient pressure difference between the crawl space and living space.

2. MATERIALS AND METHODS

2.1. The studied building

The research building is a single storey one-family house (floor area 129 m^2) which was located in Tampere on the low-lying clayey soil. Under the floor, which was constructed from low density aerated concrete, there was a crawl space. There was a plastic membrane on the surface of bearing soil and a layer of sand (Fig. 1).

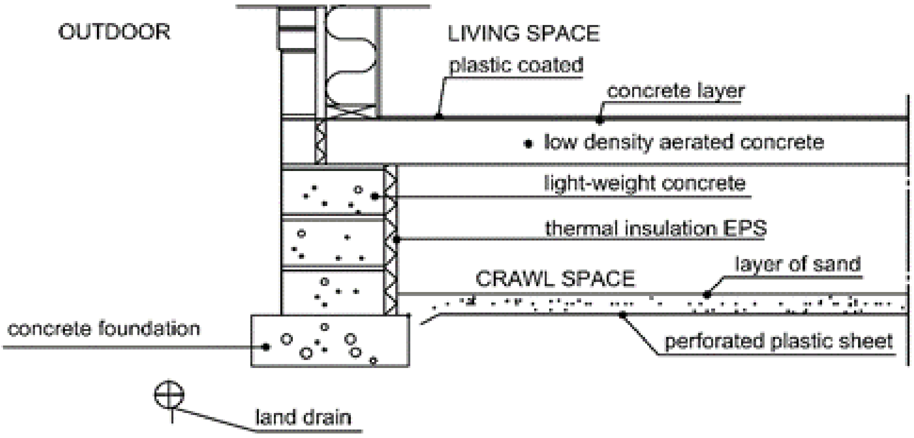

Fig. 1. The sectional drawing of the crawl space foundation in the studied building.

The house had an exhaust ventilation system that was used also for radon mitigation. In this ventilation system, indoor air was blown to the crawl space (volume 52 m^3) by the exhaust fan and air was then let to escape outdoors through an open duct through the roof. During the monitored periods, the house was inhabited by two adults and two children. Inhabitants did not use ventilation through the windows during the measuring periods.

2.2. Method for mitigation

The original pressurisation system was removed and the house was equipped with supply and exhaust system with heat recovery (Fig. 2).

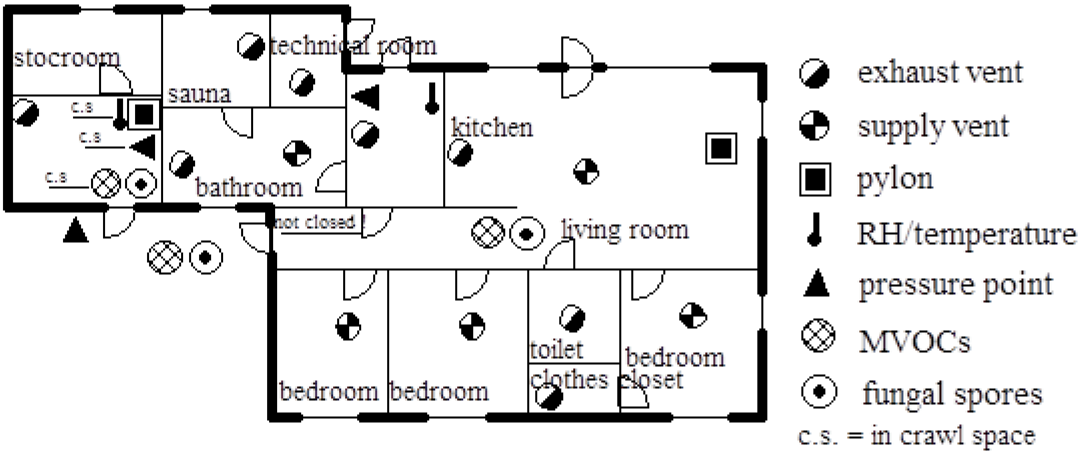

Fig. 2. Floor plan and sampling points of the crawl space in the studied building.

The crawl space was equipped with a separate two-way mechanical ventilation with ducts in the crawl space. An exhaust fan was mounted to blow the crawl space air outdoors and a supply fan was installed to blow outdoor air into the crawl space. The heater (1,2 kW) was installed in the supply duct to prevent freezing of the crawl space. Air flows were adjusted to maintain a small under pressure in the crawl space relative to indoors to reduce the crawl space air infiltration into the living space and to minimise flow of radon-bearing gas and moisture from the soil into the crawl space. We have earlier [29] found that when the indoor-outdoor pressure difference is adjusted slightly positive by combined mechanical ventilation arrangement, the concentration of indoor radon in slab-on-grade house could be minimized. In addition, the influence of various factors on the rate of radon entry were investigated statistically in different types and location houses [30]. According to this study, the effect of the wind speed on the rate of radon entry was difficult to foresee because the effect of the wind on soil depended strongly on the wind direction, location of the houses and especially the permeability of the soil.

2.3. Crawl space modelling

In this study, the simulation capabilities of COMSOL Multiphysica [31] were used to perform crawl space temperature and relative humidity calculations over a period of two years. The parameter in the modelling was a pressure of 10 Pa less in the crawl space than in the living space was obtained by exhaust ventilation, which prevents harmful air leakage from the crawl space to the living space. The air-tightness of the crawl space's ground can be improved by selecting gravel or by sealing the ground with an airtight structure such as evaporation and heat insulation or by surfacing it with concrete. Harmful substances from the ground into the crawl space will decrease as the air-tightness of the crawl space improves. At the same time, the needed air exchange and depressurisation of the crawl space, will decrease.

On the basis of the simulation model's calculation results, the mould growth risk of the crawl space was evaluated with the experimental Finnish Mould Growth Model developed by VTT Technical Research Centre of Finland Ltd and the Tampere University of Technology. The model is a tool to simulate the progress of mould and decay development under varying conditions on the surfaces of structures. Mould growth was defined in this study according to a previously developed mould index classification [32]. Mould growth is presented in the form of a mould index that may have values between 0 and 6, and it is calculated from the changing temperature and humidity conditions.

Table 1 presents the mould index classification criteria. A classification depicting the mould growth sensitivity of the most common building materials having values between 1-4 (Table 2) has been integrated into the model.

Table 1. Mould index for experiments and modelling of mould growth on building materials [33].

Mould Index	Description of the growth rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stage of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, <10 % coverage, or <50 % coverage of mould (microscope)
4	Visual findings of mould on surface, 10 – 50 % coverage, or <50 % coverage of mould (microscope)
5	Plenty of growth on surface, >50 % coverage (visual)
6	Heavy and tight growth, coverage approximately 100 %

A safe limit value for a calculated crawl space mould index is a value of < 1 [21].

Table 2. Mould growth sensitivity classes and some corresponding materials in research [21].

Sensitivity Class	Materials
1 Very Sensitive	Pine sapwood
2 Sensitive	Glued wooden boards, PUR with paper surface, spruce
3 Medium Resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool
4 Resistant	PUR with polished surface

Simulated outdoor temperature changes based on test year climate data Jokioinen Finland 2004 [34]. During the test year in question, the weather conditions were clearly more favorable than normally for mould growth and for the condensation of moisture into structures. The test year is suitable for external envelope of building whose assemblies is protected from rain and the operation of the envelope is mainly influenced by relative humidity of outdoors [35]. With regard to mould growth, the target was that for only 10 % of the years over a period of 30 years are more critical than the moisture reference test year [36].

