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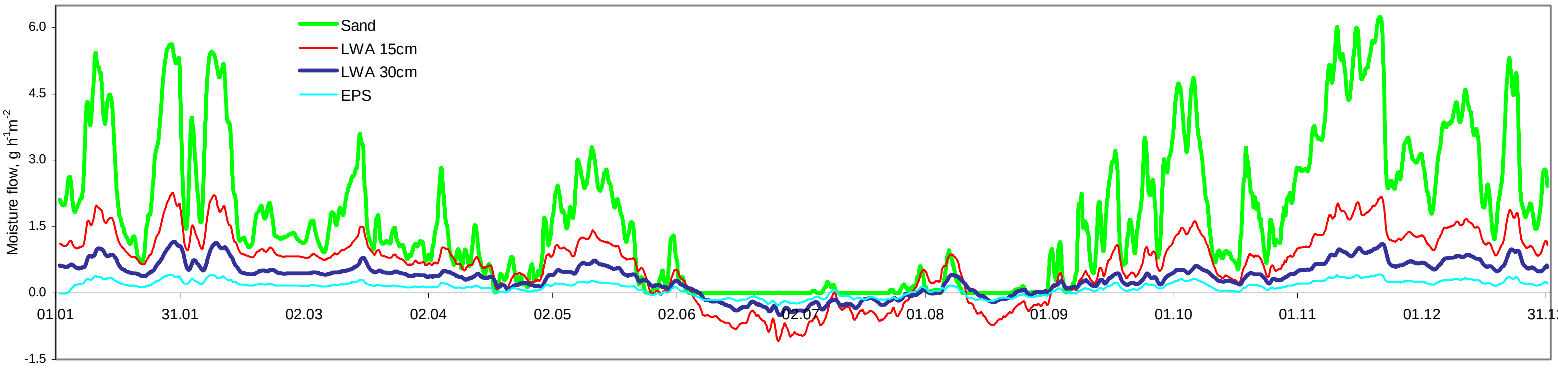

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Mechanical Engineering, for public examination and debate in Auditorium K216 at Helsinki University of Technology (Espoo, Finland) on the 21st of November, 2003, at 12 noon.

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Distribution:

Helsinki University of Technology
HVAC-Library
P.O. Box 4100
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Tel. +358 9 451 3601
Fax. +358 9 451 3611

Author's address:
Optiplan Oy
Myyrmäentie 2 B
FIN-01600 Vantaa
Tel. +358 9 560 780
Fax. +358 9 5607 8200
E-Mail: miimu.airaksinen@optiplan.fi

Supervisors:
Prof. Olli Seppänen
Helsinki University of Technology
HVAC-Laboratory

Dr. Jarek Kurnitski
Helsinki University of Technology
HVAC-Laboratory

Doc. Pertti Pasanen
University of Kuopio
Department of Environmental Sciences

Reviewers:
Prof. Pentti Kalliokoski
University of Kuopio
Department of Environmental Sciences

Dr.-Ing. Hartwig M. Küntzel
Frauenhofer Institute of Building Physics
Division of Hygrothermics

Opponents:
Prof. Pentti Kalliokoski
University of Kuopio
Department of Environmental Sciences

Prof. Gudni Jóhannesson
Royal Institute of Technology, Sweden
Department of Civil and Architectural Engineering

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ABSTRACT

A crawl space foundation is widely used in buildings and detached houses in northern countries. The relative humidity of the air in crawl spaces is the most critical factor concerning mould growth in the structures of a crawl space. Possible contamination in the crawl space might be transported indoors if the pressure inside the apartment is lower. The objective of the study was to find out the important properties of ground covers and the optimal air change rates for the controlling of moisture conditions in an outdoor air-ventilated crawl space in a cold climate and to estimate the acceptability of current moisture conditions in respect of material durability. In addition, factors affecting the transport indoors of possible pollutants from crawl spaces were studied.

The moisture conditions were calculated with a dynamic simulation model, which was validated against measured data. The moisture and thermal capacity and resistance of the ground cover were varied, as was the air change rate in the crawl space. The acceptability of moisture conditions was evaluated using a mould growth index. The concentration of fungal spores was measured both through field measurements and full-scale laboratory measurements. The penetration of inert particles of different sizes through a building envelope was studied by means of full-scale laboratory measurements. The airtightness of the building envelope and the pressure difference across the envelope were varied.

It was shown that in a relatively warm crawl space moisture problems were easy to avoid – ground soil should be covered so as to prevent moisture flow from the ground and an air change of at least 0.5 ach is enough to keep relative humidity at a low level. A relatively cold crawl space needs a ground cover with moisture and thermal resistance. A ground cover with a moderate thermal resistance, such as 15 cm lightweight aggregate, needs a higher ventilation rate, at least 2.0 ach, to warm up the crawl space in the summer. A ground cover with a high moisture capacity can stabilise the fluctuation of relative humidity in a crawl space, and thus avoid critical peaks of relative humidity in respect of mould growth. The safest ground cover solution is a thick cover with a high thermal resistance and a low air change rate of 0.5 ach; with this approach natural ventilation can be used. Heating a crawl space in summer is an excellent way to avoid mould growth. The advantage of heating is greatest if the ground cover has a high thermal conductivity. The energy consumption of heating is strongly dependent on the set point value for the relative humidity. However, if the set point value is kept reasonable and the ventilation rate remains low the specific annual energy consumption is within the range of 1.4–3.6kWh/m^2 of the crawl space area.

Results from field measurements showed a correlation between microbes in the crawl space and indoors. In the full-scale laboratory measurements it was established that inert particles and fungal spores in a size range 0.6-2.5 μm penetrate a wooden structure at moderate pressure differences. Laboratory measurements showed that the penetration was highly dependent on pressure difference and not dependent on holes in the surface boards of the structure. The results are likely to show that the surface contacts of mineral wool in the floor structure may have an important role in penetration. It is clearly difficult to control the penetration of fungal spores by sealing the building envelope. The only effective way to avoid penetration seems to be balancing the building; however, in cold climates the moisture condensation risk should be taken into account. The results indicate that mechanical exhaust ventilation causing an under-pressure in the building may cause health risks if some contamination exists in the building envelope.

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My dearest thanks are owed to my father Veijo for providing me with the spark for HVAC technology and the never-ending support and encouragement he has given me during these years. I want to give a big hug to my mother Essi for all her love and care. To my brother Pele I owe my warmest thanks for his ability always to see a reason for a smile. Most of all, my heartfelt gratitude belongs to my wonderful husband Tuukka, for all the sunshine and fresh winds at sea and in my life.

On a sunny day in October 2003

ABBREVIATIONS

CFU	colony forming unit
CH	chamber
CS	crushed stone
EPS	expanded polystyrene
HAMWall	heat and moisture wall-model for moisture transfer
IDA	dynamic simulation environment
HEPA	high efficiency particulate air
I/O ratio	indoor/outdoor ratio
Le	Lewis number
LWA	lightweight clay aggregate
MEA	malt extract agar
NMF	neutral model format, a computer code
RC network	resistance capacity network
RH	relative humidity
RH_{Cr}	critical relative humidity
TOW	time of wetness

LIST OF ORIGINAL PUBLICATIONS

I Kurnitski J. and Matilainen M., Moisture conditions of outdoor air-ventilated crawl spaces in apartment buildings in a cold climate, Energy and Buildings, 2000, **33**, 1:15-29

II Airaksinen M., Kurnitski J., and Seppänen O., On the crawl space moisture control in buildings, Proceedings of the Estonian Academy of Sciences. Engineering, 2003, **9**, 1:34-58

III Matilainen M. and Kurnitski J., Moisture conditions in highly insulated outdoor ventilated crawl spaces in cold climates, Energy and Buildings, 2003, **35**, 2:175-187

IV Matilainen M., Kurnitski J., and Seppänen O., Moisture conditions and energy consumption in heated crawl spaces in cold climates, Energy and Buildings, 2003, **35**, 2:203-216

V Airaksinen M., Pasanen P., Kurnitski J., and Seppänen O., Microbial contamination of indoor air due to leakages from crawl space – a field study, Indoor Air, accepted for publication 2003

VI Airaksinen M., Kurnitski J., Pasanen P., and Seppänen O., Fungal spore transport through a building structure, Indoor Air, accepted for publication 2003

AUTHOR'S CONTRIBUTION

The author is the main author of five publications (II-VI). In (I) the computer simulations were carried out by author, both authors were participating in the model development. In (II) author carried out and analysed the simulations, the model development were performed by both authors. In (III) and (IV) author was responsible for the computer simulations and analyse of results, selection of studied cases were performed by both authors. In (V) field measurements were carried out by author as well as the analyse of results, microbial studies were carried out by Pertti Pasanen. In (VI) the laboratory set up and measured cases were designed by author and co-authors Jarek Kurnitski and Pertti Pasanen. Measurements and analyse of results in (VI) were performed by author.

CONTENTS

1. INTRODUCTION

A crawl space foundation is widely used in buildings and detached houses in northern countries. Basements with a crawl space have a long tradition and their worth has been proven in many old buildings. In respect of radon concentrations indoors, a crawl space is an advantageous construction. The radon concentration in leakage air through a base floor decreases remarkably if the crawl space is well ventilated (Arvela 1995)

Due to higher awareness of energy consumption, the base floor U value has decreased nowadays to 0.2 W/m^{2}K, which corresponds to approximately 20 cm of mineral wool insulation. The heat losses through the base floor are smaller and, thus, a lower base floor U value leads to a colder crawl space with higher relative humidity. Crawl spaces are mostly ventilated by outdoor air and ventilation is usually natural, but mechanical exhaust ventilation is also used to some extent. There is frequently a limited number of ventilation ducts and openings in the foundation walls, which leads to low air change rates.

Alternatively, crawl spaces can be ventilated mechanically with exhaust air from the building (Anderson and Samuelsson 1987, Lehtinen and Viljanen 1991, Hagentoft and Harderup 1993). In this case the crawl space should be heated by exhaust air, i.e. the crawl space is highly insulated but there is no insulation in the base floor. The crawl space can even be left unventilated if the moisture insulation is perfect (Åberg 1990). However, as these applications are relatively difficult to build and rather expensive, they have not became a common building practice.

Moisture problems can be caused by a number of factors. Some of the problems are easy to solve; rainwater in a crawl space can be avoided by proper drainage. However, even in well-constructed crawl spaces moisture problems occur. In subarctic climates the behaviour of an outdoor air-ventilated crawl space becomes problematic in the summer, when, in the daytime, outdoor air is usually warmer and has a higher moisture content than the air in the crawl space. Thus, outdoor air can transport moisture into the crawl space and the relative humidity increases. This can be prevented by reducing the time lag between the time it takes for the temperatures of the outdoor air and the crawl space to become equal. The time lag is caused by the high heat capacity of the ground soil and foundations.

Samuelsson (1994) reports high relative humidity (85–95%) during the summer and even condensation of water during several weeks; Svensson (2001) also reports relative humidity between 80-90%. In another study (Kurnitski 2000) the relative humidity in the crawl space varied between 70–90% during the summertime. As there is often some organic material in the crawl space the conditions for mould growth are favourable; see Figure 1. In favourable conditions mould growth can start very quickly. Mould growth is usually first noticed when an unpleasant smell begins to penetrate to the living spaces on the ground floor.

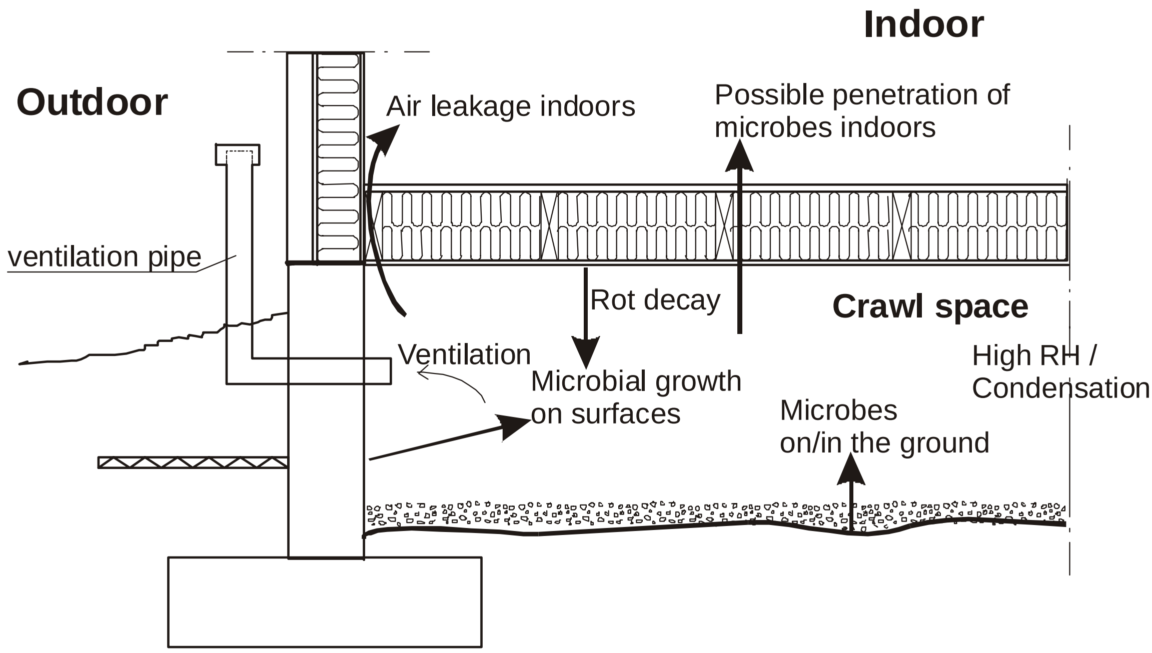


Figure 1 Some potential risks in a crawl space environment

In epidemiological population studies, moisture damage and microbial growth in buildings have been associated with a number of health effects, including respiratory symptoms and diseases and other symptoms (Verhoeff and Burge 1997, Nevalainen et al. 1998, Peat et al. 1998, Hyvärinen 2002). The health effects associated with moisture damage and microbial growth seem to be consistent across different climates and geographical regions (Hunter et al. 1988, Nevalainen 1991, Li and Kuo 1994, Ellringer et al. 2000).

Microbiologically clean buildings probably do not exist, as some contamination in the structures begins to build up even during the construction phase. In the case of moisture damage, even after repairs, a significant amount of contaminated materials can remain in structures (Nguyen Thi et al. 2000). Therefore, the potential transport of pollutants from and through structures has great importance in respect of the design and construction of buildings. It is important to know which factors affect the release and penetration of pollutants and possible measures, such as sealing and pressurising, that can be taken to avoid this.

Typical indoor under-pressures with mechanical exhaust ventilation are within the range of 5–20 Pa. A field study (Kurnitski 2000) showed high air flow rates through leaks in the base floor to an apartment at a pressure difference of around 6 or 15 Pa, depending on the speed of the exhaust fan. Field measurements (Mattson et al. 2002) have shown evidence of fungal spores being transported indoors from a crawl space.

2. REVIEW OF LITERATURE

2.1 Crawl space heat and moisture balance

To understand the behaviour of a crawl space an energy balance should be stated for the crawl space air and a heat balance for the base floor, ground soil and "walls", i.e. foundations; see Figure 2, Equation (1) (Elmroth 1975, Kurnitski 2000). The important heat and moisture flows are those from outdoor air, base floor, ground soil, and foundations. Heat transfer by radiation is only considered between the base floor and ground soil because of the small surface of the walls compared to the base floor area. The equations are shown in more detail in Kurnitski (2000). For other surfaces than the ground the convective heat transfer coefficient is assumed to be constant.

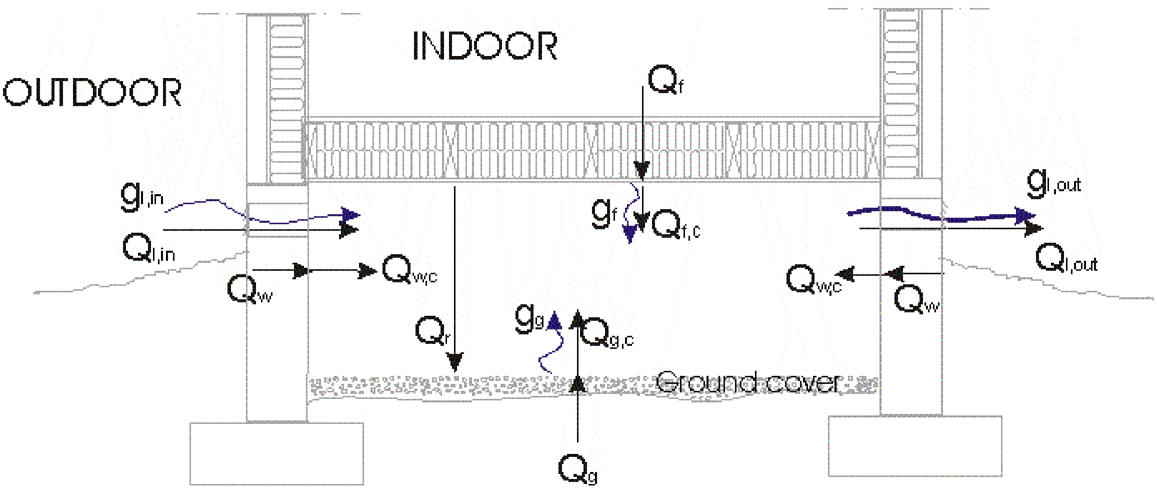


Figure 2 Heat and moisture flows in a crawl space

Energy balance with notations shown in Figure 2.

$$C_i \frac{\partial T_i}{\partial t} = Q_{f,c} + Q_{g,c} + Q_{w,c} + Q_l + Q \tag{1}$$

where C_i is the heat capacity of the air (J/K), T_i the air temperature (K), t time (s), $Q_{f,c}$ the convective heat flux from the base floor (W), $Q_{g,c}$ the convective heat flux from ground soil (W), $Q_{w,c}$ the convective heat flux from the walls (W), Q_l the net heat flux from crawl space ventilation (W), and Q the possible heat flux from a heat source or sink (W). the heat balance equations for the surfaces are:

$$\begin{aligned} Q_f &= Q_{f,c} + Q_r \\ Q_w &= Q_{w,c} \\ Q_g &= Q_{g,c} - Q_r + Q_e \end{aligned} \tag{2}$$

where Q_f is the heat from the base floor (W), Q_r the radiation heat between the base floor and the ground (W), Q_w the heat from the walls (W), Q_g the heat from the ground (W), and Q_e the evaporation heat from the ground (W).

The moisture balance consists of the moisture flows carried by air change and ground moisture evaporation.

$$V\frac{\partial v}{\partial t} = (x_{\mathrm{out}} - x)q_m + g - m \tag{3}$$

where V is the volume of the crawl space (m^3), v the humidity by volume (kg/m^3), x the absolute humidity in the crawl space (kg/kg), x_{out} the outdoor absolute humidity (kg/kg), q_{m} the air change rate in the crawl space (kg/s), g the net moisture flow of evaporation from the ground and base floor (kg/s), and m the effect of a possible dehumidification (kg/s).

Ground moisture evaporation depends on mass transfer on the surface and on moisture transfer in the ground; see Figure 3. Usually, the moisture flow is from the ground to the air, but in the summer, when the temperature of the crawl space air is higher than the temperature on the ground surface, the direction of the moisture flow is reversed.

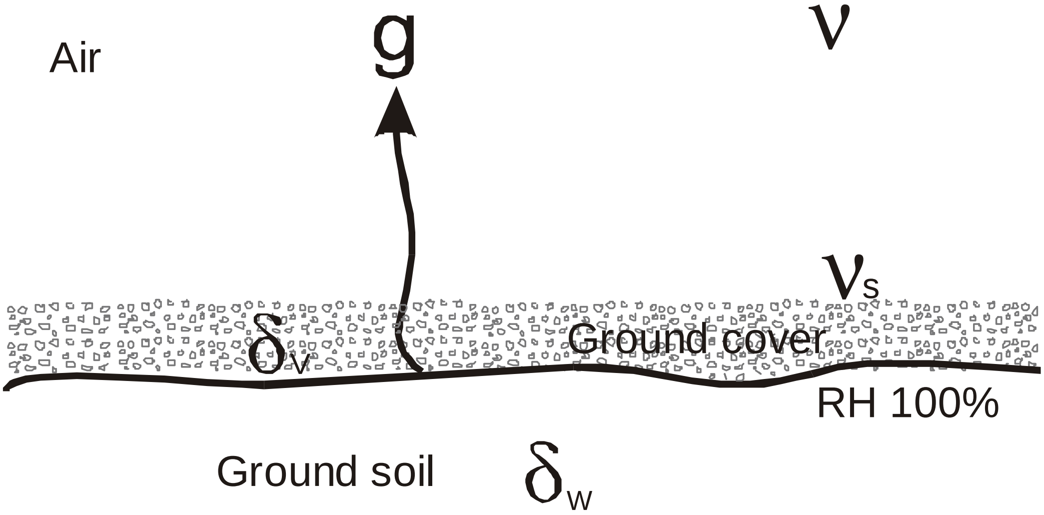


Figure 3 Moisture flow through the ground cover

For moisture transfer inside the ground soil Fick's law can be used:

$$g'' = -\delta_w \nabla w \tag{4}$$

where δ_w is the moisture transport coefficient (m^2/s), and w the moisture content in the ground soil or cover (kg/m^3). However, the ground soil under the ground cover is usually assumed to be saturated (boundary condition: 100% relative humidity below the ground cover). Thus, the moisture flow is calculated only in the ground cover.