The simulation was carried out for two crawl space structures (A and B), which are shown in Figure 3 (Fig. 3). The first structure, A, is typical in Finland. The bottom of the crawl space is covered with a layer of air-permeable gravel. The observations were made with two aggregate gravel permeability values $1x10^{-8}$ (m^2) and $1x10^{-9}$ (m^2). The permeability values for gravel used in Finnish foundation structures are usually between $1x10^{-7}$ (m^2) and $1x10^{-9}$ (m^2).

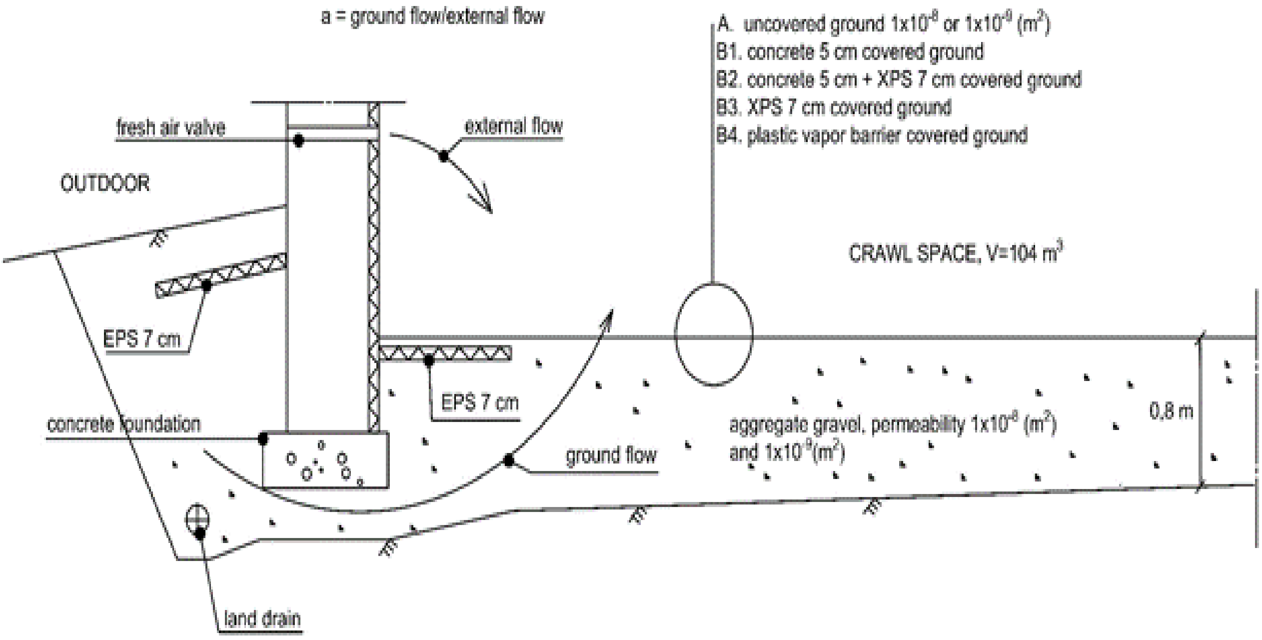

Figure 3. Sectional drawing of the simulated crawl space foundation and different covers.

The structures B1, B2, B3 and B4, comprise an air-tight crawl space ground, which prevents convective air flow via the gravel caused by depressurisation (Fig. 3). For the comparison, the different options for an insulating ground structure were concrete (5 cm), concrete (5 cm) + rigid expanded polystyrene XPS-insulation (7 cm), insulation on the surface of the ground (7 cm) and a plastic sheet on the surface of the ground. The simulation assumed that the perimeter gap between the footer and the ground cover was air-tight. The surface of the filling gravel of the crawl space was under ground level, which is typical in the Finnish crawl spaces.

Two mould growth sensitivity classes were used in the assessment of mould risk: a very sensitive SC1 and medium resistant SC3. Mould growth SC1 presents a structure that contains organic materials or e.g. the surface of a stone structure where organic dust has been collected [18]. Mould growth SC3 presents materials that do not mould easily, which in this study comprised concrete and heat insulation. The different mould sensitivity classes are presented in Table 1.

The convective flow field for a gravel filled ground structure was simulated with a 2D model. The effect of the corners of the building on the flow field's volumetric flow rate was assessed with a 3D model. Heat and moisture simulations were performed with a 2D model. Modelled heat, air and moisture transfers are shown in Fig. 4. The more detailed content of this study's heat and moisture transport modelling is presented by Salo et al. [37].

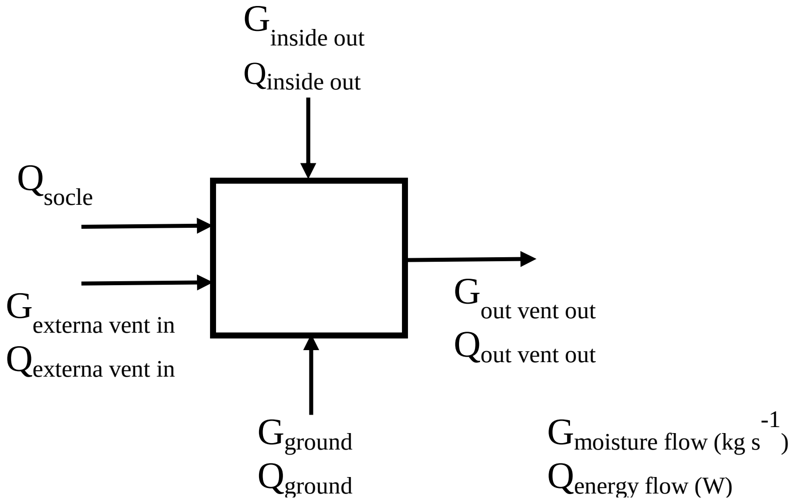

Figure 4. Modelled heat and moisture transfers in crawl spaces.

Outdoor air was brought through valves in the crawl space's socle. The crawl space has mechanical exhaust ventilation. In calculation observations the crawl space's air change and the size of the hold in the socle's valve were altered so that the crawl space had a depressurised pressure of -10 Pa.

Calculations for open ground structures, the proportion of ground air flow in the crawl space and the external flow through the socle was adjusted (Fig. 4). In the simulations, the proportions were changed by adjusting the air flow of the socle's valves. In the simulations the ratio between ground and external flows (a) varied from 0.02 to 4.8. The freezing of the ground surface outside was not taken into consideration. The effect of freezing is not significant due to the thin frozen layer on the ground surface. The modelling surface was alternatively covered by expanded polystyrene (EPS).

2.4. Instrumentation of the case study

Data collection system was used to continuous monitor of the parameters, which are given in Table 3.

Table 3. Monitored parameters and intervals of the case study.

Parameter	Measurement system	Measured interval (min)
Indoor temperature	Thermistor, 1.1m above floor	60
Crawl space temperature	Thermistor, 0,4 m above ground	60
Outdoor temperature	Thermistor, in aspirated shield, 2m above roof ridge	60
Difference in indoor-outdoor pressure	Pressure transducer ± 25 Pa with accuracy of <±1% from fs.	60
Difference in crawl space-indoor pressure	Pressure transducer ± 25 Pa with accuracy of <±0.25% from fs.	60
Indoor radon	Lucas scintillation cell [38] and Pylon AB-5 [39], 1.1 m above the floor and in the crawl space	60
Local wind speed and direction	Cup anemometer, 2m above roof ridge	15/60

The indoor pressure was measured 0.25 m above the floor beside utility room (Fig. 2) and outdoor pressure was measured at the same height at the external wall.

Mechanical supply and exhaust flow rates of air through main ducts were measured with measurement devices of flow rate of air volume with accuracy of the measurement <5%. The flow of crawl space air into the living space was investigated using tracer gas test (Brüel&Kjaer, type 7620). The tracer gas was injected into the exhaust air duct upstream of the exhaust fan where the tracer gas mixed exhaust air which was blown to the crawl space The concentrations of nitrous oxide (N_2O) were monitored downstream of the exhaust fan, in the crawl space and in the living space.

Local wind speed/direction and temperature were measured by means of a weather station. Wind direction and 1h averages were calculated by using Yamartino method [40].

The tightness of the house was determined using the blower door depressurisation test. The negative pressure was increased in step until 50 Pa.

Viable microbes were collected by six cascade impactor (Andersen Inc.) from living room air, crawl space air and outdoors. The sampling rate was 28.3 l min^{-1} and the sampling time was 15 min. Viable fungal counts were determined by cultivation and total spore concentrations were counted and identified to a genus level with a light microscope by the Laboratory of Finnish Institute of Occupational Health. Concentrations were reported as cfu m^{-3}. Dichloran-18% glycerol agar (DG18) was used as a growth medium for xerophilic fungi, 2% malt extract agar (MEA) for mesophilic fungi and tryptone- yeast-glucose agar for actinomycetes. Culturable fungal and actinomycete concentrations, fungal genera, and total spore concentrations were determined from the material samples. The material samples were taken from light weight building slab in the middle of the crawl space. Culturable micro-organisms were determined by dilution plating on Dichloran-18% glycerol agar (DG18), 2% malt extract agar (MEA) and tryptone- yeast-glucose agar for actinomycetes. Fungal colonies were identified to genus level by a light microscope. The total spore concentrations were counted from the same dilutions as those used for the cultivation with a light microscope using a Fuchs-Rosendahl counting chamber. The microbial concentrations were expressed as spores per gram of dry mass of the material (cfu g^{-1}).

Microbially produced volatile organic compounds (MVOCs) were trapped on of Tenax GR absorbent with sampling rate of ca. 200 ml min^{-1}. Tenax samples were taken from crawl space and living room. In addition, reference samples were taken at the same time outdoors. Analyses of MVOCs were conducted by the Laboratory of Eastern University. Air samples were analysed by automatic thermodesorption analyser (ATD400) combined with gas chromatography (HP-GC 6890) and a mass spectrometer (HP-MSD 5973). Analytical details have been published earlier [41,42]. Identification of compounds was accomplished by retention times, standards and GC-MS data library. MVOCs were analysed in selected ion monitoring (SIM) mode.1-chlorooctane (Fluka, >98%) was used as internal standard, and other used standards in SIM mode analysis were: The alcohols 1-octanol (Merck, >99%), 2-octanol (Merck, >97%), 3-octanol (Merck, >97%), *3-methyl-2-butanol (Aldrich, 98%), *3-methyl-1-butanol (J.T. Baker Chemicals B.V., >98%), 1-octen-3-ol (Merck, >97%), 2-ethyl-hexanol (Alfa Aesar, 99%); the ketones 2-pentanone (Fluka, >99%), 2-hexanone (Merck, >98%), 2-heptanone (Merck, >98%) and 3-octanone (Fluka, 97%). In addition, geosmin (Sigma, >98%), 2-methylfuran (Aldrich, 99%) and 3-methylanisole (Fluka, >98%). Standards were made in methanol (Rathburn HPLC grade) and added to the Tenax GR tube. Standard tubes were analysed the same way as samples. Other volatile organic compounds were sampled and analysed the same ways as MVOCs except in GC-MS analysis was done in SCAN-mode. Used standards in SCAN mode analysis were alfa-pinene (Fluka, >99%), limonene (Fluka, >97%), alfa-terpinene (Fluka, 85-90%), toluene (Ronil ctd, >99.9%), ethylbenzene (Merck, >99%), nonane (Fluka, 99%), pentanale (Merck, >98%), hexanale (Fluka, 99%), heptanale (Merck, >97%), octanale (Merck, >98%), and decanale (Merck, 97%).

*) Marked compounds are the most likely MVOCs, which probably do not have any other sources [27].

3. RESULT AND DISCUSSION

3.1. Case Study. Results before the changes in the ventilation

Before the installation of the new ventilation system the average concentration of radon in the crawl space was 340 Bq.m^{-3}, based on continuous measurements during four weeks (Table 4).

Table 4. Results when exhaust air from indoors was blown into crawl space (period 1, pressurized crawl space) and when separate supply and exhaust ventilation systems were operated both in the crawl space and in house (period 2 and period 3). In addition, the exhaust flow of the crawl space was increased during period 3.

	Period 1, March to April		Period 2, October		Period 3, February	
	House	Crawl s.	House	Crawl s.	House	Crawl s.
Radon (Bq m^{-3})	25	340	20	755	22	767
ach (h^{-1})	0.34	2.2	0.34	2.2	-	3.2
Pressure diff. (Pa)	-1.0 (in-out)	+3.7 (c.s.-in)	-0.2 (in-out)	-2.7 (c.s.-in)	-1.2 (in-out)	-2.0 (c.s.-in)
Indoor temperature (^{o}C)	+22.9	+11.9	+21.4	+12.3	+21.5	+7.2
Outdoor temperature (^{o}C)	-2.9		+5.4		-2.3	
Wind speed (m s^{-1})	1.1		1.1		1.2	
RH (%)/abs. (g m^{-3})	-	85/9.1	38/7.1	90/9.6	28/5.3	87/6.9
Fungal spores indoors (cfu m^{-3})						
Mesophilic fungi	174	10040	288	3952	59	616
xerophilic fungi.	160	7850	336	2300	67	1087
Domianant species of total species (%)	*Asperg.* 77%	*Asperg.* 90%	*Cladosp.* 79%	*Penicill.* 79%	*Penicill.* 44%	*Asperg.* 85%
Actinomycetes	-	2	-	7	-	-
MVOC (µg m^{-3})	83	44	56	5	40	8
*MVOC (metab.) (µg m^{-3})	9	7	13	2	1	0

*) Marked compounds are the most likely MVOCs, which probably do not have any other sources [27].

According to the tracer gas test and the measurements of air flow in ventilation duct, the ventilation rate (3/4 of full capacity) was only 0.34 h^{-1} (ach) and the house envelope was (ach_{50} =3.1). That depressurised the house by 1.0 Pa relative to outdoors. Indoor air exhausted to the crawl space caused the crawl space to be pressurised by 3.7 Pa relative to indoors. The ventilation rate of the crawl space was 2.2 h^{-1}. The average temperatures of indoor, outdoor and crawl space, relative humidity of crawl space and wind speed during the measuring period were 22.9 ^{o}C, -2.9 ^{o}C, 11.9 ^{o}C, 85% and 1.1 m s^{-1}, respectively. According to the tracer gas test, crawl space pressurisation caused that about 6 m^3 h^{-1} of the exhaust air infiltrated from crawl space back to the living space. Because of tight floor between the crawl space and living space, the infiltration was about 8% of exhaust flow. However, slightly high microbial concentrations were detected in the house, but only the radon concentration of 25 Bq m^{-3} indoors were caused by the flow from the crawl space.