The moisture capacity of building materials and ground covers in contact with crawl space air affects relative humidity in the crawl space in a similar way to that in which the heat capacity affects temperature. Moisture storage in summer during moist periods may decrease relative humidity in the crawl space air. In particular, wooden base floors and some ground covers, such as lightweight clay aggregate, can store and release a significant amount of moisture (Kurnistski 2000). It is possible to take the moisture transfer in all structures into account. However, the most important factors in respect of moisture transfer in a crawl space are the ground cover and base floor. The moisture flow and balance equations are the following (Kurnitski and Vuolle 2000):

$$g'' = -\delta_v \frac{\partial v}{\partial x} \tag{5}$$

$$\frac{\partial w}{\partial t} = -\frac{\partial g''}{\partial x} \tag{6}$$

where g'' is the moisture flow (kg/s m^2), δ_v the moisture permeability (m^2/s), ν the humidity by volume (kg/m^3), w the moisture content of a material (kg/m^3), and x the depth (m).

Assuming that the ground soil is saturated under the ground cover, the equation for steady state moisture from the ground cover can be written thus:

$$g = \frac{(v_g - v)}{\dfrac{d}{\delta_v} + \dfrac{1}{\beta}} A \tag{7}$$

where d is the ground soil or cover thickness (m) and δ_v the moisture permeability of the ground soil or cover, constant, (m^2/s).

Often, $\frac{1}{\beta} << \frac{d}{\delta_v}$, thus $\frac{1}{\beta}$ may be left out of consideration. As Kurnitski (2000) reports, the significance of $\frac{1}{\beta}$ with 5 cm expanded polystyrene is less than 1%.

In engineering applications the mass transfer coefficient is calculated from the convective heat transfer coefficient, although the assumption is valid only in laminar boundary conditions (Lampinen 1996). The following formula is explained through the analogy between heat and mass transfer:

$$\beta = \frac{\alpha}{\rho c_p} \cdot \frac{\rho}{\rho_{BM}} Le^{1-n} \approx \frac{\alpha}{\rho c_p} \tag{8}$$

where α is the convective heat transfer coefficient (W/m^{2}K), ρ the air density (kg/m^3), c_p the specific heat capacity of the air (J/kgK), $\frac{\rho}{\rho_{BM}}$ the logarithmic density term (-), and Le Lewis' number. This assumption is valid in crawl space conditions, where the logarithmic density term and Lewis' number are very close to 1.

When the ground soil is saturated the moisture flow from the surface to the air can be calculated as follows:

$$g = \beta(v_s - v)A \tag{9}$$

where β is the mass transfer coefficient (m/s), ν_s the saturated humidity by volume on the ground surface (kg/m^3), ν the humidity by volume in the crawl space air (kg/m^3), and A the area of evaporation (m^2).

Even if a very thin layer on the surface is not saturated the moisture flow may be calculated with sufficient accuracy by using Eq. (9). However, if the unsaturated layer has a significant moisture resistance Eq. (9) overestimates evaporation. In many previous studies (Elmroth 1975, Nieminen and Rantamäki 1991, Kurnitski et al. 1998) where evaporation from the ground surface is calculated with Eq. (9), to avoid overestimation the result is multiplied by a reduction factor. In reality the unsaturated ground surface layer varies, as does the moisture permeability of the soil, and thus Eq. (9) gives only an approximation.

2.2 Requirements for mould growth and acceptability

The most important factors causing mould growth in a crawl space are moisture, temperature, nutrients, and pH. Nutrients and pH are not normally limiting factors as the majority of building materials contain nutrition suitable for moulds; even organic dust is sufficient for mould growth. Commonly, the pH is a limiting factor for mould growth only in newly-cast concrete. A temperature range of 5–35°C (optimum 20–25°C) is suitable for many species of fungi, and the temperature in crawl spaces is nearly always within this range. This leaves the relative humidity, RH, as the critical factor for mould growth in crawl spaces.

The limit value for RH in crawl spaces is usually considered to be from 75% to 80% (Nevander 1991, Viitanen and Ritschkoff 1991, Pasanen 1992, Nevander 1994, Samuelsson 1994). Hukka and Viitanen (1999) gave a mathematical model based on experiments for critical temperature and relative humidity in terms of the initiation of mould growth; see Figure 4. Basically, the lower the temperature, the higher the relative humidity that is needed for mould growth to start. If the relative humidity is below the critical relative humidity curve (Figure 4), mould growth is radically decreased. According to the model moulds do not grow when the temperature is either below zero or above 50°C. Temperatures low or high enough prevent moulds from growing and might also kill fungi. However, some fungi can tolerate even temperatures higher than 50°C or lower than 0°C and very low levels of relative humidity (Kokko et al. 1999). Relative humidity and temperature are strongly linked to one another. The thermal mass of the structures and ground soil affects the temperature behaviour of the crawl space. When the ground is not insulated, the crawl space remains cold during the summer due to the time lag caused by the thermal mass of the massive ground.

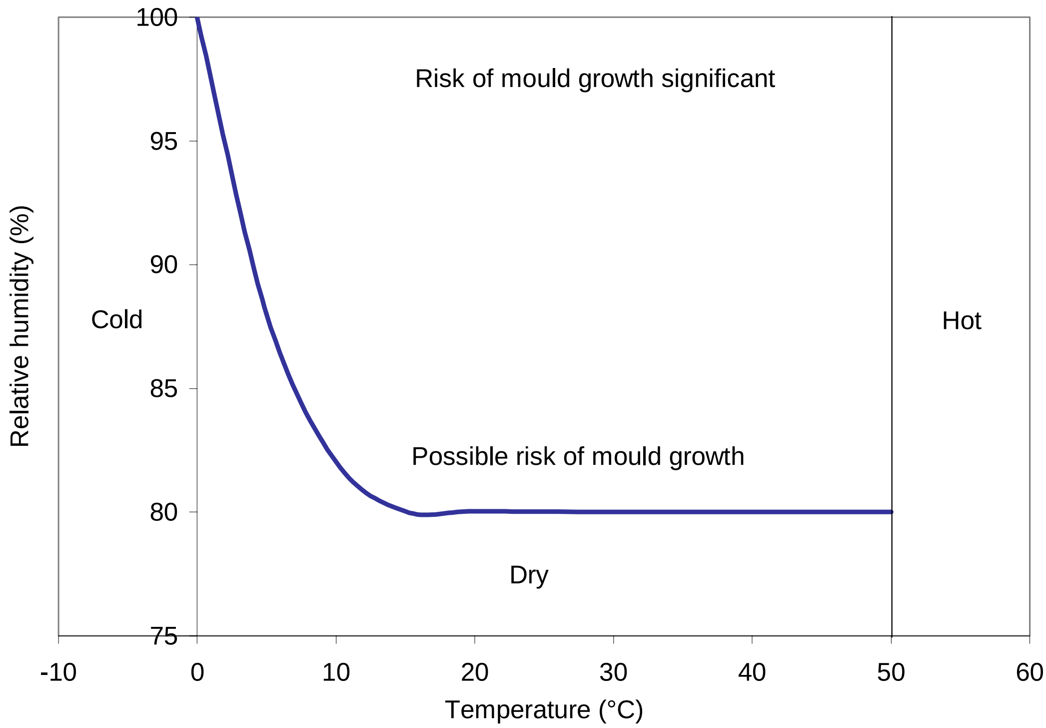


Figure 4 Conditions favourable for the initiation of mould growth on wooden material as a mathematical model (Hukka and Viitanen 1999)

In many studies (Hallenberg and Gilert 1993, Nevander and Elmarsson 1991, Svensson 2001) mould growth was estimated using a risk factor. The risk factor is a function of temperature and relative humidity and has values from 0 to 1. However, mould growth is also very dependent on time, which is not taken into account in the risk factor.

Clarke et al. (1999) estimated mould growth using six categories of mould species: highly xerophilic, xerophilic, moderately xerophilic, moderately hydrophilic, hydrophilic, and highly hydrophilic. Each category constitutes a family of mould species possessing similar growth requirements over a range of temperature and humidity conditions. For each category, growth limit curves were generated from experimental data. The third-order polynomial function curves define the minimum combination of local surface temperature and humidity for which mould growth will occur. This model, too, is unable to indicate the effects on mould growth of temperature and humidity fluctuations over prolonged periods of time.
Adan (1994) estimates mould growth by using time-of-wetness, TOW, which is defined by the ratio of the cyclic wet period and the cyclic wet-dry period. A wet period is defined as a period when relative humidity is ≥80%. Adan (1994) concludes that the growth rate increases with increasing time-of-wetness when it is above 0.167. However, Adan concludes that fungal growth remains very weak as long as TOW stays below 0.5; the growth rate increases rapidly to reach the steady state value for TOW=1.

As a criterion to estimate the acceptability of moisture conditions, an equation for mould growth given by Viitanen (1996) is used in this study. This equation estimates mould growth with the mould growth index M, which can vary between 0–6. A value of M=0 indicates no mould growth; M=1 means that some growth can be detected with a microscope, M=3 that some mould growth can be detected visually, and M=6 means very heavy and dense mould growth which covers nearly 100% of the surface. It is not completely clear which value of M is a relevant criterion. The microscopic phase, M=1, is chosen as a criterion in this study.

For varying temperature and humidity conditions Viitanen et al. (2000) give a differential equation for wood (pine and spruce)

$$\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.68 \ln T - 13.9 \ln RH + 0.14W - 0.33SQ + 66.02)} k_1 k_2 \qquad (10)$$

where M is the mould growth index (-), time t is calculated in days, T temperature (0.1-40°C), RH is the relative humidity (%), W the wood species (pine=0, spruce=1) and SQ is a factor describing the quality of the wood surface (a resawn surface after drying=0; a kiln-dried surface=1). The coefficients k_1 and k_2 are to define upper limit for mould growth index and the growth rate in favourable conditions. The mould growth index illustrates the growth rate. The growth type is defined with the coefficient k_1. During the early stages of mycelium (M<1) the coefficient k_1=1. At later stages coefficient is defined

$$k_1 = \frac{2}{t_v / t_m - 1}, \text{ when } M>1 \qquad (11)$$

where t_v is the response time for visual appearance of mould growth and t_m the response time required for initial stages of mould growth (Viitanen 1996). t_v and t_m are defined

$$t_m = \exp(-0.68 \ln T - 13.9 \cdot \ln RH + 0.14W - 0.33SQ + 66.02 \qquad (12)$$

$$t_v = \exp(-0.74 \ln T - 12.7 \cdot \ln RH + 0.14W - 0.06SQ + 61.5 \qquad (13)$$

The upper limit for mould growth when the index is approaching the level 4 to 6 or to maximum growth level is defined by the coefficient k_2

$$k_2 = \max[1 - \exp(2.3 \cdot (M + M_{\max})), 0] \qquad (14)$$

where M_{max} is the maximum value of mould growth index.

When conditions become unfavourable, the mould growth will slow down and the index M will decrease. The delay in mould growth caused by a low RH (below the critical value of RH) is given in Equation (15). The time (in days) is defined as a period from the beginning of the dry period
t-t_1.

$$\frac{dM}{dt} = \begin{cases} -0.032, \text{ when } t - t_1 \le 6\text{ h} \\ 0, \text{ when } 6\text{h} < t - t_1 \le 24\text{ h} \\ -0.016, \text{ when } t - t_1 > 24\text{ h} \end{cases} \qquad (15)$$

However, it should be noted that all the above-mentioned criteria for mould growth are valid when the durability of materials is considered. These criteria are valid in the crawl space environment, but they cannot be used when the possible health effects of fungal spores are being estimated. Since it is possible that fungal spores might be transported indoors, another criterion has to be used in the indoor environment in respect of possible health effects.

The limit value of fungal spores in indoor air is complicated due to strong variations in outdoor air. The Finnish Ministry of Social Affairs and Health (2003) give a limit value for airborne fungal spores in indoor air for urban areas in winter, 500 CFU/m^3 (colony forming units in a cubic meter air). According to this guide levels over 100 CFU/m^3 might indicated elevated concentrations of fungal spores indoors. Reponen et al. (1992) report a level >500 CFU/m^3 as being considered to be a high concentration indoors. However, Hyvärinen (2002) found out that only about 27% of possible problem buildings were above 500 CFU/m^3 and about 1% of the reference buildings were also over this limit value. Often, the level of fungal spores is considered to be elevated if the concentration is twice as high as in a reference building. The association between elevated levels of fungi and symptoms is supported by the observation that symptoms decreased after the exposure had been eliminated (Koskinen et al. 1995, Jarvis and Morey 2001). However, there are several studies in which no correlation between fungal levels and symptoms or diseases was observed (Strachan et al. 1990, Etzel et al. 1998, Garrett et al. 1998, Klánová 2000, Su et al. 2001). Additionally, in a review by Verhoeff and Burge (1997) no dose-response relationship between fungal levels and heath effects was observed or could be proposed. Hence, no straightforward guidelines on fungal levels can be set on the basis of health risks.

Hyvärinen (2002) proposed a sampling campaign of 11 days relating to the pertinent guidelines in Finland (Ministry of Social Affairs and Health 2003). First, a fungal concentration above 100 cfu/m^3 and the presence of indicator microbes (Samson et al. 1994) are alarm bells indicating a possible abnormal indoor source of fungi. The process should identify the source and control it. Second, concentrations above 500 cfu/m^3 are suggestive of an abnormal indoor source of fungi and action should be initiated to identify and control the source. Third, if neither of the above scenarios occur the sampling of indoor fungi must continue so as to take place at least six times over two months in the residence concerned. If the coefficient of variation is larger than 20%, the remaining five samples should be taken over the next two-month period in order to characterise the fungal contamination of the residence. However, even this might not be enough to achieve results. Burge et al. (2000) observed no increase in fungal levels measured with 476 samples during 14 months, even though fungal contamination was found in the air ducts of a large office building.

2.3 Transport of fungal spores

Moisture accumulation in building structures or material may lead to microbial growth on materials, subsequent microbial emissions, and other contamination of buildings. In epidemiological population studies, moisture damage and microbial growth in buildings have been associated with a number of health effects, including respiratory symptoms and diseases and other symptoms (Verhoeff and Burge 1997, Nevalainen et al. 1998, Peat et al. 1998, Hyvärinen 2002). The health effects associated with moisture damage and microbial growth seem to be consistent across different climates and geographical regions (Hunter et al. 1988, Nevalainen 1991, Li and Kuo 1994, Ellringer et al. 2000).

Microbiologically clean buildings probably do not exist, as some contamination begins as early as during the construction phase. Fungi can indeed grow on materials such as fibreglass and on galvanised steel which has an accumulated dust layer on a residue of lubricant oil (Pasanen et al. 1993, Chang et al. 1996, Buttner et al. 1999). In the case of moisture damage, even after repairs, some amount of contaminated materials can remain in building structures (Nguyen Thi et al. 2000).

Microbial contamination on the surfaces in the crawl space is typically much higher than inside the building. The level of fungal spores in the crawl space is about ten times as high as indoors. In crawl spaces, spore concentrations in a range of 10^3-10^5 colony-forming units per gram (cfu/g) of material are common. The levels have usually been highest on wood-based boards and on timber (Kurnitski and Pasanen 2000). In cases of heavy fungal colonisation, airborne spore concentrations up to 10^3-10^4 cfu/m^3 have been detected (Kurnitski and Pasanen 2000).

Residential buildings often have mechanical exhaust ventilation, where intake air comes through inlets and cracks. In cold climates, inlets will cause a draught in winter and they are often closed, resulting in a high under-pressure indoors and forced airflow through cracks. Typically, mechanical exhaust ventilation creates an under-pressure of 5-10 Pa in the apartment (Säteri et al. 1999) if the inlets are open. A field study (Kurnitski 2000) showed high air flow rates through leaks in the base floor to the apartment at a pressure difference of around 6 or 15 Pa, depending on the speed of the exhaust fan. Field measurements (Mattson 2002) have shown evidence of fungal spores transported indoors from a crawl space. According to a literature review by Hyvärinen (2002), concentrations of viable fungi in the indoor air of residential buildings vary between 10–100,000 cfu/m^3. Although the range is wide, average levels of 100–10,000 cfu/m^3 are typical. Lower levels have been reported in winter not only in a cold climate (Reponen et al. 1992) but also in a subtropical climate (Kuo and Li 1994).

Moisture and mould problems in buildings are associated with effects on the health of both adults and children occupying these buildings (Verhoeff 1997, Peat 1998). However, it is not only the moisture and microbes which cause problems, but also exposure to fine particles. According to recent studies particles smaller than 2.5 μm in diameter can reach the lower respiratory system and cause adverse health effects (Katsouyanni et al. 2000, Samet et al. 2000). However, usually the limit value for respirable particles is considered between 2.5-5 μm. Comite European de Normalisation (CEN 1992) and International Organization for Standardization (ISO 1992) both define the limit value for respirable particles 4 μm. It is still unclear what causes the health effects of such particles, but it seems that the type of particle has some role. According to studies (Laden et al. 2000, Tiittanen et al. 1999) sand dust is not so harmful as particles of the same size originating from the combustion of fuels. About 70-90% of the viable fungi in indoor air have been estimated to be in the respirable size fraction (Li and Kuo 1994, De Koster and Thorne 1995). The median aerodynamic diameter for fungi in indoor air is typically 2-3 μm (Macher et al. 1991, Reponen 1995); the highest concentrations of airborne viable fungi are also usually in the same size range.

Many studies have been carried out to estimate the penetration of particles through cracks. Vette et al. (2001) report penetration factors of 0.5-0.8 for particles in a size range of 0.5-2.5 μm. Mosley et al. (2001) found that at a pressure of 5 Pa 40% of 2-μm particles and <1% of 5-μm particles penetrate through horizontal slits of a height of 0.5 mm. In a study by Liu and Nazaroff (2001) particles of 0.1-1.0 μm are predicted to have the highest penetration efficiency, nearly unity for crack heights of 0.25 mm or larger at a pressure difference of ≥4 Pa. These results are important, since the peak of the size distribution of fungal spores is often between 2-3 μm and is very suitable for penetration. Raunemaa et al. (1989) reported that Sulfur-containing particles of sizes below 1.5 μm penetrated a office building's filter unit in ventilation channel easily, elemental removal efficiency of the filter being only 7%. Only a limited number of studies have been carried out on those structures commonly used in buildings. Liu and Nazaroff (2001) predict, by a simulation model, that penetration through mineral wool insulation is negligible. In reality structures mineral wool insulation is seldom perfectly installed, and timber frame structures are, in respect of particle transport, a combination of cracks, surface contacts, and mineral wool.

Penetration factor

The penetration factor between two chambers can be calculated with the mathematical model given by Kulmala et al. (1999).

$$V\frac{dC_1}{dt} = s_f \cdot \dot{V}_2 \cdot C_2 - \dot{V}_1 \cdot C_1 - a \cdot C_1 \cdot V + re \cdot B \cdot V + Q \quad (16)$$

where V is the volume of chamber 1 (m^3), C_1 the concentration in chamber 1 ($1/m^3$), t time (s), s_f the penetration factor from chamber 2 to chamber 1 (-), $\dot{V}_2$ the air flow from chamber 2 to chamber 1 (m^3/s), $\dot{V}_1$ the air flow outdoors from chamber 1 (m^3/s), C_2 the concentration in chamber 2 ($1/m^3$), a the deposition rate (1/s), re the re-emission rate (1/m,s), B particle surface accumulation on indoor surfaces ($1/m^2$), and Q the sink or source indoors (1/s). The deposition rate was calculated from

$$a = v_d \cdot \frac{A}{V} \quad (17)$$

where v_d is the deposition velocity (m/s) and A the total indoor surface area, including furniture etc. (m^2). Particle surface accumulation on indoor surfaces was calculated from

$$\frac{dB}{dt} = (a \cdot I - re \cdot B) \cdot \frac{V}{A} \quad (18)$$

In recent studies of buildings or room-sized chambers, the reported deposition velocities had a wide range (Lai 2002). Thus, there is considerable uncertainty as to the typical values of deposition velocities for buildings. Figure 5 shows the results of some of the recent studies. Since most of the studies referred to reported deposition loss time, but only Fogh et al. (1997) reported deposition velocity, the results in Figure 5 were transformed to average deposition velocity. The results from Nomura et al. (1997), Cheng et al. (1997), and Vette et al. (2001) are clearly higher than the others. In the studies performed by Cheng et al. (1997) and Nomura et al. (1997) the chambers were smaller than room size. In Vette et al. (2001) the particle deposition loss time of a single detached residential building was measured and the measured results were clearly higher, at particle sizes >0.6 μm, than those calculated with a model, suggesting an additional indoor loss mechanism. The average deposition velocity curve provided by Fisk et al. (2002) in Figure 5 was adapted from results reported in Xu et al. (1994) and Thatcher et al. (2002), and is extrapolated with the theoretical predictions of Lai and Nazaroff (2000).