The ratio of radon concentration between crawl space and indoor 13.5 was closed to the relation between the flow into the crawl space and leak flow back indoors 12.5. On the other hand, the ratio of MVOC concentration between crawl space and indoors was 0.5. The ratio between fungal spores in crawl space and indoors depends on microbial species, infiltration efficiency of different size spores and other microbial sources indoors.

The total crawl space concentration of mesophilic fungal spores was 10040 cfu m^{-3} in air and the total concentration of xerophilic fungal spores was 7852 cfu m^{-3}, because the conditions of microbial growth in the crawl space was favourable. The material samples were taken from light weight concrete slab in the middle of the crawl space. The total crawl space concentration of mesophilic fungal spores from the material sample was 61300 cfu g^{-1} and the total concentration of xerophilic fungal spores was 83800 cfu g^{-1}. In the material sample, the dominant specie was *Aspergillus* (90% of total species), the same which was analysed in air samples both in the crawl space and living space. The concentrations were high even though the visible growth on the subsurface of the slab was not noticed. Probably, fungal spores only attached on the subsurface of the slab and microbes grew mainly on the ground surface.

3.2. Case Study. Results after changes in the ventilation.

During the study period 2 the new supply and exhaust ventilation was adjusted so that the ventilation maintained slight under pressure of 0.2 Pa relative to outdoors and the ventilation rate (1/3 of full capacity) of the house was 0.35 h^{-1} (Table 4). The new ventilation system of the crawl space was adjusted so that the ventilation maintained depressurisation of 2.7 Pa relative to indoors and the ventilation rate of crawl space was the same 2.2 h^{-1} as before the ventilation changes. The averages temperatures of indoor, outdoor and crawl space, relative humidity of crawl space and wind speed during the first measuring period were +21.0 ^{o}C, 4.0 ^{o}C, 12.3 ^{o}C, 90% and 1.1 m s^{-1}, respectively. The radon concentration increased to value of 755 Bq m^{-3} due to increased depressurisation of the crawl space.

At the beginning of the last measuring period 3 the ventilation system of crawl space was readjusted. The averages temperatures of indoor, outdoor and crawl space, relative humidity of crawl space and wind speed during the last measuring period were +21.5 ^{o}C, -2.3 ^{o}C, +7.2 ^{o}C, 87% and 1.2 m s^{-1}, respectively. After the increased exhaust ventilation rate, the average concentration of radon in the crawl space increased to 767 Bq m^{-3}, but average indoor concentration of radon even decreased slightly to 22 Bq m^{-3}, based on continuous measurements during two weeks. The difference in crawl space - outdoor pressure was the most significant variable ($p<0.00$) according to the multiple regression analysis to explain the concentration of crawl space radon (Fig. 5).

The coefficient of determination ($100R^2$) was 79% by the difference in crawl space - outdoor pressure. The coefficient of determination became only slightly higher for all variables, 80%. The variables were difference in indoor-outdoor temperature, difference in crawl space-outdoor pressure, wind speed and ventilation rate. Wind speed and the difference in indoor-outdoor temperature were significant variables ($p<0.05$) but temperature difference and wind speed were not important variables for explain the concentration of crawl space radon. The wind had only a slight influence to the ventilation of the closed crawl space. In addition, wind speed was not found to influence the concentration of indoor radon although according to analysis of covariance the radon concentration was 12% more than grand mean in the crawl space when the wind came from shielded (houses, hills and trees) directions. In addition, the lowest concentration of radon in the crawl space was 13% less than grand mean when the wind blew from unshielded directions. Radon concentration in soil in vicinity of the house probably decreased during the wind. The influence of the crawl space ventilation was difficult to foresee because mechanical ventilation rate did not vary.

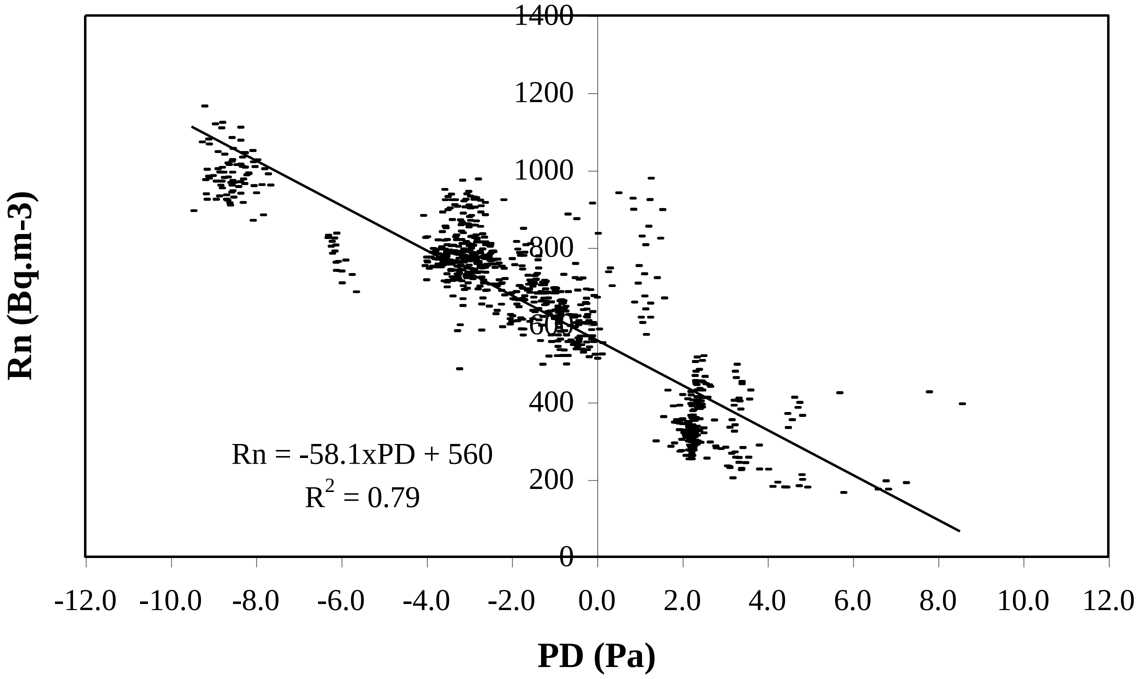

Figure 5. Dependence of measured concentration of crawl space radon Rn (Bq m^{-3}) on difference in crawl space-outdoor pressure PD (Pa), based on 859 one hour average measurements during periods 1, 2 and 3.