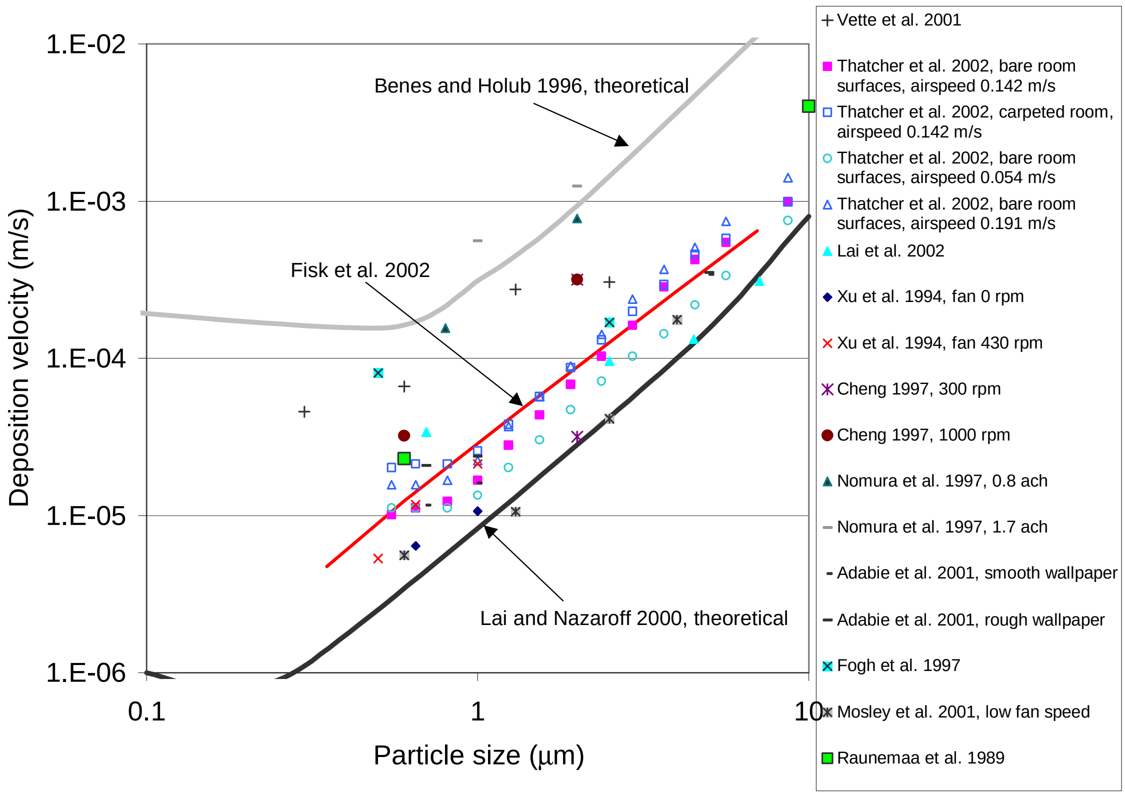


Figure 5 Average deposition velocities measured in some studies.

3. OBJECTIVES OF THE STUDY

The main objective of the study was to determine the moisture performance of the structural, heating, and ventilation solutions studied in order to control moisture conditions in a crawl space and, for that purpose, to estimate the acceptability of current moisture conditions in respect of the durability of materials and mould growth on surfaces. In order to prevent the transport indoors of possible pollutants from crawl spaces, data relating to microbiological conditions in crawl spaces were collected.
The specific objectives of this study were:

1 to study the effect of types of ground cover on the acceptability of moisture conditions, and the optimal combinations of ground covers and ventilation rates in a relatively cold (wooden) and warm (concrete, apartment) crawl space (I, II);

2 to determine the effect of extra insulation in crawl space foundations and the base floor, as well as very thick ground covers, on hygrothermal conditions and mould growth (III);

3 to consider the effectiveness and energy performance of heating in a crawl space (IV);

4 to show a possible correlation between indoor and crawl space microbes (V), and

5 to study how an under-pressure indoors affects the transport of particles and microbes from a crawl space, and to study how the airtightness of the structure and particle size affect the transport indoors of particles from a crawl space (VI).

The thesis consists of six papers. In (I) the effects of air change and ground covers were studied by means of long-term field measurements. That was necessary because of the high heat capacity of the ground (and foundations), which leads to continuously unsteady conditions in crawl spaces. The results of the field measurements were used for the identification of the required parameters and for the validation of modelling in a dynamic simulation environment.

In (II) the effects of moisture capacity and other properties of ground cover types and the base floor on the relative humidity in a crawl space were studied. The accuracy of the dynamic simulation model was improved by moisture transfer inside the ground cover and base floor. By using parametric simulations it was shown how relative humidity can be reduced by the optimal selection of ground covers and air change rates. The acceptability of the moisture conditions achieved was evaluated by carrying out mould growth analyses. The first building studied was a typical apartment building with a relatively warm crawl space (a high base floor U value); the second building was a wooden day care centre with a highly insulated base floor and a relatively cold crawl space.

(III) focuses on whether the high air change rates which are normally needed to warm up the crawl space in the summer can be compensated for with a thicker layer of thermal insulation, i.e. by reducing the time lag, which may possibly provide a similar effect to that obtained with a higher air change rate.

In (IV) the objective was to determine the effect of heating on moisture conditions in an outdoor air-ventilated crawl space. The principle of this solution is that air exchange with outdoor air removes moisture from the crawl space and heating is used to control the relative humidity in the crawl space. The heater is controlled by the relative humidity of the crawl space air. The crawl spaces studied have either moisture or thermal insulation in the ground. Since wooden material promotes far more favourable conditions for mould growth, the base floors of the buildings studied are wooden. First, the heat output was set to be constant and the effect of air change was studied. Second, the study focused on the heating control strategy and how it affects energy consumption and relative humidity in the crawl space.

In (V) eight buildings with a crawl space were studied in order to ascertain whether there is a relationship between the concentration of fungal spores indoors and in crawl spaces and whether microbes are transported indoors from crawl spaces. Samples of fungal spores were collected indoors, outdoors, and from crawl spaces. The samples were taken both in the spring and wintertime.

In (VI) a laboratory setup with a common building structure with a high concentration of particles on one side was used to study the penetration of inert particles and fungal spores. Particle type, air leakage, and pressure difference were varied. *Penicillium* and *Cladosporium* were selected to represent fungal contamination in the study.

4. METHODS

4.1 The crawl spaces studied

The crawl spaces studied were chosen to represent typical outdoor air-ventilated crawl spaces used in Finland. Detached houses and smaller houses often have timber frames. Their base floor is wooden, with thick insulation in the base floor. The crawl spaces in these buildings are often relatively cold due to the low U value of the base floor, about 0.2 W/m^{2}K; see Figure 6 (left). Apartment buildings and industrial buildings are often built from sandwich elements, and the base floor is typically made of hollow core slabs (base floor U value 0.4 W/m^{2}K). The foundations of these buildings are on piles due to clay ground soil; see Figure 6 (right).

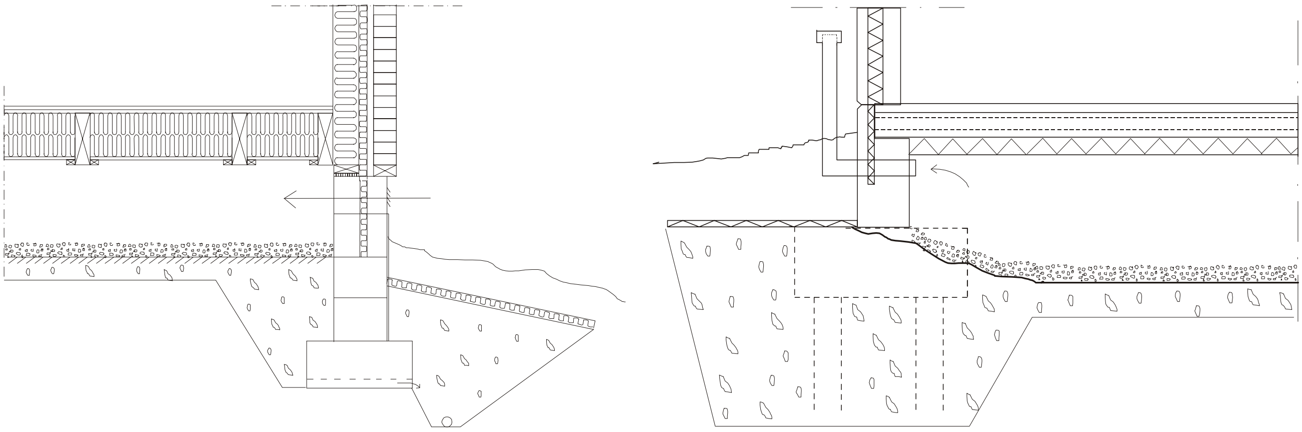


Figure 6 A wooden (left) and a concrete (right) crawl space

The crawl spaces and ground covers studied are shown in Table 1. In (III) the placement of the insulation of the base floor and foundations was also varied in the building with a concrete base floor. Here a crawl space with a base floor U value of 0.2 W/m^{2}K is referred to as a cold crawl space and a crawl space with a base floor U value of 0.4 W/m^{2}K a warm crawl space.

Table 1 Crawl spaces studied in (I-IV)

Paper	Base floor U value [W/m^{2}K]	Base floor area [m^2]	Base floor type	Ground covers used
I	0.4	95	concrete	Uncovered, PVC, [1]EPS
II	0.4 0.2	95 470	concrete wooden	Uncovered, PVC, EPS, [2]LWA
III	0.4/0.2 0.2	470/100 470	concrete wooden	PVC, EPS, LWA
IV	0.2 0.2	470 117	wooden wooden	PVC, EPS, LWA, [3]CS

[1]EPS expanded polystyrene
[2]LWA lightweight clay aggregate
[3]CS crushed stone

In (I) and (II) the ventilation rate of the crawl spaces was varied. In (II) also the thickness of the LWA (lightweight clay aggregate) ground cover was varied, and in the case of cold crawl space the ventilation rate had two-step being higher in the summer and 0.5 ach during the heating season (October 1st–April 30th).

In (II) in Table 1 that gives the material properties of the studied case, one important material is missing. The material properties of the 13 mm fibre board in contact with crawl space air in the wooden base floor are: thermal conductivity 0,05 W/mK, specific heat capacity 1350 J/kgK, volume weight 285 kg/m^3, moisture permeability 4×10^{-6} m^2/s, 1st point of sorption isotherm 40 kg/m^3 and 80% RH, 2nd point of sorption isotherm 95 kg/m^3 and 100% RH.

In (III) the effect of insulating foundations, base floor, and ground soil was studied. The effect of the placement of the base floor insulation (on or under the base floor slab) was calculated. The foundation was insulated in two ways: 1) 5 cm of insulation in the foundation, 2) 5 cm of insulation in the foundation with an extra 10 cm of insulation on the crawl space side of the foundation. Frost insulation in the ground was used in every case. The simulations were carried out for four insulation layer thicknesses, both for EPS (expanded polystyrene) and LWA ground covers. The air change rate was varied from 0.5 ach to 5 ach. During the heating season (October 1st–April 30th) a low air change rate of 0.5 ach was used.

The effects of summer heating in an outdoor air-ventilated crawl space with different ground covers and air change rates were simulated in (IV). The heat output used varied between 2.5–10 W/m^2 of base floor. The aim was to find out whether heating is a feasible alternative for crawl space moisture control with reasonably low energy consumption. Additionally, the effect of control strategy on energy consumption was considered.

In (V) concentrations of fungal spores in eight buildings in Southern Finland were measured. Three of the buildings were primary schools, two day care centres, and three dwellings; see Table 2. Half of the buildings had a wooden base floor. The dwellings had mechanical exhaust ventilation. Both of the day care centres had mechanical exhaust ventilation in the crawl space, but all the other crawl spaces had natural ventilation, except for two crawl spaces which had no ventilation. Buildings 2 and 6 were divided into two parts, *a* and *b*, as the crawl spaces of the buildings were in two separate sections.

Table 2 Buildings studied in (V)

	Building type	Base floor	Base floor area (m^2)	Ventilation system in the building	Ventilation system in the crawl space
Building 1	Apartment building	Wooden		Mechanical exhaust	Natural ventilation
Building 2a	Apartment building	Concrete slab	82	Mechanical exhaust	Mechanical exhaust
Building 2b	Apartment building	Concrete slab	127	Mechanical exhaust	Natural ventilation
Building 3	Apartment building	Wooden	200	Mechanical exhaust	Natural ventilation
Building 4	Primary school	Concrete slab	650	Mechanical supply and exhaust	Natural ventilation
Building 5	Primary school	Concrete slab	350	Mechanical supply and exhaust	No ventilation
Building 6a	Day care centre	Wooden	210	Mechanical supply and exhaust	Mechanical exhaust
Building 6b	Day care centre	Wooden	285	Mechanical supply and exhaust	Mechanical exhaust
Building 7	Day care centre	Wooden	820	Mechanical supply and exhaust	Mechanical exhaust
Building 8	Primary school	Concrete slab	550	Mechanical supply and exhaust	No ventilation

4.2 Dynamic IDA simulation environment

In (I) the results of field measurements by Kurnitski (2000) were used to validate the modelled crawl space in the IDA simulation environment. The crawl space modelled in (I) was concrete, while in (II, III, and IV) a wooden crawl space was also modelled. The crawl spaces were modelled in the IDA simulation environment. IDA is a modular simulation environment which consists of a translator, solver, and modeller. The solver and physical models are separated, which makes it possible to change the mathematical formula of any component without changing the model description file. The modules are written in Neural Model Format (NMF), which serves at the same time as a readable document and a computer code. Via the translator, the modules can be used in several modular simulation environments (Sahlin 1996, Sahlin and Bring 1989, 1991).

The model uses Equation (1) for the energy balance of the crawl space air. In the RC (resistance capacity) network of heat transfer model the main simplification is to model the heat transfer of the ground soil by a semicircular flow pattern; see Figure 7.

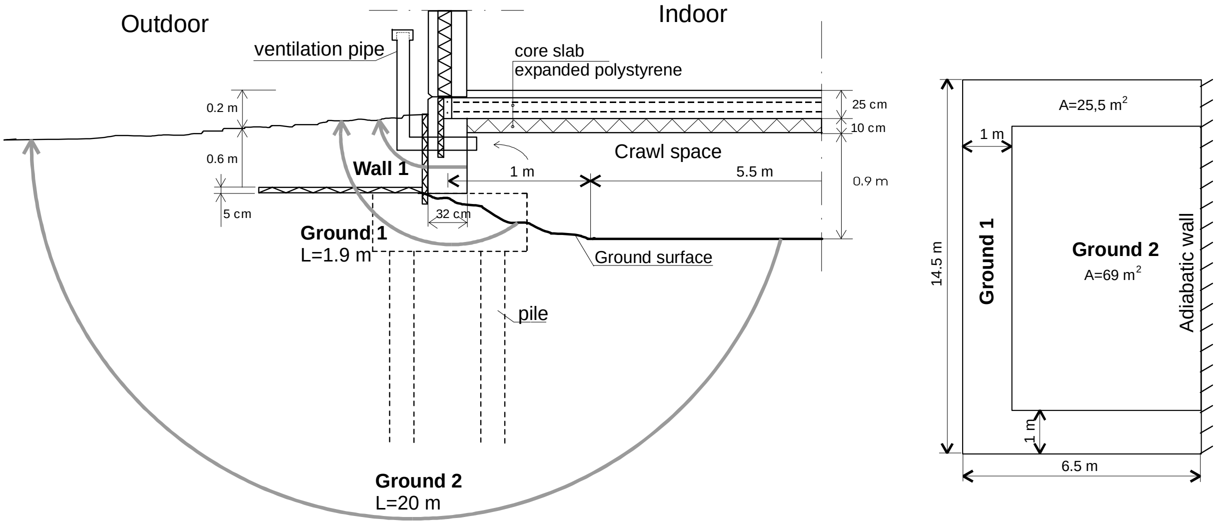


Figure 7 Heat flow patterns, Ground 1, Ground 2, and Wall 1 in the modelled crawl spaces.

In (I) a warm crawl space was considered. Ground moisture evaporation from the uncovered ground surface was calculated as mass transfer from the surface. Moisture transfer in the base floor and ground cover is applied in (II, III, and IV) by using the HAMWall model. The model uses Equations (2) and (5-6). The moisture permeability in Equation (7) is a function of relative humidity. Sorption isotherms can be given by a linear fit (in two parts) or by logarithmic equation. A detailed description of the HAMWall model is given in Kurnitski and Vuolle (2000).

In (II) the calculations were carried out with three different assumptions of the moisture transfer model. In the first version, no moisture capacities were taken into account. Here, the balance equation (3) and the evaporation equation (9) were used. In the second version, the moisture capacity of the ground cover and, in the third, the moisture capacities of the ground cover and base floor were taken into account. The moisture capacity of the foundations was not taken into account since they are of concrete, which has a low moisture capacity. Furthermore, the area of the foundations is relatively small compared to the area of the base floor. The moisture capacity of the ground soil was not considered because the constant value of an RH of 100% was used below the ground cover.

Parameter identification in (II) was carried out for the thermal conductivity and capacity of the ground soil and for the U value of the base floor. The last-mentioned was necessary because of a cold bridge in the joint of the base floor and the foundation beam. The other material properties used were obtained from the manufacturers of the materials used. The properties used for ground soil (shown in II) are typical in Finland. The data measured during the six-month period from the beginning of the measurement period were used for the parameter identification. The measured outdoor temperature and RH were used as boundary conditions for the model. Approximate values for air change rate were used in both buildings. In the cold crawl space of the wooden building the measured air flow of the crawl space exhaust fan was used. In the warm crawl space of the apartment building, the average air change rate of a three-month measurement period with natural ventilation was used. The final values of ground thermal conductivity and volume weight were identified by using the measured data from the test building. The parameters used in the calculations are shown in II.

In (I) the effects of ventilation and ground cover were studied, but neither the ground cover nor the base floor had a moisture capacity. In (II and III) the moisture capacity (HAMWall model) was applied to the ground cover and base floor. In (III) the effect of the thickness of the insulation was also studied. In (IV) the effect of a heating device in the crawl space was calculated.

As a criterion to estimate the acceptability of the moisture conditions, an equation for mould growth, given in Viitanen (1996) and Viitanen et al. (2000), was used in (II, III, and IV). The microscopic phase of mould growth, M=1, is chosen as a criterion in this study. In this study the critical value for RH is considered to be 70%, 75%, or 80% and thus, Equation (10) should be used when RH<70%, 75%, or 80%.

4.3 Sampling and analysis of fungal spores in field measurements

In (V) the concentrations of airborne fungal spores and bacteria were measured in eight buildings in Southern Finland (Helsinki region). The buildings were chosen to represent typical buildings with crawl space foundations. Some of the crawl spaces were suspected of causing indoor air quality problems. Three of the buildings were primary schools, two day care centres, and three dwellings. Half of the buildings had a wooden base floor. The dwellings had mechanical exhaust ventilation. Both of the day care centres had mechanical exhaust ventilation in the crawl space, but all the other crawl spaces had natural ventilation except for two crawl spaces without any ventilation.

Airborne fungal spores were sampled by using six-stage cascade Andersen impactors (Andersen 1958). Samples were taken from indoor, outdoor, and crawl space air. Sets of samples were taken in the winter and others in the late spring. The fungal spores were collected on 2% malt extract agar (MEA). To avoid contamination due to spore transportation on clothes, the indoor successive samples (2 samples) were taken first. Two successive samples were also taken from the crawl space, but if the crawl space had clearly different sections, such as different ground cover materials, two samples were taken from each section. According to previous studies, e.g. Reponen (1994), fungal spore concentrations are low during winter. During the winter sampling, the temperature was below 0°C, and, therefore, outdoor samples were not taken. In the summer, one sample from outdoor air was taken on each study site. The sampling time was 10 min indoors and outdoors and 5 min in the crawl space, and thus the computational limit of identification was 7 CFU/m^3 and 3.5 CFU/m^3. The incubation time of the samples was seven days (14 days for the actinomycetes) at 25°C.

4.4 Penetration of inert particles and fungal spores

(VI) focuses on the transport of inert particles and fungal spores indoors through the structure of a building. To measure the particle penetration a full-scale floor structure was built in the laboratory. The base floor was located between two chambers; CH1 corresponds to indoors and CH2 to the crawl space, as shown in Figure 8. As gravitational force is of minor importance for small particles, the floor was rotated through 90° for practical reasons. The air was exhausted only from CH1, forcing a flow through the base floor. To control the pressure difference between the chambers the supply airflow rate to CH1 was controlled. The supply of air to CH2 was filtered using a HEPA (high efficiency particulate air) filter, and it flowed through a diffuser to ensure that the supply of air was fully mixed in CH2. To ensure that the particles were fully mixed in the air of CH2, the concentration of particles was measured at three different heights (70 cm, 110 cm, and 190 cm from the bottom of CH2). The airflow to CH2 was measured using air velocity measurements and the exhaust from CH1 was measured with an air duct measuring ring. The supply to CH1, which was mainly zero, was measured with the measuring ring. The pressure difference between CH1 and the laboratory hall and between CH2 and the laboratory hall was continuously measured at 60-second intervals by differential pressure transmitters, Furness Controls FCO 44 ± 50 Pa, and the pressure differences between the chambers were calculated from the measured results.

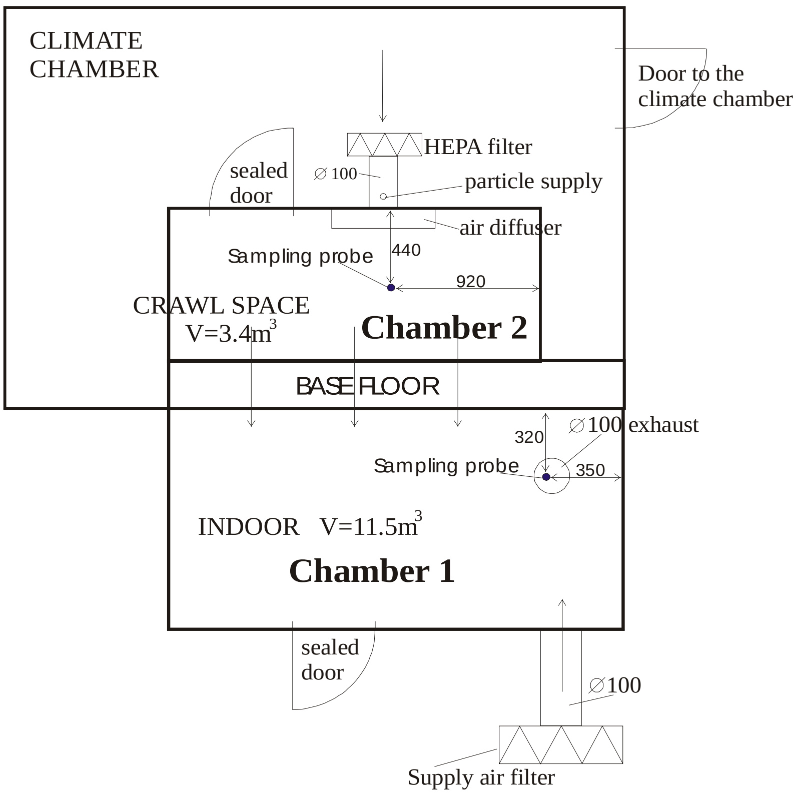


Figure 8 Chambers 1 and 2 and the placements of sampling probes.

Four different variations of a wooden floor structure were studied. The floor had 20 cm mineral wool insulation (stone wool with a volume weight of 30 kg/m^3), 22 mm chipboard on the indoor chamber side, and 13 mm porous fibreboard on the CH2 side; see Figure 9. The joints between the boards were installed so as to be as tight as possible, and the joints between the wooden base floor and the chamber walls were well sealed. Air leakage through the wooden floor was measured according to EN 13829 (2000) at an under-pressure of 50 Pa. The measured air leakage values varied with different penetrations, as shown in Table 8. The airtightness of the wooden floor changed with different penetrations.

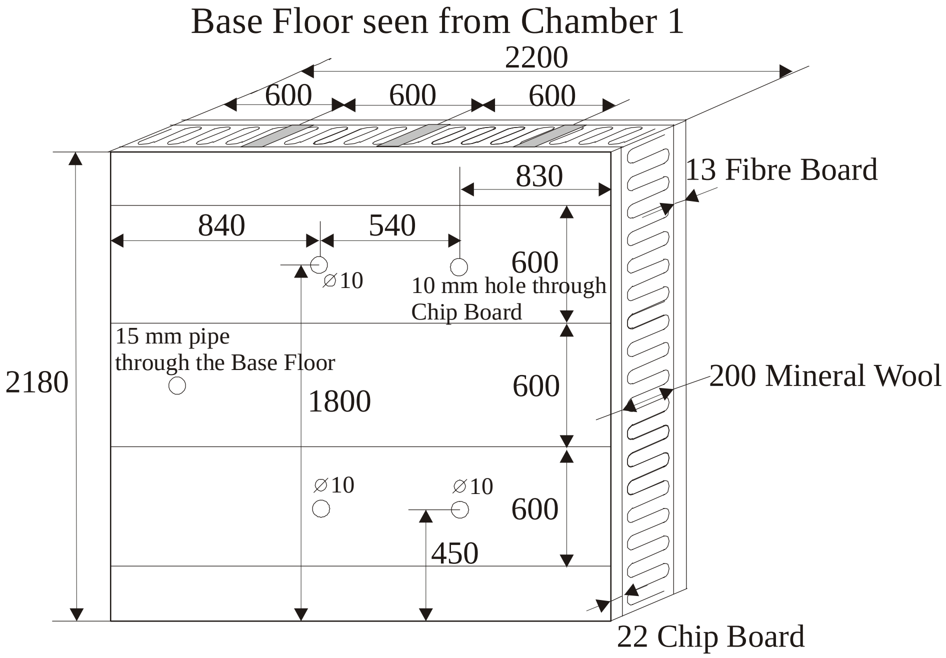


Figure 9 The construction of the floor (dimensions in mm)

Inert particles

In the laboratory measurements six different sizes (0.6 µm, 1.3 µm, 2.5 µm, 4 µm, 7 µm, and 15 µm) of inert monodisperse latex (polystyrene) particles were generated in CH2. The particle supply flow to the supply air channel of CH2 was 3 L/min. The pressure difference between the chambers was either around 6 Pa or 20 Pa. The concentration of particles was measured continuously, using an optical particle counter in both chambers. The size ranges of the optical particle counter were 0.3-0.5, 0.5-1.0, 1-5, 5-10, 10-25, and ≥25 µm. A detailed description of the measurement is given in (VI).

The penetration factor was calculated from Equation (16). Since the measurements were taken in the test chambers, the re-emission was assumed to be zero.

In this study the deposition velocity used was adapted from results reported in Xu et al. (1994) and Thatcher et al. (2002), and was extrapolated with the theoretical predictions of Lai and Nazaroff (2000). The same deposition velocity is also used in Fisk et al. (2002). The deposition velocity, Equation (19), used here is based on a combination of measured data from full-size rooms and extrapolations consistent with theoretical predictions, and it is valid for particle diameters between 0.3–8 µm; see Figure 5

$$v_d = 3 \cdot 10^{-5} \cdot \left(d_p \cdot 10^6\right)^{1.58} - 1 \cdot 10^{-6} \qquad (19)$$

where d_p is the diameter of the particle (µm).

Since the penetration factor is strongly dependent on deposition velocities the factors were also calculated for the highest and lowest measured values presented in recent studies; see Table 3. Since most of the studies referred to reported deposition loss time, but only Fogh et al. (1997) reported deposition velocity, the results in Table 3 and

Figure 5 were transformed to average deposition velocity. If the measured particle size in other studies was different than the size used in this study, the deposition velocities were extrapolated to the particle size used in this study. The results from Nomura et al. (1997), Cheng et al. (1997), and Vette et al. (2001) are clearly higher than the others. In the studies of Cheng et al. (1997) and Nomura et al. (1997), the chambers were smaller than room size, and thus they were excluded. In Vette et al. (2001), a single detached residence was measured and the measured results were clearly higher, at particle sizes >0.6 µm, than those calculated with the model, suggesting an additional indoor loss mechanism. This study was also excluded, as it most probably overestimates the deposition velocity in laboratory conditions.

Table 3 The highest and lowest average deposition velocities used in calculations.

Particle size (µm)	**Lowest deposition velocity (m/s)**	**Highest deposition velocity (m/s)**
0.6	5.6 E-6 [1]	3.2 E-5 [3]
1.3	1.1 E-5 [1]	5.5 E-5 [2]
2.5	4.1 E-5 [1]	1.7 E-4 [4]
4.0	4.8 E-5 [2]	3.4 E-4 [5]

[1] Mosley et al. 2001
[2] Lai et al. 2002
[3] Cheng 1997
[4] Fogh et al. 1997
[5] Thatcher et al. 2002

Penicillium* and *Cladosporium

Spores of *Penicilium crustosum* and *Cladosporium spaerospermum* were supplied to CH2 by using circulating air; thus the supply did not affect the air change rate in CH2. The fungi grew on malt extract agar moulded into a half-circle inside a glass tube (Ø 35 mm). The fungal spores were released from the glass tube at an air speed of 7 m/s. A thin plastic string was used to facilitate the release of the fungal spores from the glass tube. The pressure differences between the chambers were 6 Pa and 18 Pa. The concentrations of airborne fungal spores were measured in both chambers using six-stage cascade Andersen impactors, and three samples were taken from both chambers. The fungal spores were collected on 2% malt extract agar (MEA). The incubation time of the samples was five to seven days at 25°C. The number of colonies counted was corrected according to Andersen (1958). The concentration of particles was also measured continuously, using an optical particle counter (Climet LI 500) in both chambers. The sampling time for the optical particle counter was one minute.

The penetration factor s_f, for inert particles was calculated from Eq. (16). For *Penicillium* and *Cladosporium* it was not possible to achieve steady state concentrations with the equipment used for the generation of the spores and, therefore, the penetration factor was estimated as a percentage of the particles that penetrated through the structure.

$$s_{f,\%} = \frac{C_1}{C_2} \cdot 100 \qquad (20)$$

5. RESULTS

How to prevent relative humidity in a crawl space increasing during summer is studied in the following sections . First, in Section 4.1, the effect of moisture capacity on modelling results is considered. Optimal selections of ground covers and ventilation rates, as well as the acceptability of moisture conditions, are shown in Section 4.2. The effects of heating in the summer and the use of energy are studied in Section 4.3. In Section 4.4 the penetration indoors of fungal spores and particles from crawl spaces is studied both with field and laboratory measurements.

5.1 Validation of the simulation model

In (I) good results were achieved in a warm crawl space when the ground moisture evaporation from the uncovered ground surface was calculated as mass transfer from the surface.

In (II) in the cold crawl space, the calculated temperature was slightly lower when the capacities were not taken into account, and in the warm crawl space moisture capacity had no effect (not shown in Figure 10). In the winter, during the two last weeks of February, the outdoor air sensors were covered with snow, which explains some disagreement between the calculated and measured temperatures during this period (calculated T and RH are somewhat higher).

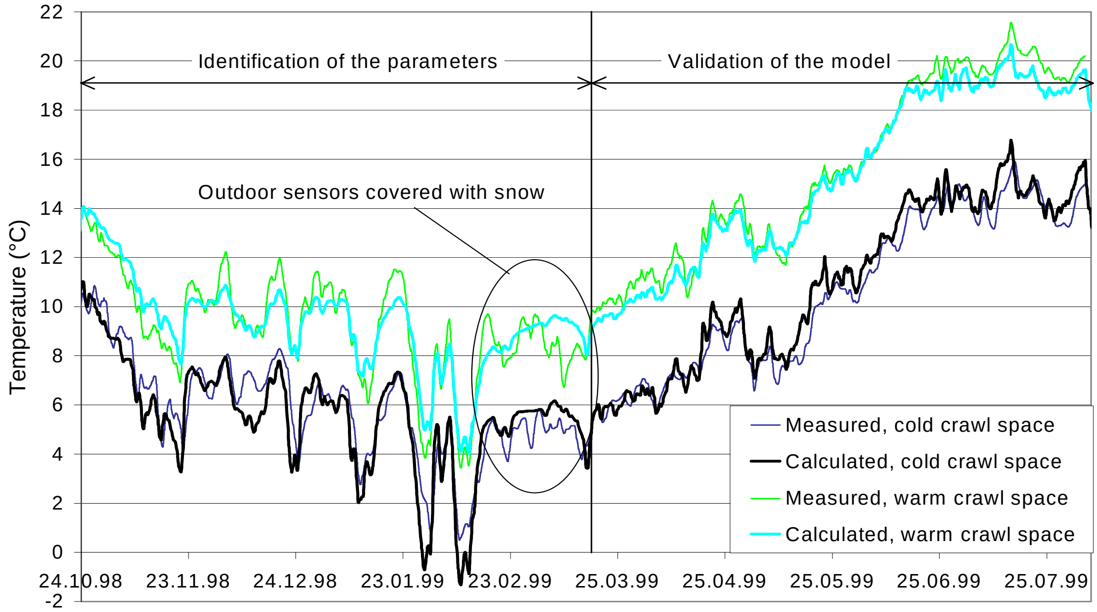


Figure 10 Calculated and measured temperatures in the crawl spaces. The air change rate in both calculations is 1.1 ach (24-hour moving averages). Ground cover in both crawl spaces was lightweight clay aggregate (15 cm in the cold and 17 cm in the warm crawl space)

The relative humidity in the cold and warm crawl spaces is shown in Figure 11 and in Figure 12. In the warm crawl space, the expanded polystyrene insulation in the base floor did not affect the RH, but lightweight clay aggregate ground cover slightly reduced RH fluctuations. The effect of moisture capacity in the cold crawl space with a wooden base floor was remarkable. The RH calculated with the first version (no moisture capacity) fluctuated far too much. In the winter, the calculated RH was too low, and in the summer condensation occurred. Both LWA and the base floor affected the RH, and the most accurate result was obtained with the third version (both moisture capacities taken into account). Similarly, moisture capacity had an effect on the mould growth index. In fact, the influence was much stronger than would have been expected on the basis of the RH results as shown in Figure 15. Neglecting the moisture capacity evidently leads to an overestimation of the risk of mould growth.

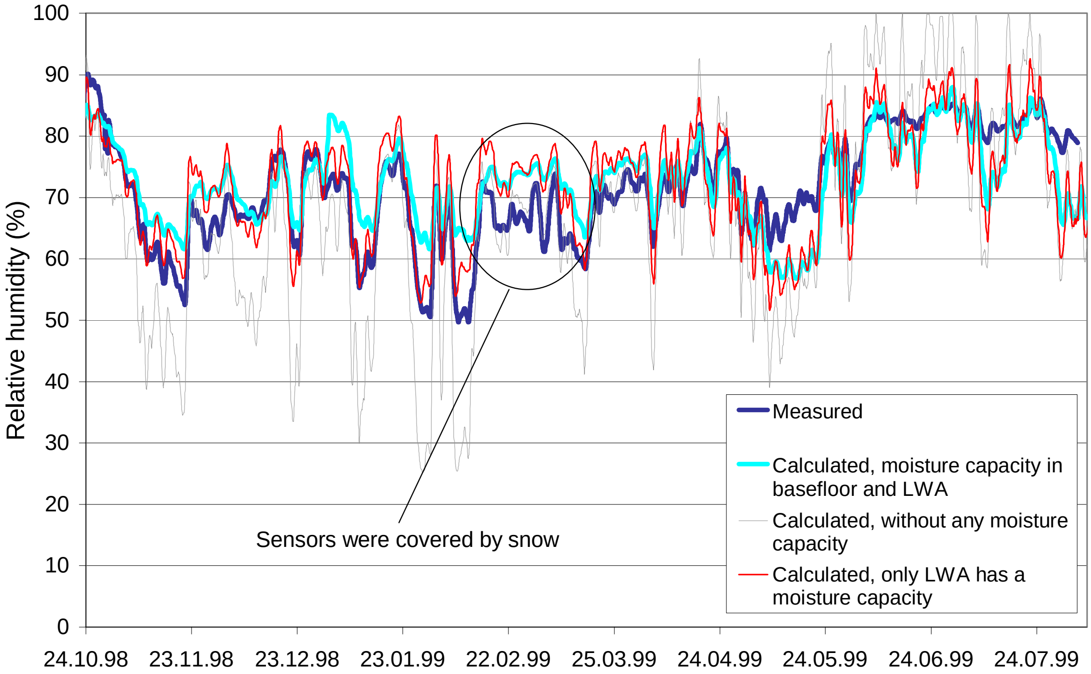


Figure 11 Calculated and measured relative humidity in the cold crawl space, 1.1 ach (24-hour moving averages)

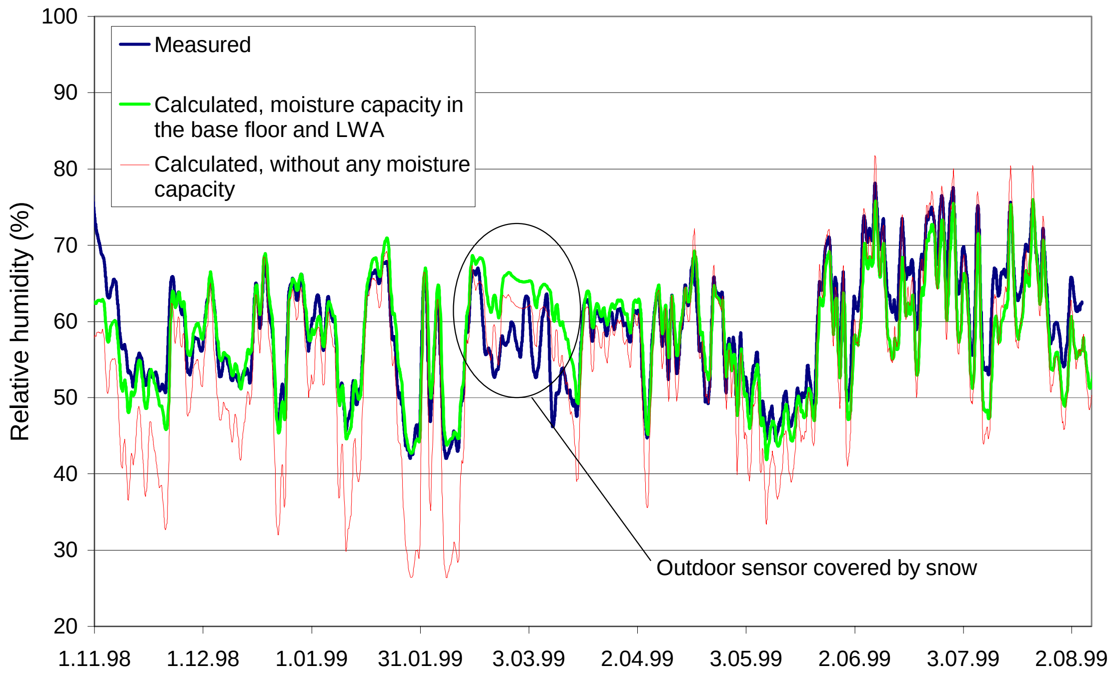


Figure 12 Calculated and measured relative humidity in the warm crawl space, 1.1 ach (24-hour moving averages)

The absolute value of the difference between the measured and calculated values (absolute difference) in both crawl spaces is highest in the case when the moisture capacity is not taken into account; see Figure 13 and Figure 14. In the case when moisture capacity in the base floor and LWA ground cover are taken into account the absolute difference of RH is small, mostly under 5% in both cases during the three-month period shown in Figure 13 and Figure 14. In (II) Figure 7, showing an absolute difference in relative humidity in the cold crawl space, is incorrect due to an incorrect time step.

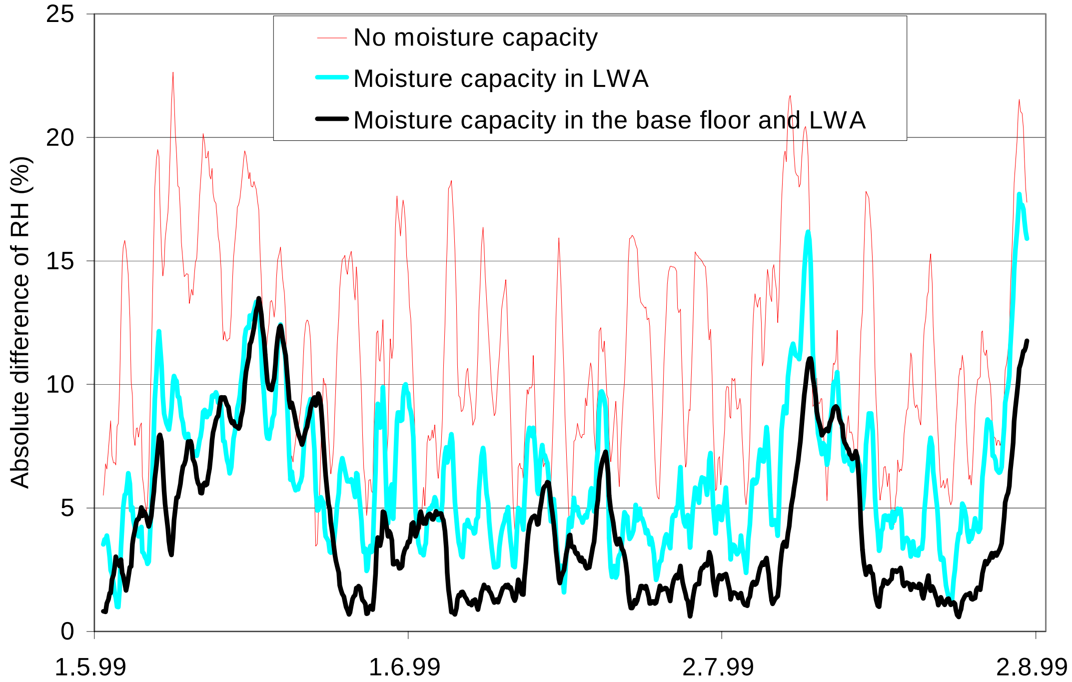


Figure 13 Absolute difference of RH between measured and calculated values in the cold crawl space, 24-hour moving averages

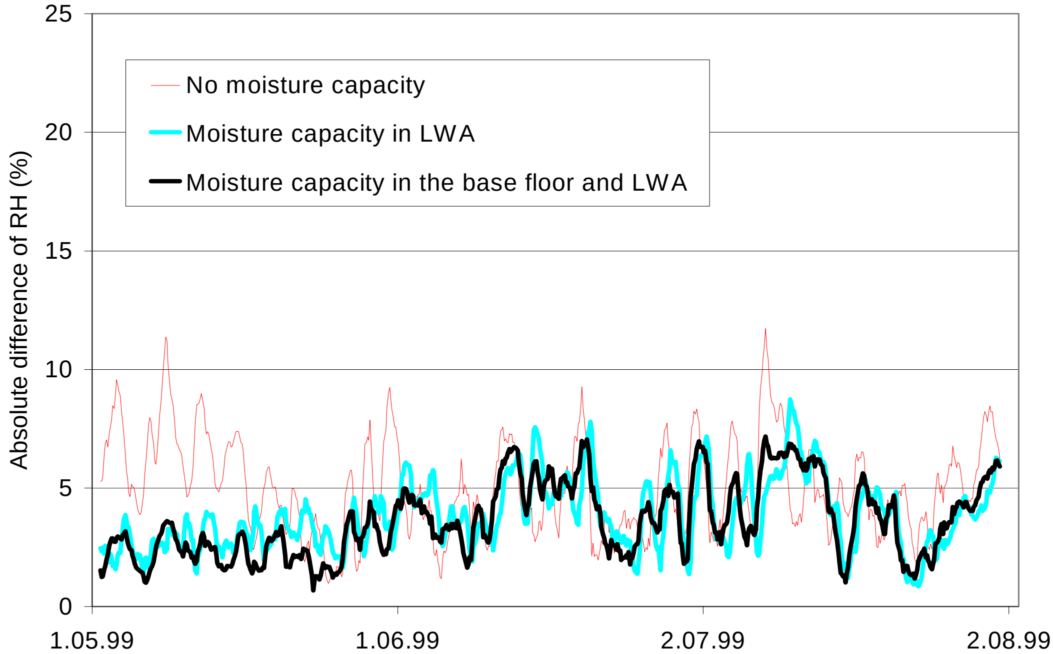


Figure 14 Absolute difference of RH between measured and calculated values in the warm crawl space, 24-hour moving averages.