The new supply and exhaust ventilation maintained under pressure of 1.2 Pa in living space relative to outdoors, which is due to air leakage into crawl space and due to higher difference in indoor-outdoor temperature during the last period compared to the earlier period. In order to maintain a small negative pressure in the crawl space relative to indoors, the exhaust flow had to be increased during the cold weather condition at the beginning of the last measuring period. Thus, the crawl space was depressurised by 2.0 Pa relative to indoors. The ventilation rate of the crawl space was increased from 2.2 h^{-1} to 3.2 h^{-1}. The average radon concentration was doubled 767 Bq m^{-3} in the crawl space and stayed indoors at the same level 22 Bq m^{-3} during continuous measurements lasting two weeks. However, the negative pressure relative to the living space prevented successfully the flow of crawl space air into the living space. Unexpectedly, air moisture of the crawl space did not decrease immediately after changes in ventilation because the moisture capacity of the crawl space and soil is high and evaporation of the moisture is a slow process. However, the total concentration of mesophilic fungal spores in the crawl space decreased from 10040 cfu m^{-3} to 3952 cfu m^{-3} and after last measuring periods still more to 616 cfu.m^{-3} after the installation of the new ventilation system. Similarly, the total concentration of xerophilic fungal spores decreased from 7852 cfu m^{-3} to 2300 cfu m^{-3} and finally to 1087 cfu m^{-3}. Also the dominant fungal genera changed after changes in the ventilation. Before changes in the ventilation the dominant species was *Aspergillus* (90% of total species) in the crawl space and indoors in the living room (77% of total species). After installation of the combined mechanical ventilation the dominant species was *Cladosporium* (79% of total species) and *Penicillium* (44% of total species) in the living spaces and *Penicillium* (79% of total species) and *Aspergillus* (85% of total species) in the crawl space. The change of the dominant species and total concentrations in the crawl space indicated that the conditions of microbial growth in the crawl space had changed. The temperature and relative humidity in the crawl space decreased in comparison between periods 2 and 3. At the same time air exchange rate increased by the value of 1 h^{-1} obtaining the more effective dilution of fungal spores.

The total concentration of MVOCs in the crawl space decreased as a result of the separate ventilation system. The concentrations of MVOC of specific microbial species decreased when the concentration of fungal spores decreased. The crawl space concentration of MVOC of specific microbial species was very low and also lower in the crawl space than in the living space in spite of the higher concentration of fungal spores in the crawl space than indoors.

It was difficult to adjust ventilation of the crawl space so that the ventilation maintained slight under pressure relative to indoors when the weather conditions changed. During the coldest weather conditions the difference in indoor-outdoor pressure was caused by temperature difference although the ventilation was in balanced. Maximum pressure differences under northern winter condition with flow balanced ventilation and no wind are –2 Pa and –4 Pa, calculated due to the thermal stack effect in a single story house and in a two-story house. The ventilation rate of the crawl space had to be increased, because a small under pressure in the crawl space relative to indoors had to exist to prevent infiltration of contaminants into the living space. In the winter the ventilation rate of the crawl space was high (3.2 h^{-1}) and for this reason the ventilation cooled the crawl space and slab and also increased the heat losses of the house. However, special attention should be paid when designing the ventilation and structure of the crawl space because cooling increases the relative humidity and condensation. On the other hand, in a tight crawl space the sufficient pressure difference will be obtained with a lower ventilation rate without cooling problem of the structures.

3.3. Results of crawl space modelling

The parameter for the calculation was a pressure of -10 Pa in the crawl space compared to the living space, which was assumed to be constant and to be maintained by correctly adjusted valves and flow rate of exhaust fan. The convective air flow via the ground depended on the permeability of gravel. More permeable gravel 1x10^{-8} (m^2) allowed the convective air flow via the ground caused by depressurisation to be 0.028 m^3 s^{-1}, and similarly only 0.003 m^3 s^{-1} with less permeable gravel 1x10^{-9} (m^2). Also gravel materials that were coarser than 1x10^{-8} (m^2) were used in foundations. When permeability was 1x10^{-7} (m^2), the convective flow via the ground increased to the unreasonable value of 0.28 dm^3 s^{-1}. Table 5 presents the values of the air change rate (ach) in the crawl space and of the external flow used in the simulation.

Table 5. Calculated air change rate (ach, h^{-1}) in a mechanically ventilated and depressurised crawl space based on the external and ground flow (m^3/s).

External flow (m^3 s^{-1})	ach (h^{-1})		
	Uncovered ground		Covered ground
	Permeability 1x10^{-8} (m^2)	Permeability 1x10^{-9} (m^2)	-
0.005	1.2	0.3	0.2
0.0115	1.4	0.5	0.4
0.0173	1.6	0.7	0.6
0.0230	1.8	0.9	0.8
0.0288	2.0	1.1	1
0.0576	3.0	2.1	2
0.144	6.0	5.1	5

An open base structure's (Fig. 3) air change rate is greater than ach of sealed ground structure because soil gas flow is less in the sealed crawl space. The external air flow caused by the depressurisation (-10 Pa) of the crawl space during mould critical time dries up significantly as it travels via the soil to the crawl space; see the simulation result (Fig. 6). The phenomenon depends on the characteristics of gravel and air flow, and it would require more research.

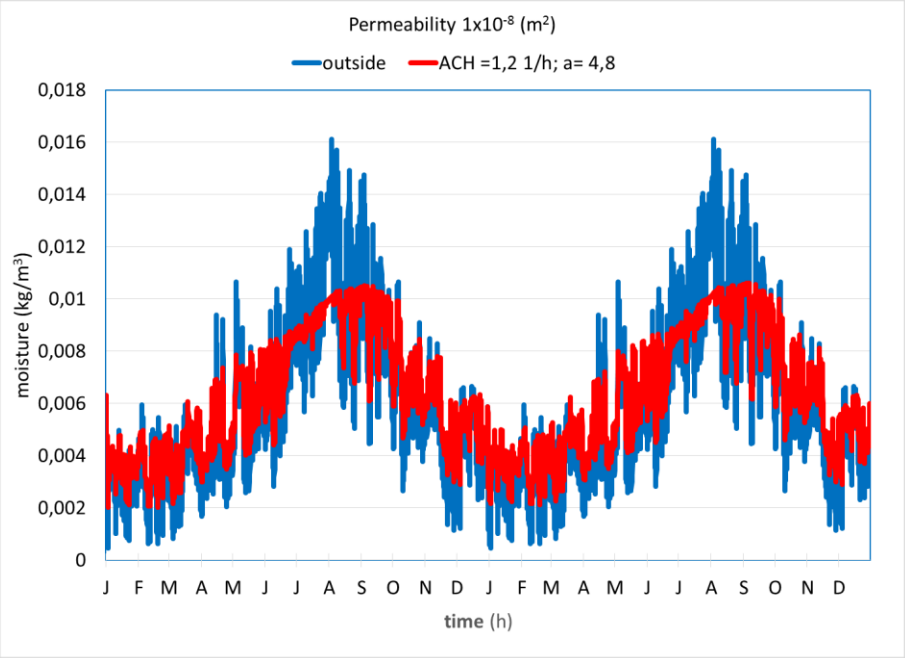

Figure 6. Change in moisture content of external air flow ($m^3 s^{-1}$) as it travels via the soil by convective flow to the crawl space. a=ground flow/external flow

The results for mould index for an open ground structure with two permeability values when the mould sensitivity classes of building materials are 1 and 3 are presented in Table 6 and at a permeability of $1x10^{-8}$ for gravel in Figures 7 and 8.

Table 6. Maximum value for the mould index of a crawl space with an open ground structure, when the SC of building materials is 1 and 3 and with two ground permeability values. Subscript”SC 1” means mould growth sensitivity class 1 (very sensitive) and “SC 3” mould growth sensitivity class 3 (medium resistant).

Permeability 1 x 10^{-8} (m^2)								
ach (h^{-1})	1.2	1.4	1.6	1.8	2.0	3.0	6.0	outside
a= ground flow/external flow	4.8	2.4	1.6	1.2	1.0	0.48	0.19	-
Mould Index, SC 1	**5.8**	**5.9**	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**	5.9
Mould Index, SC 3	0.31	0.34	0.36	0.37	0.36	033	0.26	0.19
Permeability 1 x 10^{-9} (m^2)								
ach (h^{-1})	0.3	0.5	0.7	0.9	1.1	2.1	5.1	outside
a= ground flow/external flow	0.48	0.24	0.16	0.12	0.10	0.05	0.02	-
Mould Index, SC 1	**5.9**	**5.9**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**	5.9
Mould Index, SC 3	0.35	0.37	0.40	0.37	0.37	0.32	0.25	0.19

The mould index for open ground structures increases at an earlier point in time at all air change rate values than the mould index for outdoor air. The temperature of the crawl space is lower than that of outdoor air, which means that outdoor air introduced to the crawl space cools causing arise in relative humidity and thus a higher mould index. The mould index is not dependent on the permeability values used in calculation, but only a bit on the air change rate in the crawl space. When the mould growth sensitivity class (SC) for building materials is 3 (concrete etc.) the structure is effective because the mould index remains under 1, and no mould growth is estimated to exist (Table 6, Fig. 7). Respectively, the structure is not recommended when the mould growth sensitivity class (SC) of building materials is 1 (e.g. pine sapwood), because the mould index rises over the permitted value of 1 (Table 6, Fig. 8).

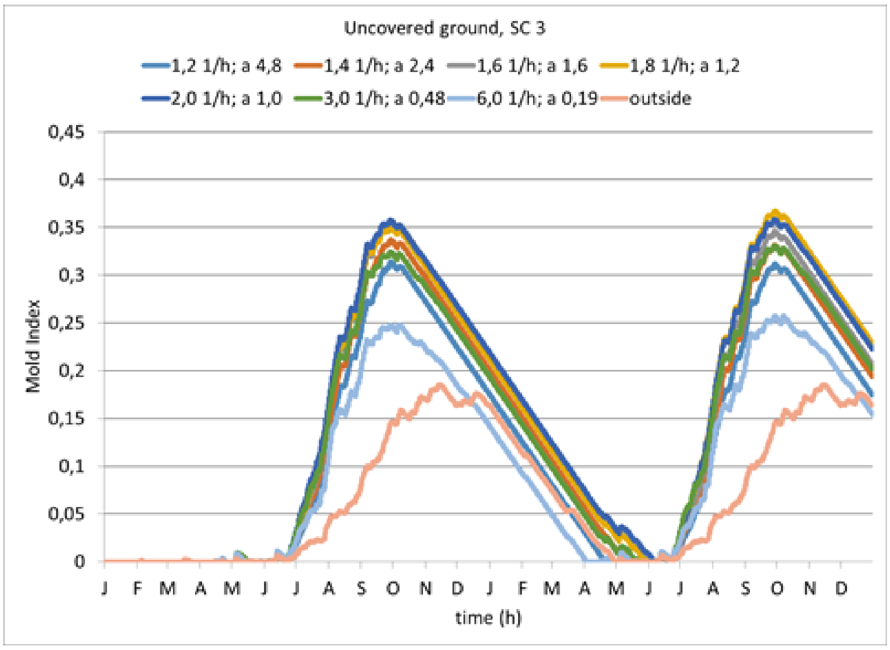

Figure 7. Mould index on the gravel (permeable 1x10-8 m^2) surface of crawl space with mould sensitivity class of SC 3 during simulated conditions similar to those of the test year’s climate.

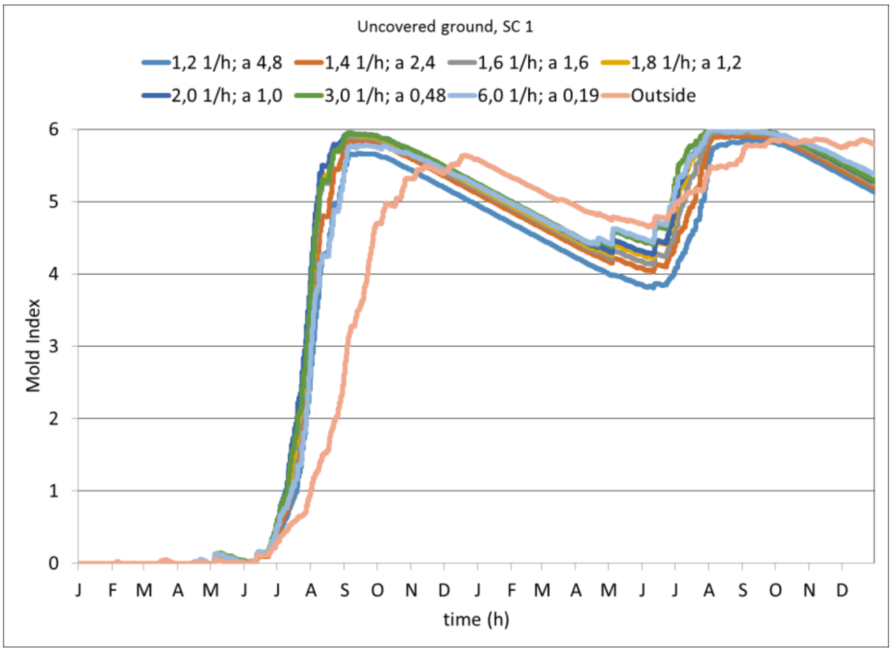

Figure 8. Mould index on the gravel (permeable 1x10^{-8} m^2) surface of crawl space with mould sensitivity class of SC 1 during simulated conditions similar to those of the test year’s climate.

In the air-tight crawl space convective air flow via the ground was prevented. For the purpose of the simulation, the ground structure used was alternatively concrete, concrete+insulation, and insulation and a plastic sheet (Fig. 3). The mould index values for crawl space building materials at SC 1 and 3 is presented in Table 7 (Table 7).

Table 7. Maximum mould index values of a crawl space with an air-tight ground structure at SC 1 and 3. Subscript"SC 1" means a mould growth sensitivity class of 1 (very sensitive) and "SC 3" a mould growth sensitivity class of 3 (medium resistant).

ach (h^{-1})		0.2	0.4	0.6	0.8	1.0	2.0	5.0	outside
Concrete 50 mm ground cover	SC1	0.15	0.59	**1.01**	**1.38**	**1.88**	**3.91**	**4.74**	5.87
	SC3	0.00	0.01	0.03	0.05	0.08	0.12	0.12	0.19
Concrete 50 mm+ XPS insulation 70 mm cover	SC1	0.00	0.02	0.14	0.31	0.43	0.92	**1.75**	5.87
	SC3	0.00	0.00	0.00	0.01	0.01	0.03	0.05	0.19
XPS insulation 70 mm cover	SC1	**5.66**	**5.81**	**5.93**	**5.93**	**5.94**	**5.95**	**5.91**	5.87
	SC3	0.26	0.28	0.33	0.32	0.31	0.27	0.20	0.19
Plastic sheet cover	SC1	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**	**6.00**	5.87
	SC3	0.61	0.57	0.52	0.47	0.44	0.35	0.27	0.19

The mould index was less than 1 in all the simulations when air-sealed structures were used and the mould growth sensitivity class of building materials was 3. An increase in the mould index was only estimated when the air change rate increased as time passes in plastic covered ground crawl space. The plastic insulated ground structure (Fig. 9) obtained greater mould index than that of XPS insulated ground structure (Table 7.). The mould index of plastic or XPS insulation covered ground structures with SC 3 decreases as the air change rate increases. When the mould growth sensitivity class of building materials in the crawl space is 1 (e.g.. pine sapwood) with a concrete surfaced ground structure, the mould index remained less 1 when air change rate was up to 0,6 h^{-1} (Fig. 10). The mould index exceeds the value of 1 with higher air change rates. The mould index for a ground structure built with concrete and XPS insulation with SC 1 was less than 1 when the air change rate did not exceed the value of 2 h^{-1} (Fig. 11). The low mould index of concrete structures is due to concrete's high moisture capacity; concrete absorbs excess moisture to itself and balances out changes in humidity.