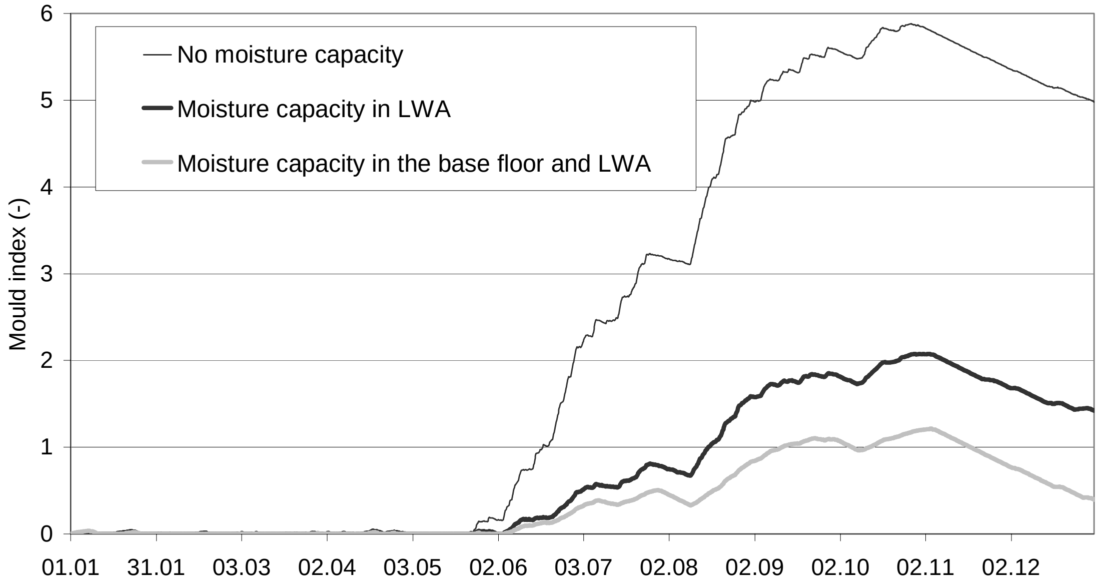


Figure 15 Mould index with 15 cm LWA cover calculated with and without moisture capacity in the cold crawl space, 1 ach, RH_{cr}=75%

It was possible to predict the RH inside the LWA layer with the third version (when moisture transfer in the ground cover and in the base floor was taken into account); see Figure 16. Some disagreement between the calculated and measured relative humidity can be explained by the simplified heat conduction calculation in the ground soil.

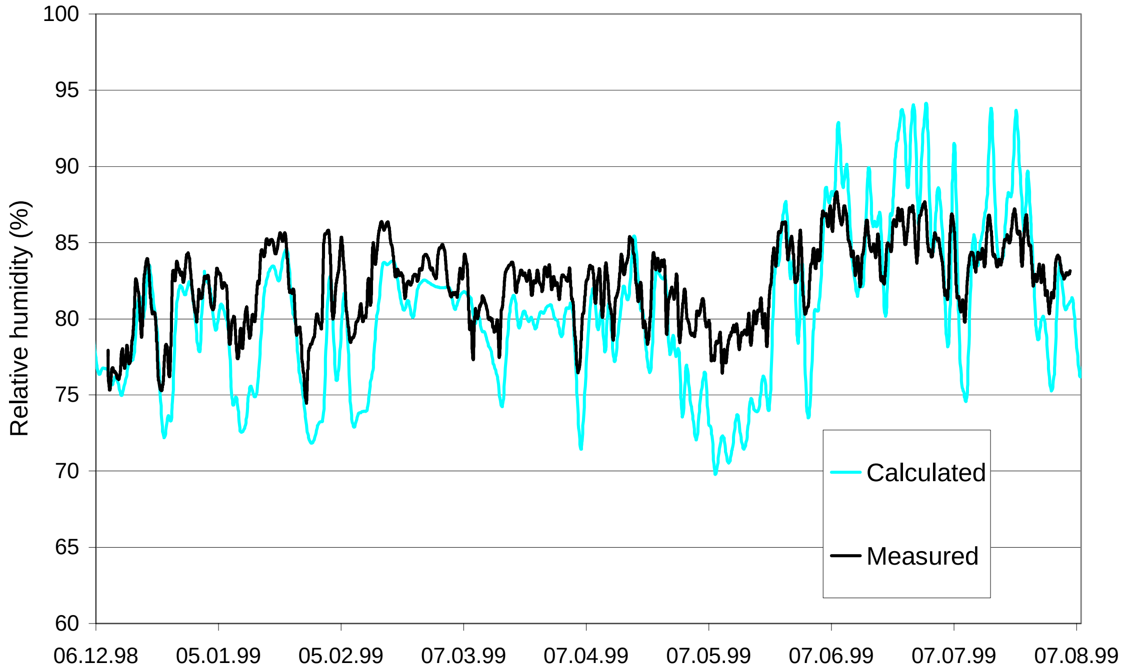


Figure 16 Measured and calculated relative humidity in the middle of the lightweight clay aggregates layer in the cold crawl space.

5.2 The effect of air change rate and ground covers on moisture conditions

Air change rate and ground covers have a different impact on moisture conditions, depending on the temperature conditions in the crawl space. A relatively warm crawl space is less sensitive to the air change rate and type of ground cover than a colder crawl space. In the following section the effect of air change rate, as well as different ground covers and their thicknesses, on crawl space temperature and relative humidity is studied. Additionally, the moisture content and moisture flow from different ground covers with different ventilation rates are calculated. The acceptability of moisture conditions in the crawl space is estimated by calculating the mould index, Eq. (10).

5.2.1 A warm crawl space with uncovered ground

The air change rate in a crawl space affects both thermal and moisture behaviour, but the change in relative humidity in a crawl space is not a straightforward sum of these. Due to thermal behaviour the optimum air change rate is different in the summer and winter. In (I) a relatively warm crawl space was studied, and, as can be seen from Figure 17, the lowest air change rate results in the warmest and thus driest crawl space in the heating season.

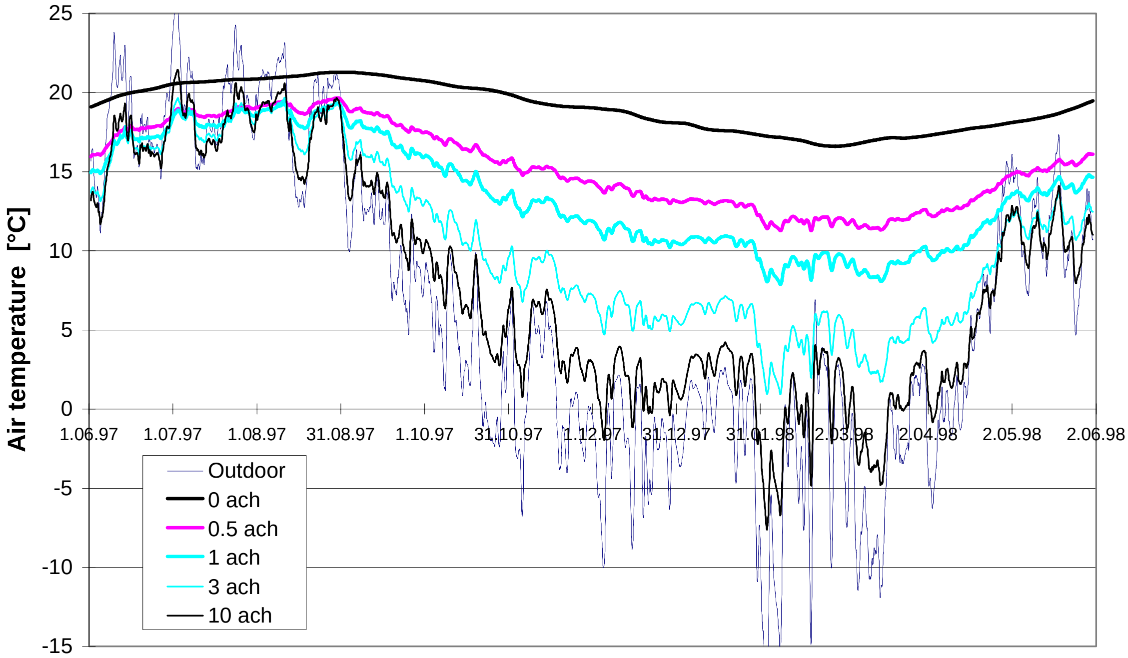


Figure 17 The effect of air change on temperature in the crawl space with uncovered ground (24-h moving averages)

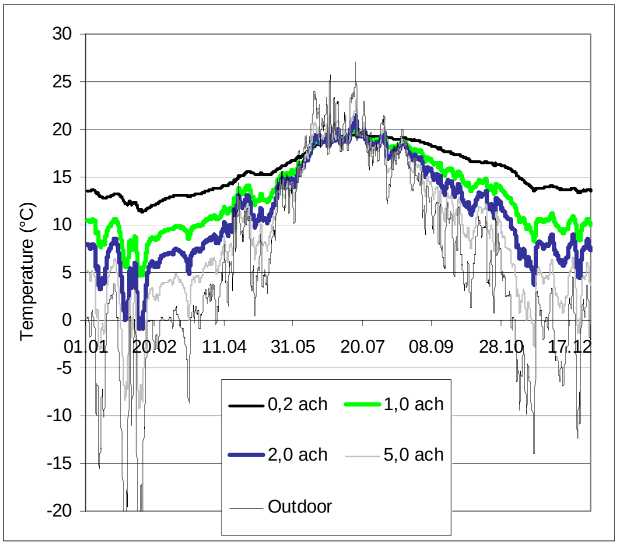
Although a higher air change rate increases the moisture evaporation from the uncovered ground surface, it still results in a lower relative humidity. In (I) increasing the air change rate from 0.5 ach to 3 ach increased ground moisture evaporation from 2.4 g/m^{2}h to 4.9 g/m^{2}h but decreased the highest monthly average of relative humidity in summer from 81% to 74%.

5.2.2 A warm and cold crawl space with an LWA ground cover

If a ground cover is applied the air change rate in a crawl space does not affect ground moisture evaporation much. In (II) a relatively warm (apartment building) and cold wooden crawl space with an LWA ground cover were studied. The average moisture evaporation in (II) through the LWA cover was 0.72 g $h^{-1}m^{-2}$ in the cold crawl space and 0.92 g $h^{-1}m^{-2}$ in the warm crawl space.

Warm crawl space (II)

A high air change rate cools down the crawl space in the winter and warms it up slightly in the summer; see Figure 18. The lowest RH in the crawl space is achieved when the air change rate during the heating season is 0.2-1.0 ach. In the summer, the RH is not sensitive to the air change rate due to the crawl space being relatively warm.



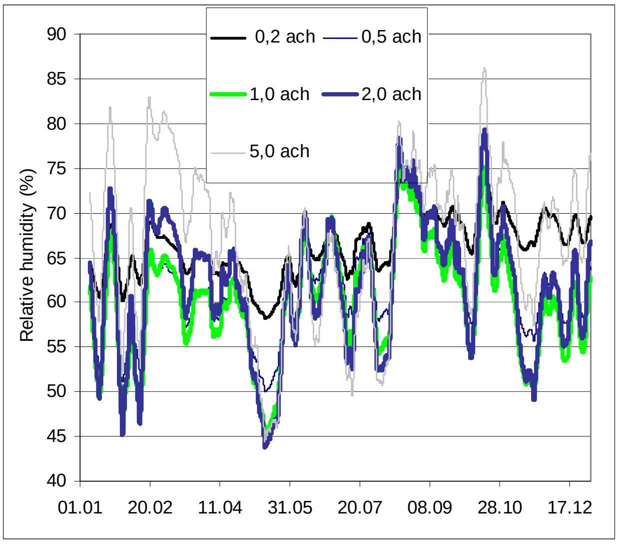


Figure 18 Temperature (left) and relative humidity (right) in a relatively warm crawl space at various air change rates. The ground is covered with 17 cm LWA (Temperature 24-hour moving averages, RH, weekly moving averages).

When the mould index *M* was calculated in (II), it can be seen that the risk of mould growth is very low in a warm crawl space with a ground cover; see Table 4. Relative humidity and the mould growth index were not sensitive to air change rate. The mould index was calculated during the whole year, and the critical RH was assumed to be 75%. In the calculations it is assumed that the wood is pine and the surface is not sawn after drying (in Equation (10) *W*=0, *SQ*=1).

Table 4 Maximum value of mould index at various air change rates for the apartment building with a 17-cm ground cover

	M (RH_{Cr}=75%)
0.2 ach	0.01
0.5 ach	0.01
1.0 ach	0.02
2.0 ach	0.05
5.0 ach	0.15

The moisture content in the LWA cover is rather stable throughout the year due to the crawl space being warm and relatively dry; see Figure 19. Slightly increased values can be seen in the summer but they are still much less than the hygroscopic limit value, 2 kg/m^3.

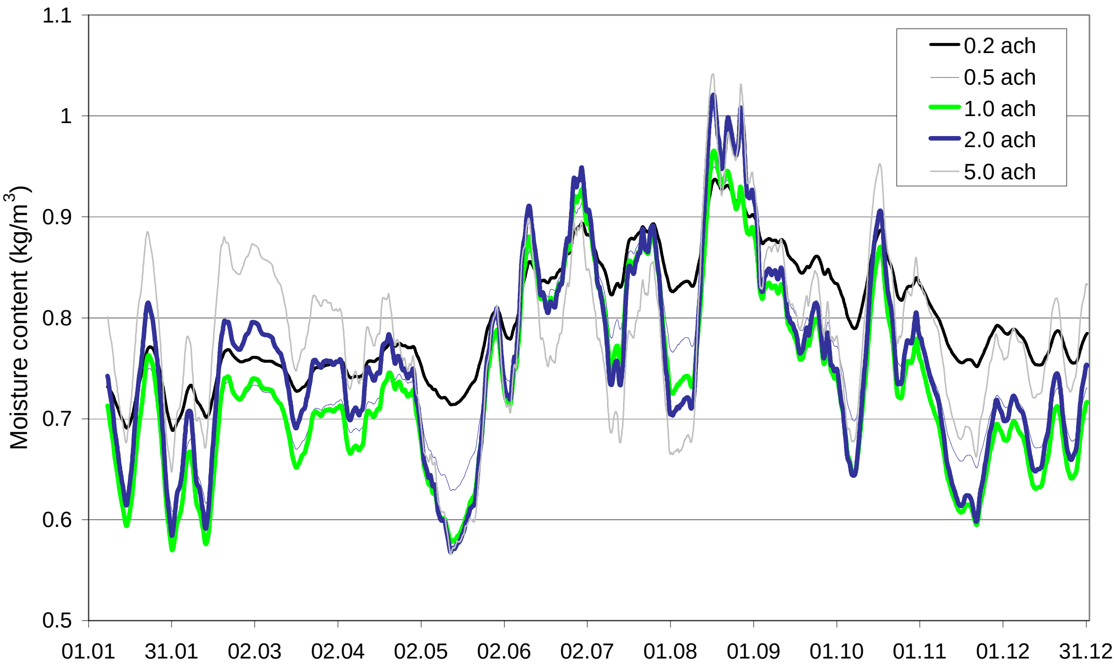
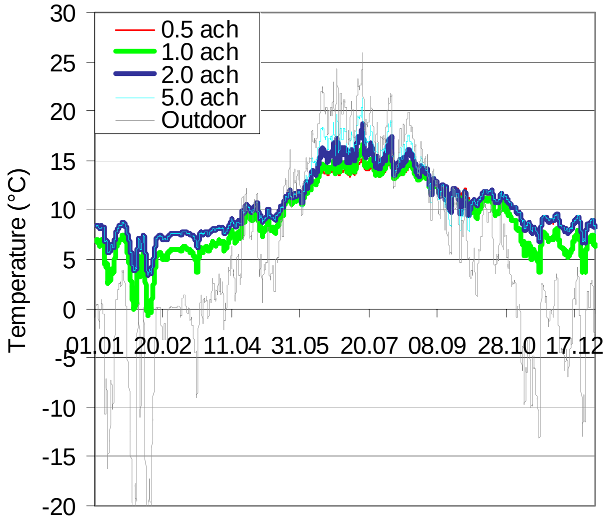


Figure 19 Moisture content inside the LWA at a depth of 6.7 cm (weekly moving averages).

Cold crawl space (II)

The crawl space of the wooden building was relatively cold throughout the year. High air change rates warm the crawl space up in the summer; see Figure 20 (left). The RH is clearly higher than in the warm crawl space - see Figure 20 (right) - exceeding 75% at the end of May. The highest air change rate, 5 ach, gives the lowest RH in the summer. Still, even in this case *M* is close to reaching the critical value of 1 for mould growth to start. *M* is calculated for the cases RH_{Cr} > 75%, 80%, 85%; see Table 5. In the calculations it is assumed that the wood is pine and the surface is not sawn after drying (*W*=0, *SQ*=1). In the case of higher air change rates (2.0 and 5.0 ach), a two-step air change rate was used (2.0 or 5.0 ach in the summer, May 1–September 30, and in the cold season 0.5 ach).



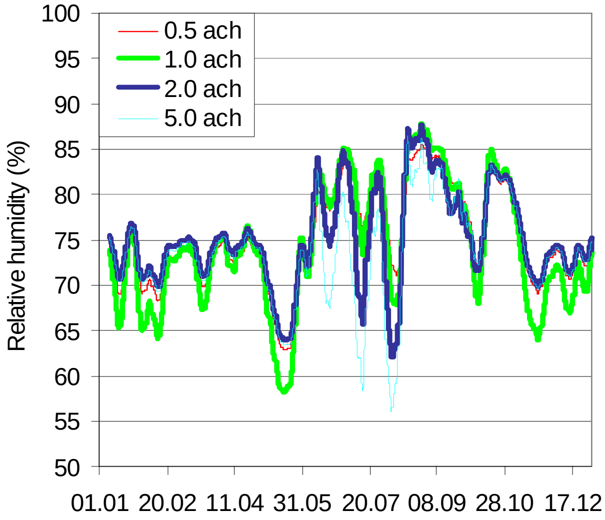


Figure 20 Crawl space air temperatures when the ground is covered with a 15-cm layer of LWA. (Temperature 24-hour moving averages, RH weekly (left) and RH (right) at various air change rates. The moving averages).

Table 5 Maximum value of mould index at various air change rates for the cold crawl space with a 15-cm LWA cover.

	M (RH_{Cr}=75%)	**M (RH_{Cr}=80%)**	**M (RH_{Cr}=85%)**
0.5 ach	0.95	0.52	0.07
1.0 ach	1.14	0.70	0.33
2.0 ach	1.20	0.79	0.47
2.0-0.5 ach*	0.82	0.58	0.35
5.0 ach	1.29	1.08	0.72
5.0-0.5 ach*	0.70	0.47	0.31

* The higher air change rate is used in the summer, 0.5 ach between Oct 1^{st}–Apr 30^{st}

In a relatively cold and humid crawl space LWA shows its capability to reduce RH fluctuation; see Figure 21. In summer, when the outdoor air becomes a humidity source, the LWA cover stores moisture inside itself.

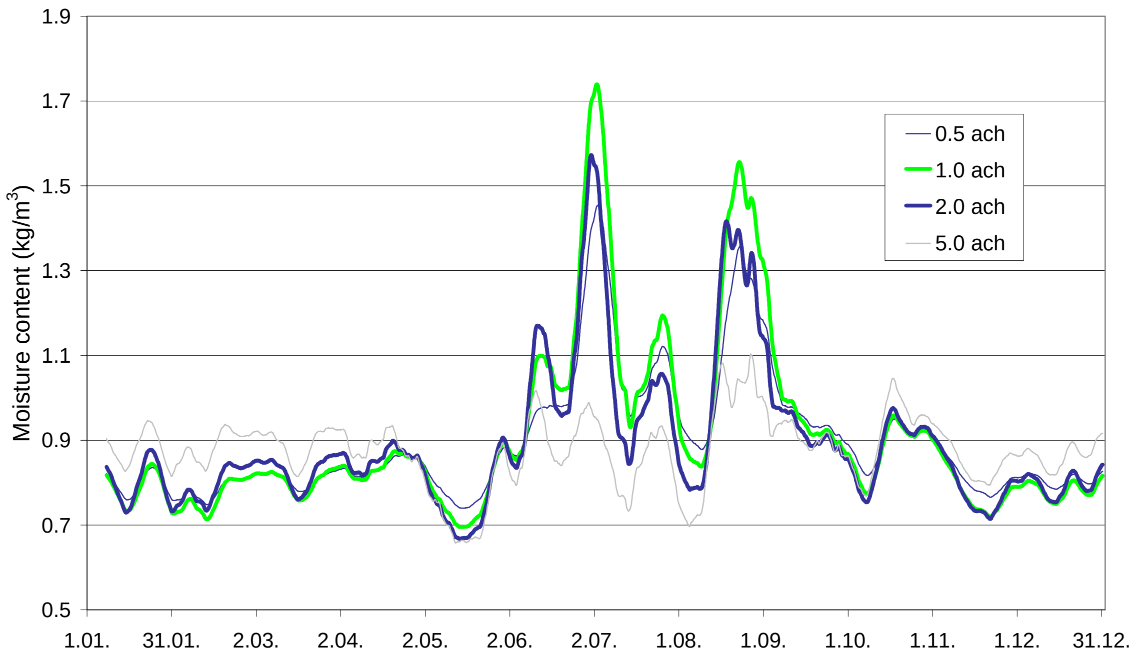


Figure 21 Moisture content inside the LWA at a 5-cm depth (weekly moving averages).

5.2.3 Different ground covers (II)

Ground covers may have an effect in two ways; they reduce the moisture evaporation from the ground and, on the other hand, they may act as a thermal insulation.

In the relatively warm (apartment building) crawl space all ground covers reduced the relative humidity in the crawl space sufficiently. In the cold (wooden) crawl space the relative humidity varied considerably, depending on the properties of the ground cover. For the simulations in (II) an air change rate of 2 ach was used to warm up the cold wooden crawl space in the summer. Uncovered ground (sand) and that covered with a PVC sheet behaved in nearly the same way in the summer, both having a very high relative humidity; see Figure 22. This is caused by the high heat capacity, which is the same in both cases and demonstrates that the outdoor air is the main moisture source during the summer.