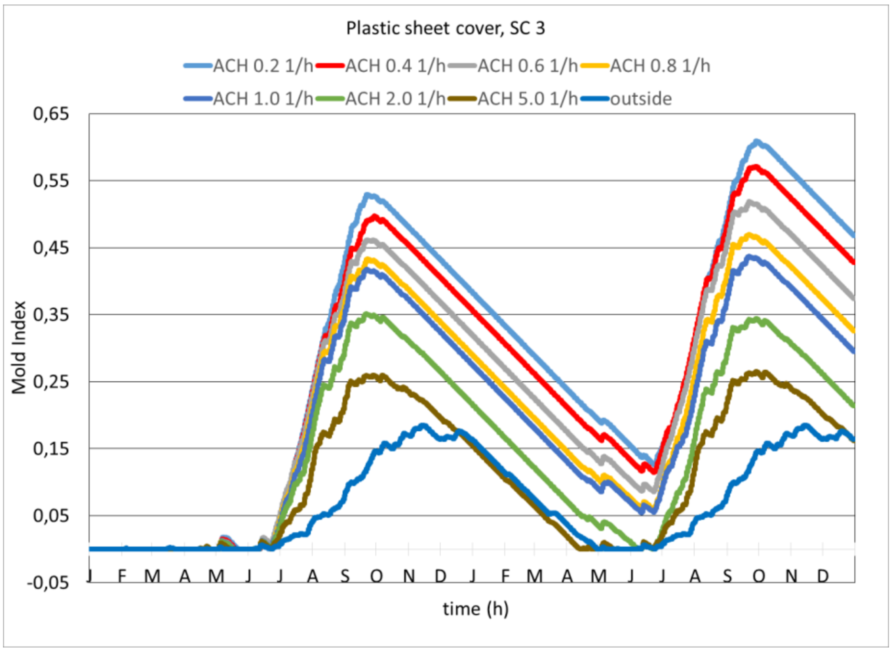

Figure 9. The mould index of crawl spaces with plastic sheet covers with an SC 3 for building materials under simulated conditions similar to those of the test year’s climate.

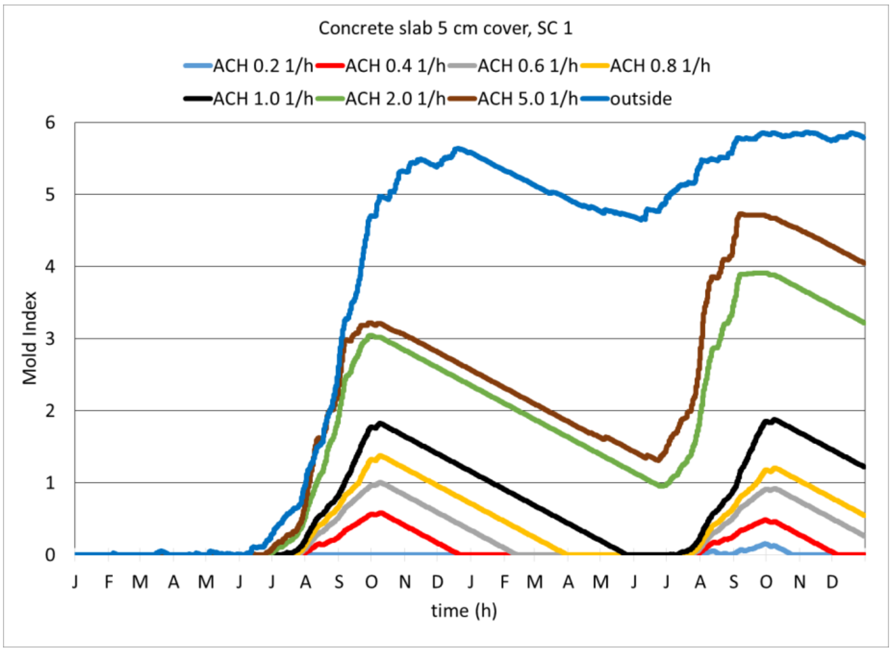

Figure 10. The mould index in a concrete covered crawl space with an SC 1 for building materials under simulated conditions similar to those of the test year’s climate.

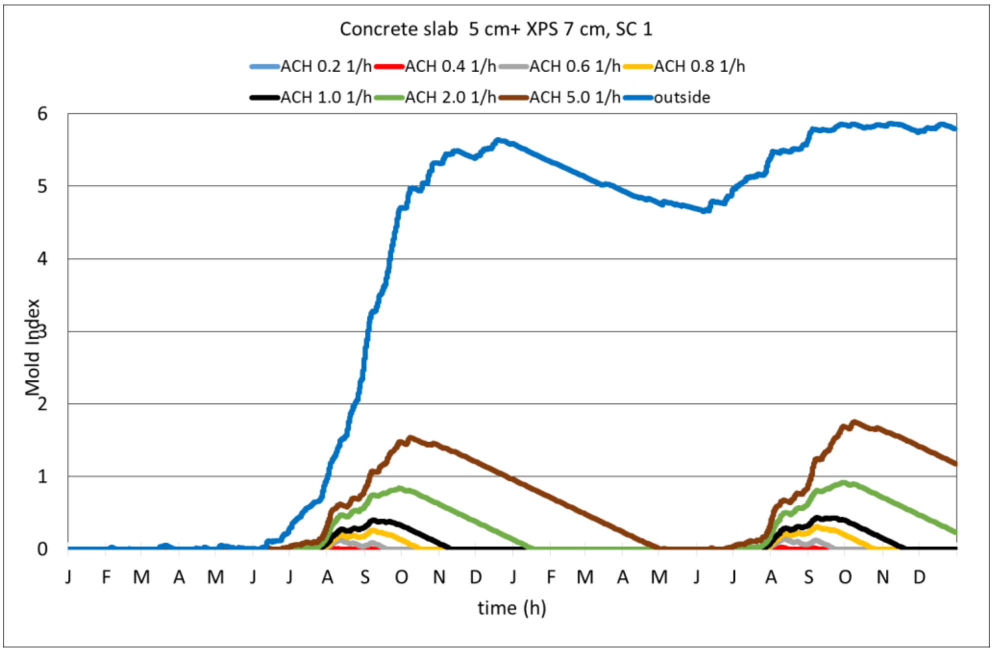

Figure 11. The mould index in a crawl space with a concrete+XPS-insulate cover with an SC 1 for building materials under simulated conditions similar to those of the test year’s climate.

Figure 12 shows a comparison of the temperature in crawl spaces constructed with ground cover of concrete, concrete+XPS, XPS and plastic when the estimated air change rate was 0.6 h^{-1}. In summer period the temperature in a crawl space insulated with concrete or plastic was lower than in one which was sealed with XPS or concrete+XPS. In winter period the situation is the opposite.

Figure 13 presents a comparison of the relative humidity of crawl spaces constructed with concrete, concrete+XPS, XPS and plastic when the estimated air change rate was 0.6 h^{-1}. During the examination period when the humidity of outdoor air was high, the relative humidity in a crawl space insulated with concrete was lower and the fluctuation was smaller than in one which was sealed with plastic or XPS.