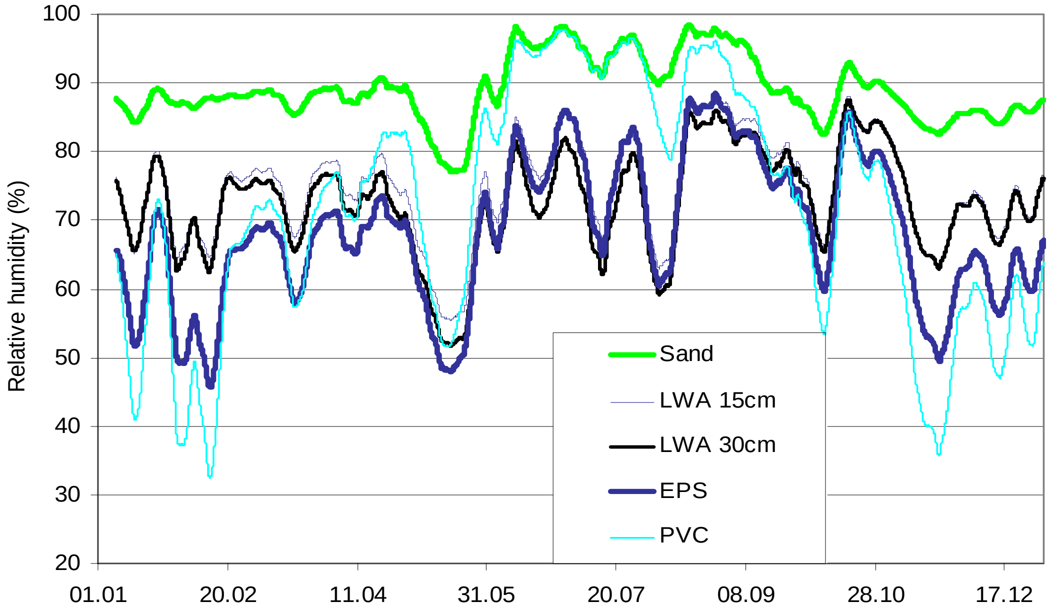


Figure 22 Crawl space air RH with different ground covers in the cold wooden crawl space (2.0 ach, 24-hour moving averages).

The uncovered ground showed the highest average evaporation rate, on average 1.7 g $h^{-1}m^{-2}$. Although EPS insulation evaporates far less (on average 0.15 g $h^{-1}m^{-2}$) than the 15-cm LWA cover (on average 0.74 g $h^{-1}m^{-2}$), there are only small differences in the mould index values; see Table 6. The lowest *M* was reached with a 30-cm LWA cover. Table 6 shows that in a cold crawl space with a PVC cover or uncovered ground the risk of mould growth is obvious.

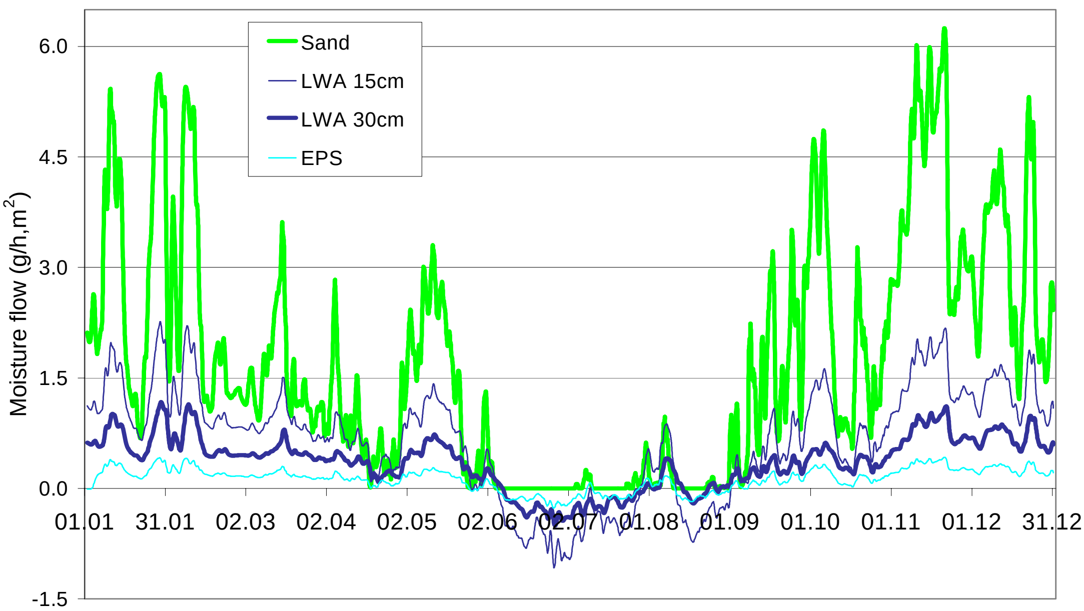


Figure 23 Moisture flow from ground (evaporation rate in the case of sand). Positive values indicate evaporation and negative values moisture flow from air to ground; in the case of sand 0 values can be interpreted as condensation (24-hour moving averages).

Table 6 Mould index M for RH_{Cr} = 75, 80, or 80% at various ground covers.

	M (RH_{Cr}=75%)	M (RH_{Cr}=80%)	M (RH_{Cr}=85%)
Sand	6	6	6
LWA 15 cm	1.2	0.79	0.47
LWA 30 cm	0.67	0.42	0.15
EPS	0.84	0.6	0.4
PVC sheet	6	6	6

5.2.4 The effect of extra thermal insulation (III)

The temperature and relative humidity were nearly the same, regardless of whether the insulation was on or under the base floor slab. In the case with no insulation in the foundations, the heat flow from outside warmed the crawl space up by 1°C in the summer, and RH was 5% lower compared to the case with insulation; see Figure 24. The insulation of the foundations had the most significant effect on the temperature and RH when the ground was covered with LWA and the crawl space was small, i.e. the area of the crawl space was the same as that of the foundations.

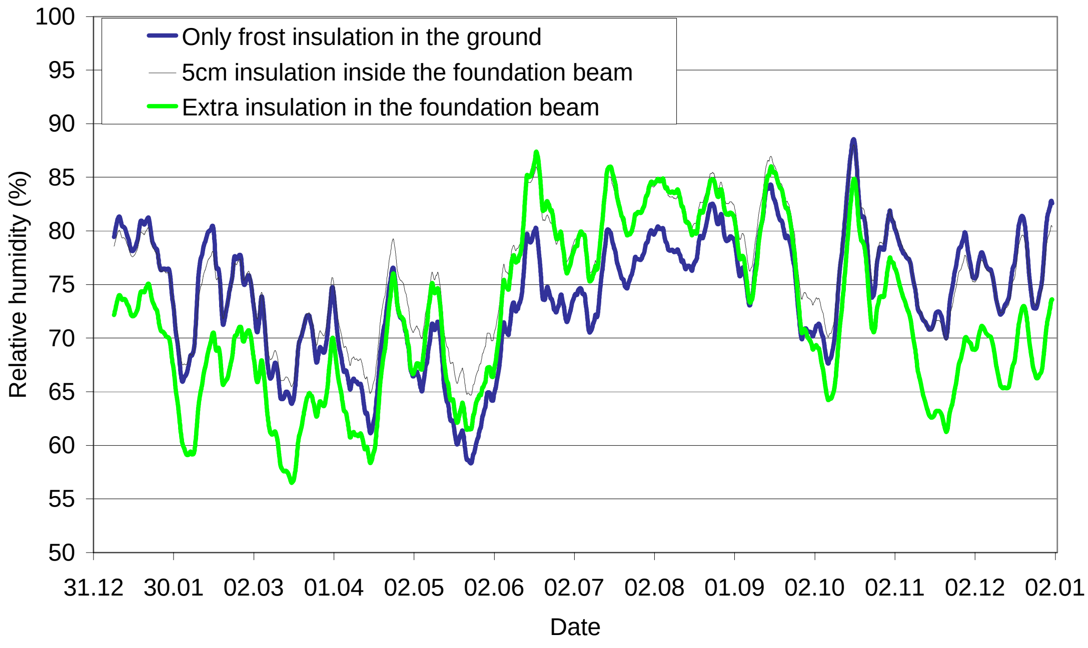


Figure 24 Relative humidity (weekly moving average) in the crawl space with 15 cm LWA ground cover when the insulation of the foundations is varied. The U value of the base floor is 0.2 W/m^2K and the air change rate is 1.0 ach.

Thickness of ground covers (III)

In the following section only the wooden building is considered, due to its higher sensitivity to mould growth. Results for the concrete apartment building are shown in (III).

In cold climates, the critical months in respect of mould growth are usually July and August, when the temperature and absolute humidity of the outdoor air are at their highest. In July, the higher the thermal resistance of the ground cover, the less important the value of the air change rate is. When the thermal resistance of an LWA cover is high (≥ 4 m^2K/W), the RH is nearly the same at all air change rates; see Figure 25. On the other hand, if the heat resistance is less than 1 m^2K/W, the difference in RH between air change rates is nearly 6%.

In August, the situation is different, due to different temperature behaviour. As August is already slightly cooler than July, higher air change rates cool the crawl space down. At lower air change rates, the crawl space remains warmer and the RH is also lower. Thus, the smallest air change rate (0.5 ach) gives the lowest RH; see Figure 25 (right). Only in the case of the thinnest LWA is the RH lower at high air change rates. When the thickness is increased, the behaviour is again the same – the lowest air change gives the lowest RH.

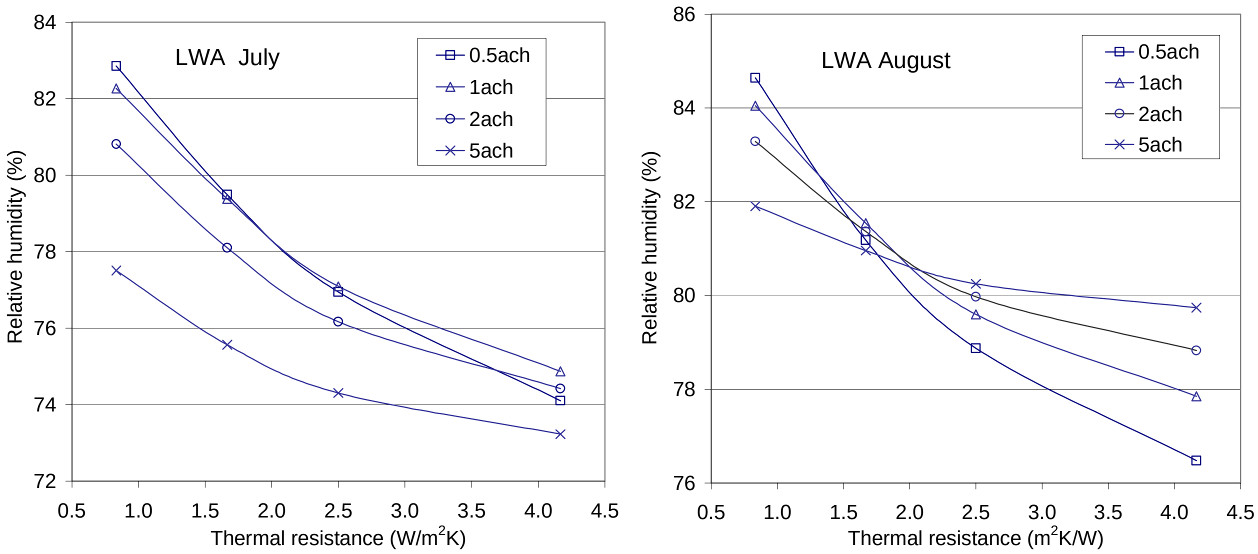


Figure 25 Monthly average value of RH in the crawl space in July (left) and in August (right) as a function of the thermal resistance of the LWA ground cover and air change rate. Thermal resistance of 4 W/m^2K corresponds to 50 cm LWA and 0.8 W/m^2K to 10 cm LWA.

The EPS ground cover shows basically the same performance as the LWA cover; see Figure 26. When comparing the RH in July with the same thermal resistance and air change rate, the RH is approximately 2% lower with an EPS cover. At low air change rates EPS shows better performance than LWA. It should be noted that EPS represents a theoretical case because in general building practice EPS is usually covered with a layer of crushed stone, which increases thermal capacity as well as RH values.

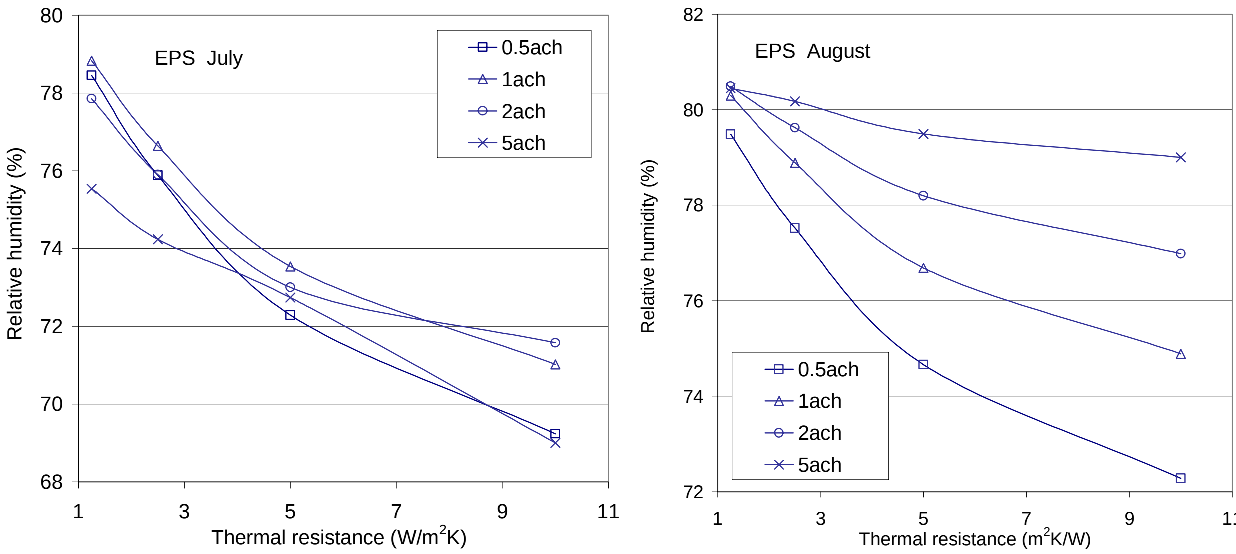


Figure 26 The monthly average value of RH in the crawl space in July (left) and in August (right) as a function of the thermal resistance of the EPS ground cover and air change rate. Thermal resistance of 10 W/m^2K corresponds to 40 cm EPS and 1.3 W/m^2K to 5 cm EPS.

With the EPS ground cover there is no risk of mould growth (Figure 27) as the index does not exceed 0.5 even when the ground cover is only 5 cm thick. With the thinnest LWA cover there is a definite risk of mould growth because the index exceeds 1. To achieve acceptable conditions, a heat resistance higher than 1,5 m^2K/W has to be used. The critical RH value used was 75%.

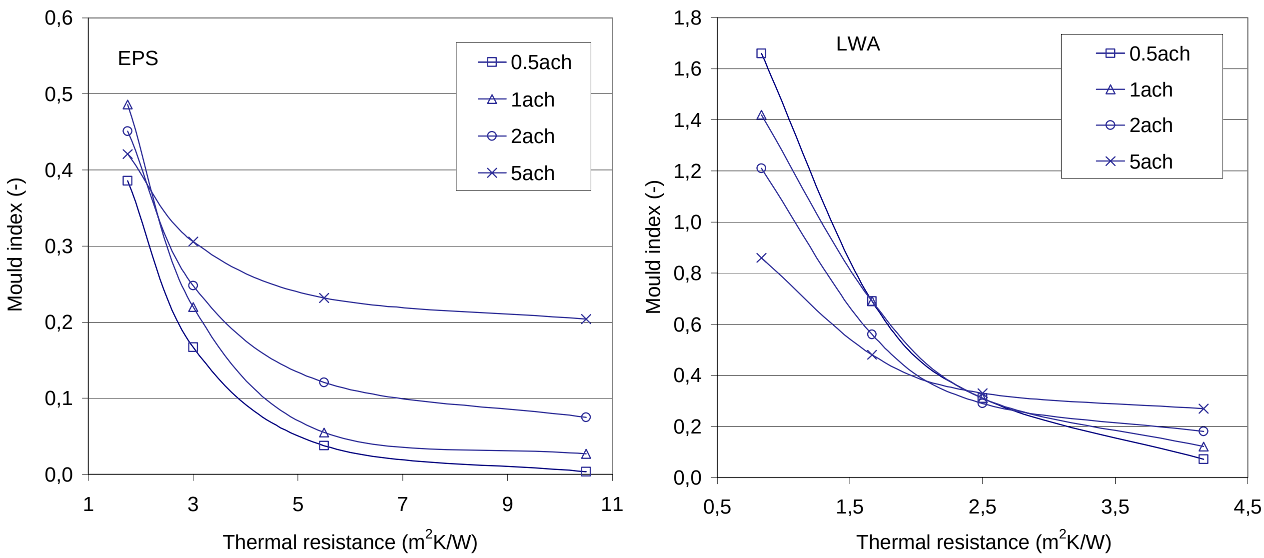


Figure 27 The maximum mould growth index as a function of the thermal resistance of the ground cover: EPS on the left and LWA on the right.

5.3 Heating (IV)

5.3.1 Crawl space moisture conditions with heating

The difference in relative humidity in the summer between the heated and unheated cases is shown in Figure 28. In the case of 20 cm crushed stone (CS) the relative humidity is, on average, over 10% higher when heating is not used. Also, when a 30-cm LWA ground cover is used, there is a clear difference in the RH levels. When a PVC ground cover without heating is used, relative humidity rises to over 90% in some periods, showing an ultimate need for moisture control. Basically, the behaviour is similar in the apartment building, and the RH of the detached house is only slightly lower. The different levels of RH in a crawl space with PVC ground cover in Figure 22 and Figure 28 are due to different air change rates and base floor areas.

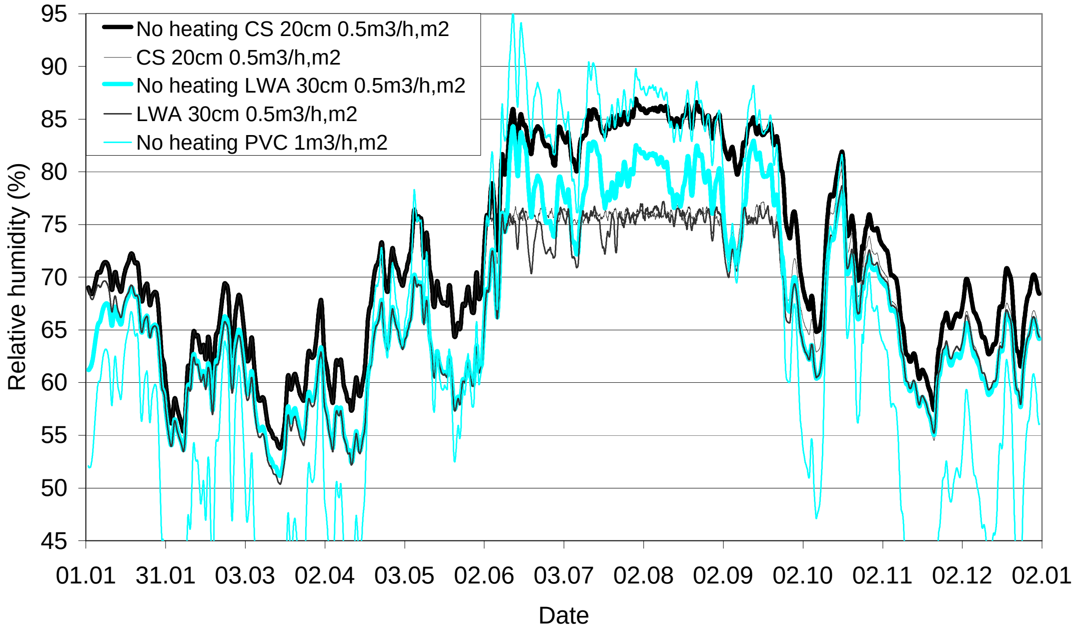


Figure 28 Relative humidity in the crawl space of the wooden detached house when the crawl space is unheated or heated. The operation time of heating was from May 1st to September 30th. The set point of the heating was 75% RH.

Although with the 30-cm LWA cover the RH is higher when the heating is not used, it is still an acceptable solution, since the mould index M is clearly below M = 1; see Figure 29. The PVC cover without heating causes mould growth but, when the heating is used, the mould index is nearly zero in both cases.

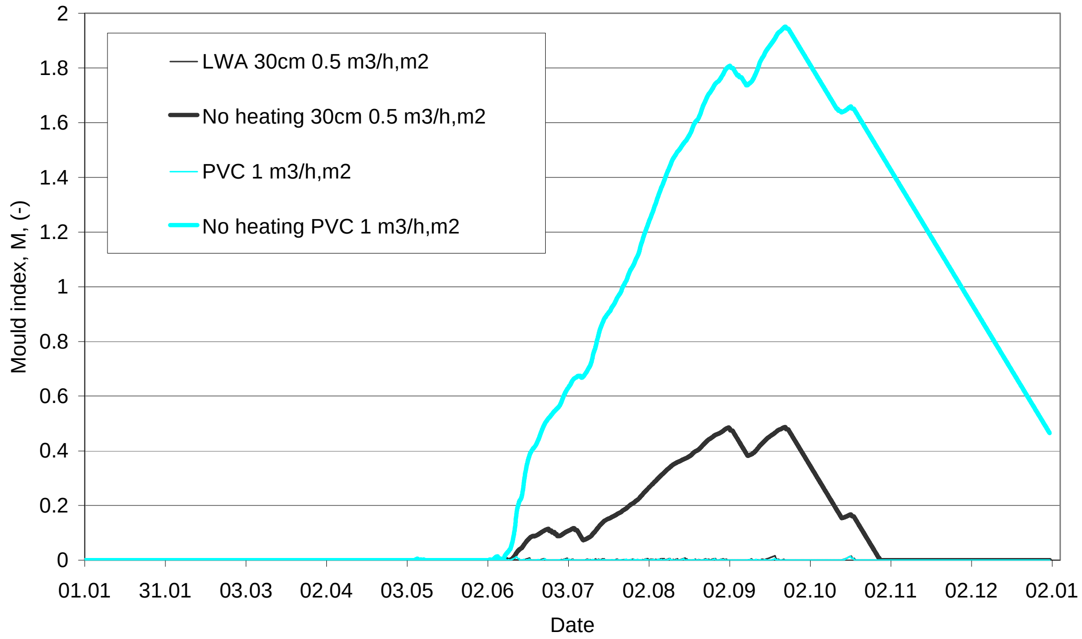


Figure 29 Mould growth index M with different ground covers and heating in the detached house.

5.3.2 Energy consumption and control strategy

If the ground cover has a high thermal mass, this has a significant effect on the energy consumption of the crawl space heating. As the on/off control is used, energy consumption is directly dependent on the amount of time the heater is on. In the apartment building the crawl space with 20 cm crushed stone has the heating on 23% of the time; see Figure 30. The difference, compared to a 20-cm LWA cover which is on 12% of the time, is remarkable; again, see Figure 30. The changes in the relative humidity of the crawl space are slow, and the shortest period of time that the heating is on is approximately 6 hours (not shown in Figure 30). The performance of the heating is basically the same in the detached house, but LWA needs less heating.

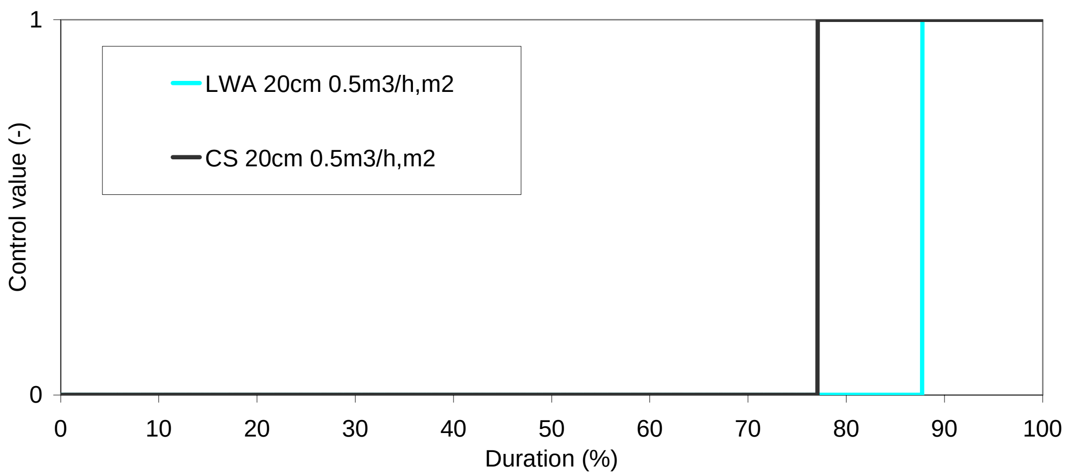


Figure 30 Duration curve of operation of heating in the apartment building with 20 cm crushed stone and 20 cm LWA. Heating is turned on when the control value is 1 and turned off when the value is 0. The set point of the heating was 75% RH. The duration curve is drawn for the heating period, May 1st–30th September.

The specific annual heat energy consumption does not differ much between the apartment building and detached house; see Figure 31. The cases of 20 cm crushed stone and PVC sheet appear to show the highest heat consumption. The lowest heat consumption is less than one third of the highest one. The highest heat energy consumption was with PVC with 1 $m^3/h,m^2$ and the lowest with 30 cm LWA with 0.5 $m^3/h,m^2$. As the heat consumption is dependent on air change rate, a lower air change rate gives lower energy consumption.

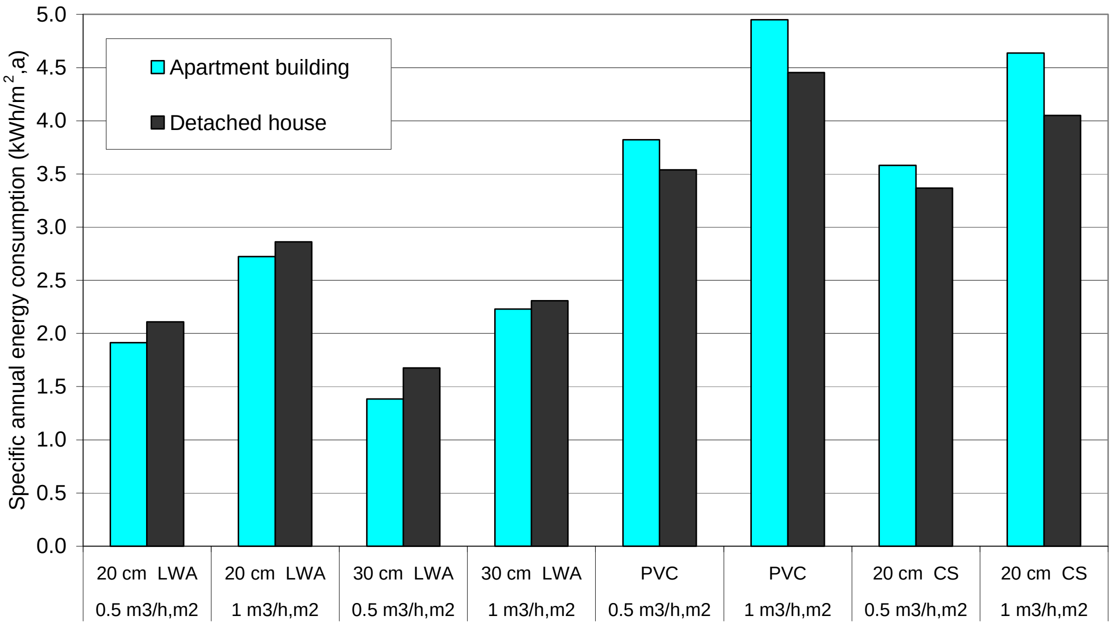


Figure 31 Specific annual energy consumption for heating a crawl space in the apartment building and detached house. Different ground covers and air change rates; the set point of RH was 75%.

To determine the effect of the set point value and heat output rate on energy consumption and moisture conditions in the crawl space, the set point was varied between 70%, 75%, and 80%, and the heat output between 2.5 W/m^2, 5 W/m^2, and 10 W/m^2.

The energy consumption rose considerably when the RH set point was lower; see Figure 32. At a heat output of 5 W/m^2 the energy consumption in the case of the RH set point 75% was from 45% to 66% of the energy consumption with the RH set point 70%. Energy consumption was lowest with 30 cm LWA, and the case of 20 cm LWA showed only slightly higher values. The cases of PVC and 20 cm crushed stone consume roughly the same amount of energy.

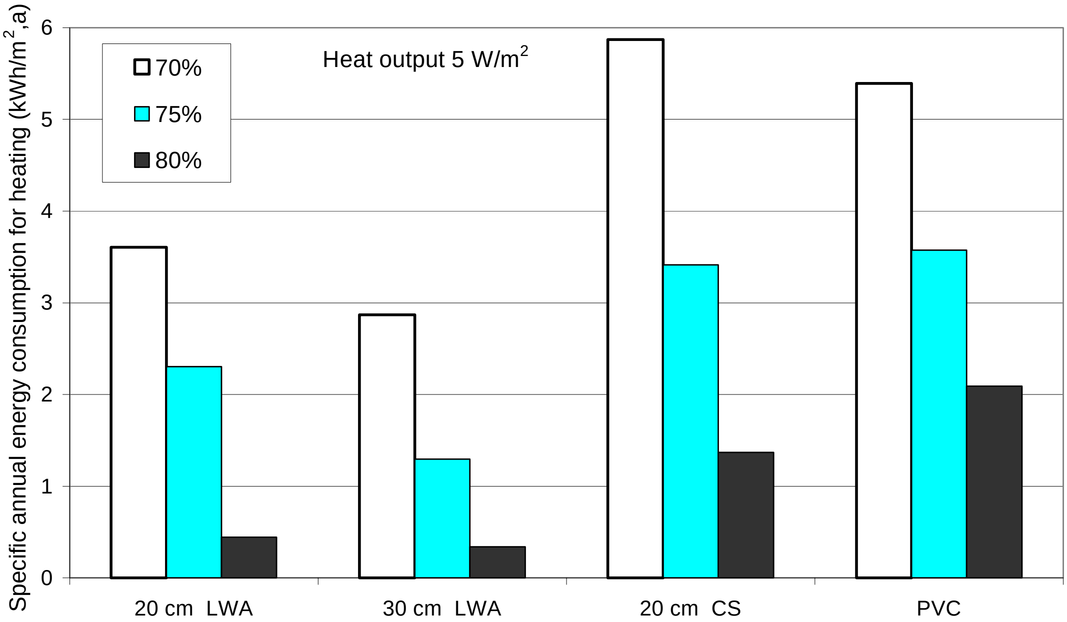


Figure 32 Specific annual energy consumption with different set points of RH and ground covers. Detached house, air change rate 0.5 m^3/h,m^2

Even with the lowest RH set point (70%) and lowest heating power of 2.5 W/m^2, the RH in the crawl space with 30 cm LWA exceeds the upper limit of the RH set point (72.5%) only 3% of the time; see Figure 33. This is in good agreement with the results found in (II) and (III). Although the cases with 20 cm crushed stone and PVC ground cover consumed roughly the same amount of energy, PVC exceeds the RH set value in a significant time period at every RH set value, but 20 cm crushed stone only with the lowest RH set value, showing the advantage of the moisture capacity of the ground cover.

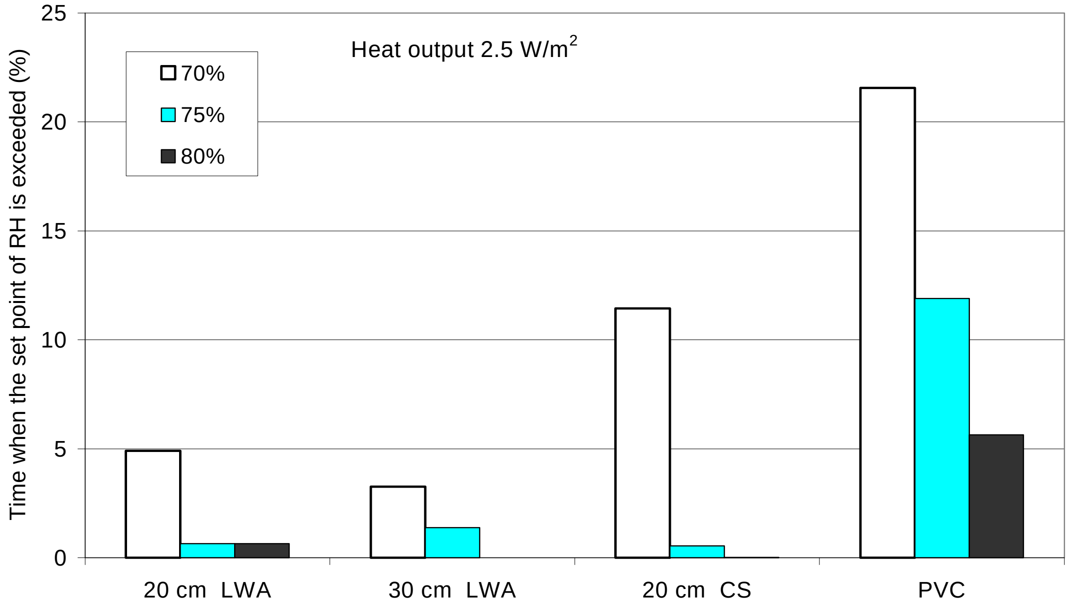


Figure 33 Time when the set point of RH is exceeded in the summer from May 1st to September 30th. Detached house, ventilation rate 0.5 m^3/h,m^2

5.4 Transport of particles and fungal spores indoors from crawl spaces

5.4.1 Concentrations of fungal spores in field measurements (V)

In most cases the concentration of microbes was clearly higher in the crawl space than indoors or outdoors; see Table 7. Typically, the mean concentrations of fungal spores varied between 1000–3000 CFU/m^3, but concentrations of tens of thousands were measured. The most common species in all the environments of the measured buildings were *Penicillium, Acremonium,* and *Cladosporium*.

Table 7 Concentration of different fungal species (CFU/m^3), their average, median, minimum, and maximum values and standard deviations.

	Spores (CFU/m^3)	**Average**	**Median**	**Min**	**Max**	**Std**	**n**
Penicillium	Indoor	290	90	5	1620	460	20
	Crawl Space	4020	2760	60	17150	4190	20
	Outdoor	20	20	5	30	10	10
Acremonium	Indoor	160	40	2	730	240	15
	Crawl Space	2240	1870	0	8970	2600	15
	Outdoor	15	10	7	30	10	4
Cladosporium	Indoor	30	15	5	150	40	15
	Crawl Space	100	30	8	500	140	20
	Outdoor	110	90	6	240	100	6
Aspergillus	Indoor	70	70	15	130	80	2
	Crawl Space	110	50	2	270	140	3
	Outdoor			0	0		0
Yeasts	Indoor	10	8	3	40	10	10
	Crawl Space	15	15	3	20	8	10
	Outdoor	15	20	3	30	8	6
Sterile	Indoor	50	20	4	250	70	10
	Crawl Space	20	10	3	80	30	10
	Outdoor	220	80	30	1000	380	6

Std Geometric standard deviation
n prevalence of fungal species in the samples; the total number of samples was 47.

5.4.2 Correlation between indoor and crawl space microbes (V)

The correlation between concentrations of indoor and crawl space microbes was tested with the Pearson correlation coefficient. The concentrations of *Penicillium* indoors and in the crawl space did not correlate (Pearson coefficient 0.11), although it was the dominant species both indoors and in the crawl space; see Figure 34. The concentration of *Acremonium* in the indoor air and crawl space air had a relationship (Pearson coefficient 0.89), indicating the presence of high counts in crawl spaces reflected as high counts in indoor air; see Figure 34.

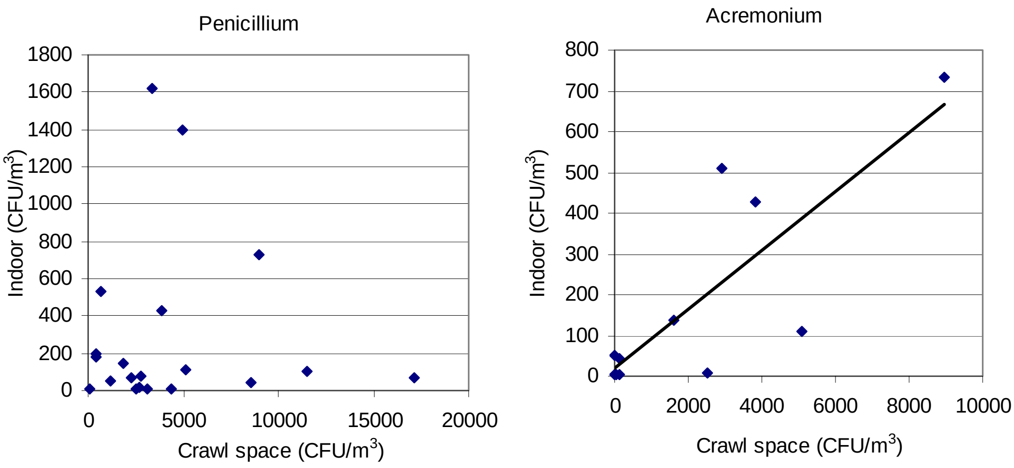


Figure 34 Correlation between indoor and crawl space fungal spores.

The total concentration of fungal spores between indoor air and crawl space air did not correlate. However, from Figure 35 it can be seen that the elevated levels of fungal spores in the crawl space can be seen as elevated levels of fungal spores in indoor air.

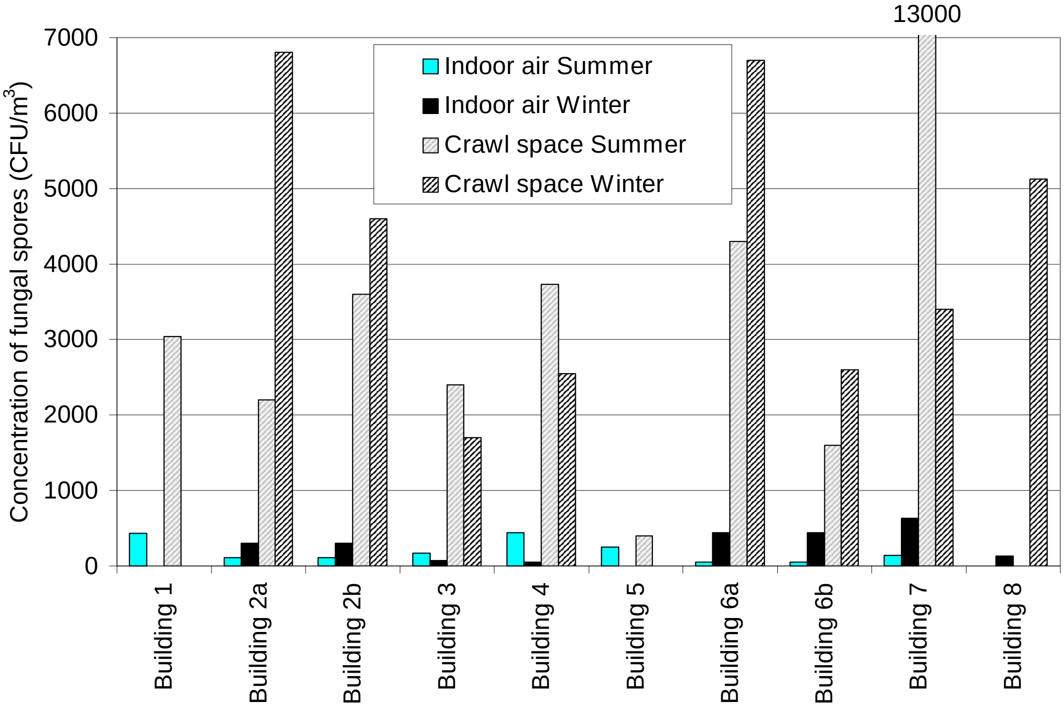


Figure 35 The total concentration of fungal spores in the crawl space and indoors

Size distribution

The size of a particle has an important role in respect of the penetration of a crack in a building envelope, and thus it is important to study the size distribution of fungal spores in order to be able to estimate their penetration indoors. The size distribution varied according to microbial species. The size distributions of *Penicillium* in the crawl space and indoor air were similar in shape, and most microbes were impacted in a stage whose average aerodynamic diameter was 1.4 µm. However, the concentration was clearly higher in the crawl space; see Figure 36. Outdoors, the highest *Penicillium* counts were received for the smallest sizes. The size distributions of *Cladosporium* were equal in shape in indoor air, in the crawl space, and in outdoor air; see Figure 36. Most of the fungal spores of *Cladosporium* were impacted in a stage whose cutoff aerodynamic diameter was 2.6 µm. Compared to *Penicillium*, the size distribution of *Cladosporium* is clearly skewed towards bigger particles, indicating that *Cladosporium* spores are bigger and more uniform in shape. The size distributions of *Acremonium* were similar in all the environments measured. Yeasts indoors were clearly bigger in size; most microbes were impacted at a stage whose cutoff aerodynamic diameter was 4.2 µm; see Figure 36. Yeasts may have sources indoors, which seem to produce yeast particles in bigger size fractions. Also, the species of yeast might be different indoors and in the crawl space. There were only a few non-sporulating microbes, and their size distributions differed in the different environments. The maximum counts for *Penicillium, Cladosporium* and *Acremonium* were observed in smaller fungal spores, between 1.4–2.6 µm, indicating that the fungal spores are mainly detected as single spores and not as aggregates. The data presented are based on the counts and identification of the fungi growing on the MEA.