The mould index exceeded the value of 1 with all air change rates when ground structures were constructed with XPS insulation or plastic and the mould growth sensitivity class of building materials was 1.

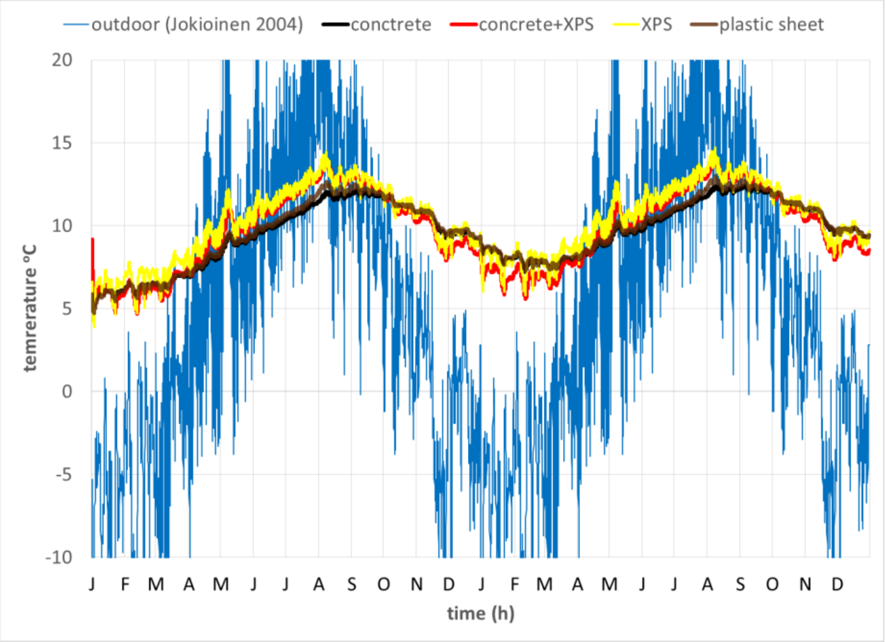

Figure 12. Temperatures in the crawl space with different ground covers and an air change rate of 0,6 h^{-1}.

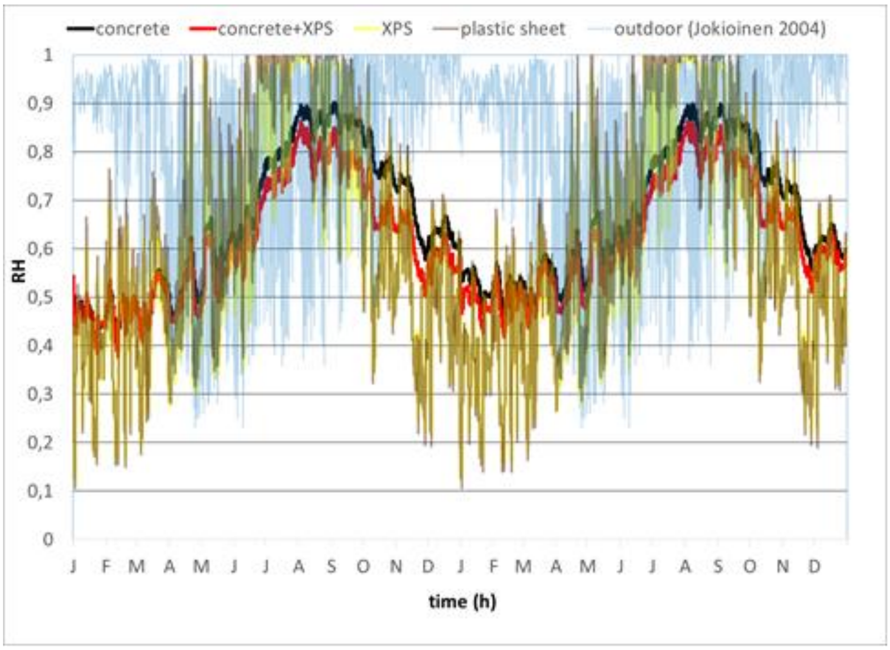

Figure 13. The relative humidity (RH) in the crawl space with different ground covers and an air change rate of 0,6 h^{-1}.

4. CONCLUSIONS

According to this case study, the crawl space pressurisation system with exhaust air from indoors was successful to prevent the convective flow of radon from the soil. However, high microbial concentrations were detected in the crawl space, because moist and warm air was blown into the space. This kind of crawl space pressurisation is effective in control of the indoor radon with certain qualifications; the slab has to be totally tight and organic materials should not exist in a filling soil and in structures of the crawl space. Carefully balanced separate two-way ventilation in the crawl-space and supply and exhaust ventilation in the living space and also tight slab between them appears to be beneficial to prevent the crawl space air infiltration into the living space.

In this study, the concentration of fungal spores and MVOC decreased as a result of the separate ventilation system in the crawl space during short follow-up periods. The crawl space concentration of MVOC of specific microbial species was very low and also lower in the crawl space than in the living space in spite of the higher concentration of fungal spores in the crawl space than indoors. These findings are consistent with the previous findings that microbial contaminated areas might not be verified by the MVOC measurements [23].

The air change rate of the crawl space which maintained under pressure relative to indoors was high in the winter and summer conditions. This should be noticed in design of the ventilation and structure of the crawl space, because in a tight crawl space the sufficient pressure difference will be obtained with a lower ventilation rate. Then cooling or high humidity problems of structures could be avoided. The tight solutions of the crawl space should be developed when reduced ventilation in the crawl space is designed. In summary, practical instructions, which are based on the research, would be needed on the ventilation and the structure solutions of the crawl space.

A microbiologically safe crawl space was determined with hygrothermal simulation utilizing the Finnish Mould Growth Model. The optional structures of the crawl space being depressurised 10 Pa relative to indoors to reduce air infiltration from the crawl space into the living space. According to the simulation, the recommendable air change rates depend on insulation of the crawl space, its structure and the mould growth sensitivity class of the materials. A crawl space with an open base uncovered ground (gravel) structure can be kept depressurised with moderate exhaust ventilation when the soil's permeability value is $1x10^{-9}$ and $1x10^{-8}$. However, when permeability increases, the air change rate must be increased to achieve depressurisation. This causes excessive cooling of structures and building technology devices in the crawl space in winter. An open ground structure covered with gravel and depressurised with exhaust ventilation is an effective solution when the mould growth sensitivity class of used building materials is 3, and there are no organic substances in the crawl space. But the structure with the mould growth sensitivity class of building materials 1, is not effective for any air change rate.

The simulation assumed that the perimeter gap between the footer and the ground cover was air-tight. All the simulated structures for crawl space with an air-sealed ground structures in mould growth sensitivity class 3 were satisfactory with various exhaust air change rates. However, air change rates of over 2 h^{-1} caused too much cooling of the crawl space in winter and were not economically feasible. In mould growth sensitivity classes 1 the most recommended building material for ground structures was concrete+XPS insulation and the recommended air change rates are from 0.2 to 1 h^{-1}. The next most effective structure of the crawl space ground was concrete with no insulation and recommended air change rates are from 0.2 to 0.6 h^{-1}. Mould index rises if the air change rate exceeds the value of 0.6 h^{-1}. The low mould index of concrete structures is due to concrete's high moisture capacity; concrete absorbs excess moisture to itself and balances out changes in humidity. XPS insulation and a plastic-sealed ground structure are less effective options and these structures are not recommended due to their high mould index.

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