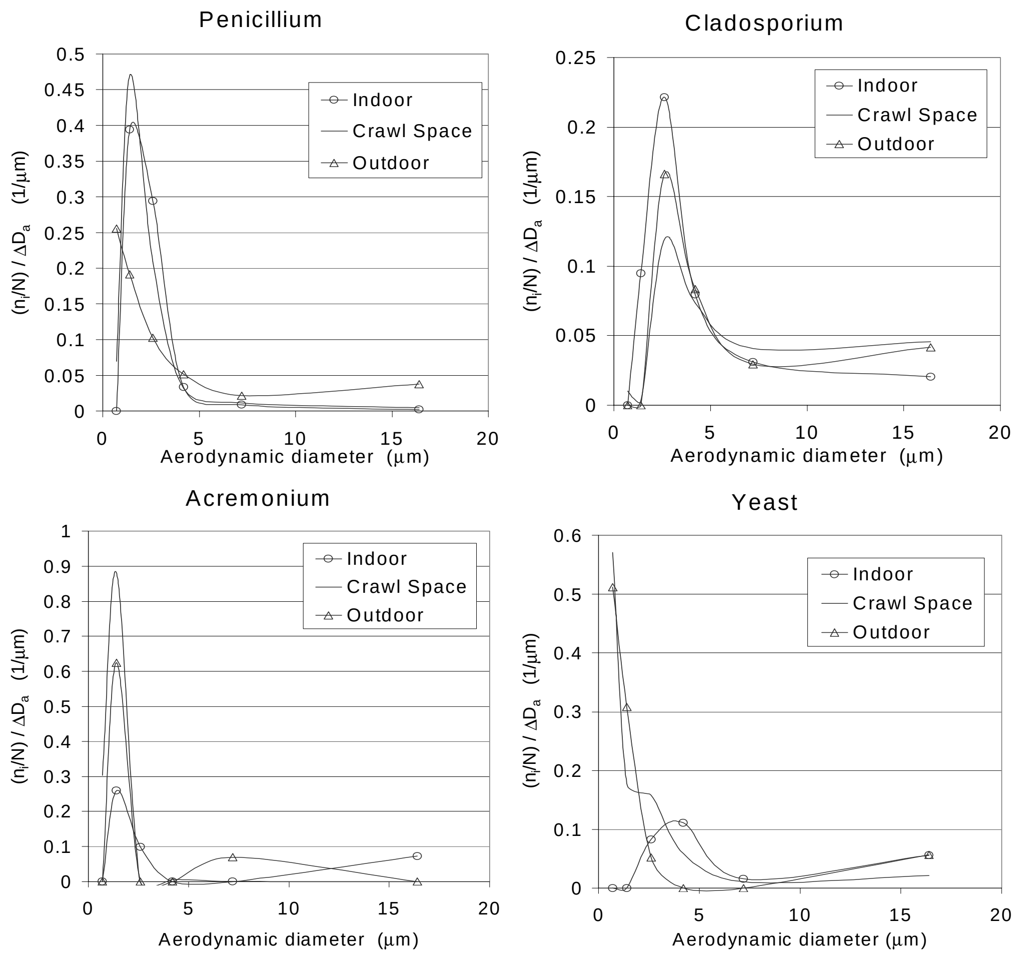


Figure 36 The count size distribution of fungal spores of different microbes indoors, outdoors, and in the crawl space. The explanations of abbreviations in the figure: n_i number of spores in size interval I, N total number of spores, ΔD_A width of a size interval.

5.4.3 Penetration factor and pressure difference (VI)

In (VI) penetration indoors through a base floor structure was first measured with inert particles whose supply, monodispersion, and concentrations were relatively easy to control. A constant supply rate led to steady state concentrations on both sides of the structure under study and thus it was possible to derive penetration factors at different airtightness rates and pressure differences. In the case of *Penicillium* and *Cladosporium*, steady state conditions were not achieved and the results only indicate the fact that penetration occurred.

Inert particles

The penetration factor s_f was calculated from Equation (16); penetration from the laboratory hall was assumed to be zero, since the chambers were well sealed. The results in Table 8 show that there are very small differences relative to the air flow paths of the first three cases for particles of 0.6, 1.3, and 2.5 µm. Smaller particles show an only slightly higher penetration factor. This indicates that holes in the surface boards of the structure (which increase airtightness only from 1 to 1.4 ach) do not affect the penetration of these particles. It seems that mineral wool and, probably, especially its surface contacts, is likely to dominate the penetration of these particles. The penetration factor 0 for 4 µm seems to confirm the importance of the mineral wool layer (and its installation) for smaller particles. For 4-µm particles mineral wool acts as a perfect filter. The last structure, with an open pipe, shows a completely different performance, with much higher penetration factors for all particles. All the results in Table 8 stress the importance of pressure difference across the structure. In all the particles and structures studied a higher pressure difference resulted in a significantly higher penetration factor.

Table 8 Penetration factors for the base floor structure with different airflow paths and pressure difference.

Description of the Floor Structure	**Air tight-ness* (ach)**	**Pressure difference (Pa)**	**Penetration factor with different sizes of supplied particles (-)**			
			0.6(µm)	**1.3(µm)**	**2.5(µm)**	**4(µm)**
No penetrations	**1.0**	**20**	0.19	0.19	0.18	Not detected
		6	0.12	0.08	0.06	Not detected
Sealed Ø15-mm pipe	**1.0**	**20**	0.20	0.20	0.16	Not detected
		6	0.08	0.07	0.05	Not detected
Ø10-mm holes in the surfaces	**1.4**	**20**	0.14	0.15	0.10	Not detected
		6	0.06	0.03	0.02	Not detected
Open Ø15-mm pipe	**1.4**	**20**		1.0		0.47
		6		0.54		0.19

*For residential and apartment buildings, an air leakage value of 1-2 ach is often considered to mean an airtight building (Persily 1998).

The deposition velocity is very important for the penetration factor. In Figure 37 the error bars for the penetration factors were calculated from the lowest and highest measured deposition velocities in recent studies, shown in Figure 5. The difference between the minimum or maximum value and the value used in this study might, depending on deposition velocity, be as high as 48% (2.5 µm). However, the difference in the value of the penetration factor was only from 0.01-0.08, depending on the case, expect in the case of an open pipe with particles of 1.3 µm.

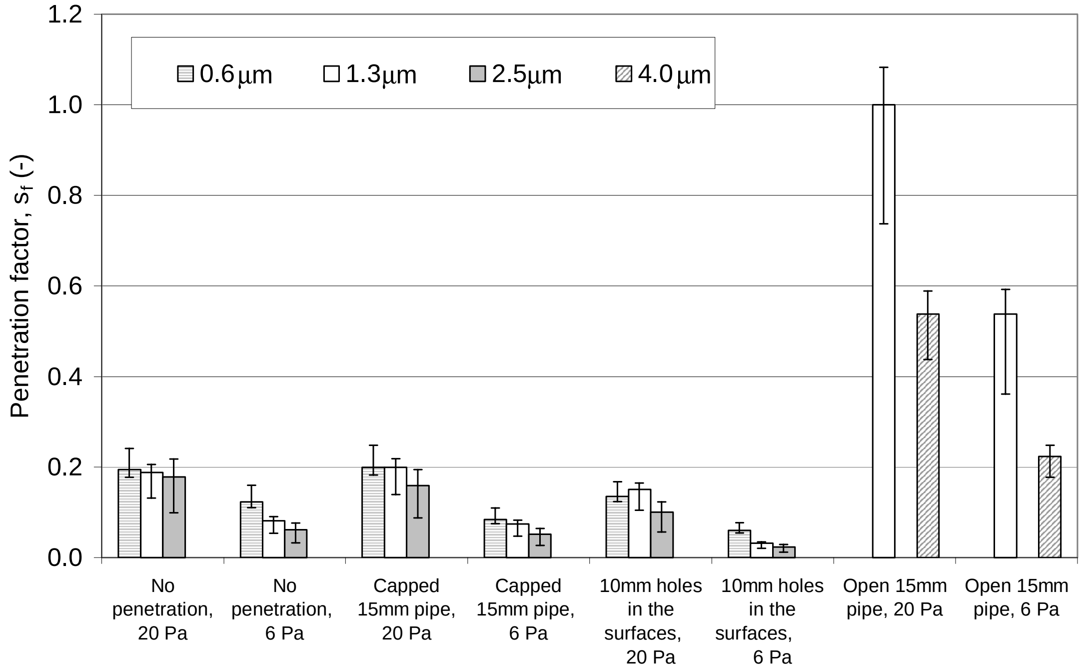


Figure 37 Penetration factors calculated with different deposition velocities

Penicillium and Cladosporium

The penetration of fungal spores was also estimated from the results of the optical particle counter. Since the chambers did not reach a steady state and only the range of the particle diameter was known, the penetration rate was estimated as a percentage of the particles that penetrated through the structure. These percentages are compared to the results of inert particles in Table 9. The results show the same tendency as in the case of inert particles; the penetration rate is strongly dependent on pressure difference, but holes in the surface boards have only a minor effect on penetration.

Table 9 Percentage of fungal spores that penetrated through the structure measured with the optical particle counter, compared to the results of inert particles

Floor Structure	**Airtightness (ach)**	**Pressure**	**Inert**	**Inert**	***Penicillium***	***Cladosporium***
			1.3 µm	**2.5 µm**	**1.0-5.0 µm**	**1.0-5.0 µm**
No penetrations	1.4	high*	3.20	1.60	0.79	1.16
		low**	1.00	0.70	0.17	0.42
Ø13-mm holes in the surfaces	2.4	high*			0.70	0.63
		low**			0.21	0.31

* high pressure 20 Pa for inert particles and 18 Pa for fungal spores
** low pressure 6 Pa for both inert particles and fungal spores

Most of the spores of *Penicillium* were impacted at Stage 4, corresponding to a mean geometric diameter of 2.6 µm. Spores of *Cladosporium* were mainly impacted at Stages 4 and 5, corresponding to mean geometric diameters of 2.6 µm and 1.4 µm.

During the testing of *Cladosporium*, which was carried out 21 hours after the testing of *Penicillium*, spores of *Penicillium* could still be detected. According to the optical particle counter, the levels of particles were low, but spores of *Penicillium* were still detected with the Andersen impactor in all the measurements with *Cladosporium*. Supplying the spores was problematic, causing too high concentrations in CH2, resulting in all the samples taken from CH2 being overcrowded after the cultivation of impactor plates. Thus, the results shown in Table 10 are only indicative estimates and the real values may be lower due to higher concentrations in CH2 than it was possible to measure with the impactor. The penetration rates calculated in percentages again show a strong dependence on pressure difference. In CH1 (indoor) the results between the optical particle counter and Andersen impactor correlated well, with a correlation factor of 0.93. However, for CH2 the correlation factor was only 0.60, which was due to overcrowded results with the Andersen impactor in CH2.

Table 10 Penetration of spores (%) of *Penicillium* and *Cladosporium* from CH1 to CH2 detected with Andersen impactors.

Floor structure	Pressure	Supply of *Penicillium*	Supply of *Cladosporium*	
	[Pa]	Detected *Penicillium*	Detected *Cladosporium*	Detected *Penicillium*
No penetrations	18	6	24	1
	6	1	5	0
Ø13-mm holes in the surfaces	18	-	50	1
	6	3	2	3

6. DISCUSSION

6.1 Accuracy of the simulation model

The simulations were carried out in the IDA simulation environment and the model uses the RC network, with about 70 calculation points. The main simplification of the model, the effect of heat transfer in the ground on the inaccuracy of the calculation of the temperature, reflects the inaccuracy of the calculation of relative humidity. However, the deviation is, at its maximum, 1.5 °C, and usually less than 0.5 °C.

When the calculated and measured results are compared, some uncertainties in boundary conditions should be taken into account. It was not possible to use exact air change rates in (I and II), but the air flow rate of the exhaust fan of the crawl space was used as the air change rate in the relatively cold wooden building, and in the relatively warm crawl space the average of a three-month measurement period with natural ventilation was used. Nevertheless, when the calculated temperatures are compared to the measured ones, a reasonably good agreement between the crawl space temperatures can be seen.

The measured crawl space of the wooden building was complex in its geometry – the L-shaped building had 2 x 3 sections, which causes some disagreement when the measured and calculated results are compared, since in the model the air mixing was assumed to be complete.

In (II) the moisture models were compared. The improved model took the moisture transfer in the ground cover and base floor into account. The simplified model without moisture capacity overestimates the fluctuation of relative humidity and the RH levels in the summer. Although the model was improved, it still calculated the moisture transport in the base floor and ground cover with a relatively rough model. The slope of the sorption isotherm was a linear approximation with two sorption isotherms, of which the last point was the upper hygroscopic limit value of the moisture content (at 100% relative humidity). In addition, vapour permeability was taken as constant. Although most building materials have humidity depending diffusion properties and a steeper sorption isotherm in the high humidity range, the model calculated the relative humidity in a crawl space with reasonable accuracy.

The absolute value of difference between the measured and calculated values of relative humidity was highest if no moisture capacity was taken into account (II). The effect of moisture capacity was clearly higher in the cold crawl space with a wooden base floor. If the moisture capacity of lightweight clay aggregate and the base floor are taken into account, the absolute difference between the measured and calculated values was mostly under 5%.

To assess the sensitivity of the main simulation parameters the DSA method was used in (IV). However, the use of DSA is not straightforward, as the underlying assumption of DSA is that the effect of an uncertainty is linear over the perturbance. Still, DSA is widely used since it enables the sensitivity of the program outputs to input parameter changes to be explored directly (Lomas and Eppel 1992). It also permits the total uncertainty in a chosen output due to changes in many inputs. However, the total uncertainty is only strictly correct if the sensitivity to each individual input is independent of the value of the other inputs. This assumption is nevertheless not true for such thermal systems as buildings or crawl spaces. In this study, the DSA method was useful in analysing the sensitivity to temperature of the parameters studied. The sensitivity results regarding relative humidity did not have any physical meaning as its behaviour in respect of varied parameters was not linear. The most important factors, and those having the strongest effect on crawl space thermal behaviour, were air change rate and the thermal properties of the ground cover.

6.2 Ground covers and air change rate

Thermal and moisture capacity, as well as moisture and thermal resistance, proved to be important properties of ground covers in (I, II, and III). In a warm crawl space a PVC cover (high moisture resistance and negligible thermal resistance) and other ground covers reduced relative humidity in the crawl space. In a colder crawl space, PVC cover did not provide any benefit in the critical summer period because it does not insulate the cold ground from the crawl space. Another disadvantage of PVC might be that a water- and vapour-tight cover can provide circumstances for microbial growth in the ground soil. However, how the microbes behave in these kinds of circumstances has not been widely studied. An LWA ground cover has moisture capacity and, in (II), the ability to reduce fluctuations in relative humidity was shown. A 15-cm layer of LWA and 5 cm of EPS have the same thermal resistance. However, the crawl space with EPS insulation on the ground showed slightly lower relative humidity due to the smaller heat capacity of the EPS cover. Thus, an ideal ground cover should have a high moisture and heat resistance, a high moisture capacity, and a low heat capacity.

Air change rate affects the thermal behaviour of, and, thus, the relative humidity in a crawl space. For a warm crawl space air change rates of 0.5-1.0 ach are sufficient to avoid mould growth. For colder crawl spaces a higher air change rate for the summer has to be used to warm up the crawl space. Ground covers with a thermal resistance of ~1.3 m^2K/W (i.e. 15 cm LWA or 5 cm EPS) and an air change rate of 2 ach or higher gave acceptable conditions in summer. The highly-insulated (thickness of ground cover ≥ 30cm LWA or ≥ 10cm EPS) crawl spaces studied in (III) behave differently; a low air change rate gives the driest conditions in the summer. In July, which is one of the most critical months of the summer, the higher the thermal resistance of the ground cover, the less important was the value of the air change rate.

The highest safety level in respect of mould growth may be achieved, especially when taking into account varying weather conditions, by using highly insulating ground covers. The study in (III) concerning the effect of insulating foundations showed rather surprising results. It seems that a heat flow through the foundation warms the crawl space in the summer, and thus the crawl space was at its warmest and the RH was at its lowest when there was no insulation in the foundations. Heat flow is modelled as the average heat flow through the whole of the foundation, and it may cause some inaccuracy in the results. Another significant result was that the location of the insulation on the base floor construction seems to have no effect on crawl space conditions. The results were the same regardless of whether the insulation was on or under the slab.

6.3 Acceptability of moisture conditions

In order to avoid mould damage to structures, the lowest threshold conditions at which fungal growth is possible are critical. The duration time of the conditions is also significant in respect of mould growth (Grant et al. 1989, Viitanen 1997[a], 1997[b]). For mould development the humidity conditions or moisture content close to the surface of materials are most critical, since the moulds grow on the surface (Grant et al. 1989, Adan 1994, Viitanen 1997a). However, if materials are wet the humidity of the microclimate near the surface can be higher for a longer time and may promote fungal growth, so that even though the humidity in the whole ambient air mass is low, growth can be faster.

The mould growth model used, developed by Viitanen (1996) and Viitanen et al. (2000), is based on mathematical relations for the growth rate of the mould index in different conditions, including the effects of exposure time, temperature, relative humidity, and dry periods. The model is purely mathematical in nature since the mould growth is only investigated by visual inspection and it does not have any direct connection to biology in the form of the number of living cells and particles. The model also assumes that all microbes behave in a similar way, although the range of conditions in which microbes can grow is wide (Chang et al. 1995, Clarke et al. 1999).

In this study the critical value of relative humidity in the mould growth index equation was chosen to be between 75-80% and the criterion for the mould index value 1, which indicates that some mould growth can be detected using a microscope. The values for relative humidity have been used in many studies (Nevander et al. 1991, Viitanen 1991, Pasanen 1992, Nevander and Elmarsson 1994, Samuelsson 1994), but it can be argued whether the value for the mould index is correct. However, once mould growth has started it can grow even after long dry periods, and thus the lowest limit value was chosen to be the critical one.

Weather data have a strong effect on mould growth in outdoor air-ventilated crawl spaces. In this study the calculations were basically calculated with the weather data of the year 1998, which was considered to be a typical year in respect of temperature and humidity conditions. In an outdoor air-ventilated crawl space it is impossible to avoid favourable conditions for mould growth if the outdoor air is very humid. In (II) the conditions in the crawl space were calculated with the modified weather data of 1979, i.e. the so-called Finnish test year, which had a humid and cold summer. In these conditions mould growth cannot be avoided, as reported in (II). Hyppel (1990) and Åberg (1993) reported similar conditions in the year of 1988. Therefore, in exceptional humid summers mould growth simply cannot be avoided in surfaces that are in contact with outdoor air.

The mould index used in this study to evaluate the acceptability of moisture conditions is a good measure for the durability of structures. However, the mould index is not a limit value for conditions indoors and it should be noted that even if the mould index shows a low risk of microbial growth sensitive inhabitants may have symptoms. Usually, in indoor environments the concentration of fungal spores in indoor air is measured. Elevated concentrations of fungi in residences have been associated with several health effects, such as respiratory symptoms and asthmatic symptoms (Waegemaekers et al. 1989, Björnsson et al. 1995). Some case studies have shown an increase in asthmatic and other respiratory symptoms and even an outbreak of occupational diseases due to exposure to mould (Hodgson et al. 1998, Seuri et al. 2000). However, in many studies no correlation between fungal levels and symptoms was found (Strachan et al. 1990, Klánová 2000, Su et al. 2001). Generally, the viable fungal counts have great temporal and spatial variations (Hunter et al. 1988, Pasanen 1992). Fungi fail to release spores continuously, and the release depends on ambient conditions (Pasanen et al., 1991).Therefore, short-time samples of viable fungi do not always indicate exceptionally high exposure to fungi.

6.4 Measurement of fungal spores

Generally, viable fungal counts exhibit great temporal and spatial variations (Hunter et al. 1988, Pasanen et al. 1991). Fungi fail to release spores continuously and the release depends on ambient conditions (Pasanen et al. 1991). Short-term samples of viable fungi are not always indicative.

Samples for airborne microbes were collected with a six-stage Andersen impactor. Majority of the results in Finland in respect of airborne microbes have been collected by using Andersen impactor, thus, this method was also used in this study to guarantee the comparability between previous and these results. Andersen impactor makes possible not only the identification of airborne microbes but also the determination of their size distribution. However, microbial cells that are unable to form colonies on the selected medium or cells that are not viable will not be detected. It is known that viable counts comprise only about 1% of the total counts of the spores in residential environments (Toivola et al. 2002). However, the six-stage impactor is one of the recommended choices for the collection of viable microbes proposed by the International Aerobiology Symposium and the American Conference of Governmental Industrial Hygienists (Jensen et al. 1992, Willeke and Macher 1999).

In a subarctic climate, the concentration of fungal spores indoors in summer is usually smaller than the concentration outdoors, whereas in winter the indoor/outdoor ratio is often over 1 in apartments, as well as in offices (Pasanen et. al. 1990). Generally, outdoor air is the main source of fungal spores and the seasonal variation is wide; there is a three-to-four order of magnitude in a subarctic climate (Finland). In this study the indoor/outdoor ratio in the summer was between 0.4 and 0.8 in most buildings, which is in the same range as measured in earlier studies, e.g. Reponen et al. (1989).

The indoor/outdoor ratios in this study did not differ between buildings with mechanical exhaust ventilation and mechanical supply and exhaust ventilation. However, according to an earlier study (Reponen et al. 1989), the indoor/outdoor ratio was higher in buildings with mechanical exhaust ventilation than in buildings with mechanical supply and exhaust ventilation. A reason for this might be that in this study all the measured buildings that had mechanical supply and exhaust ventilation were primary schools or day care centres and the measurements were taken during the working day, so that the influence of outdoor air on indoor air concentrations could not be avoided. Additionally, the clothes of the children might be potential carriers of spores (Pasanen A-L 1992).

The concentrations of *Penicillium* indoors and in the crawl space did not correlate (Pearson coefficient 0.11). *Penicillium* is a very typical fungus indoors and outdoors, and there are several sources of *Penicillium* indoors, which makes the correlation complicated. Furthermore, previous results show that *Aspergillus* and *Penicillium* spores are released into the air more easily than *Cladosporium* spores. This is one reason why *Penicillium* spores are common in indoor air (Pasanen et al. 1991). Compared to *Penicillium*, the size distribution of *Cladosporium* was clearly skewed towards bigger particles, indicating that *Cladosporium* spores were bigger and more uniform in their shape, as reported in the literature (e.g. Reponen 1994). On the other hand, previous studies have shown that the size of the spores increases when humidity increases (Pasanen A.-L. et al. 1991).

According to many studies the most abundant fungi found in indoor air has been *Penicillium*, together with *Aspergillus*, and *Cladosporium* (Hunter et al. 1988, Waegemaekers et al. 1989, Pasanen 1992a, Kuo and Li 1994, Li and Kuo 1994, Burge et al. 2000) as well as yeasts (Hunter et al. 1988, Pasanen 1992a). Kalliokoski et al. (2002) studied school kitchens and dining halls which are considered to be vulnerable for fungal growth due to large amounts of water used for cleaning. The dominant fungal genera and groups were *Penicillium*, yeasts, *Cladosporium* and *Aspergillus*, and these fungi were also the most common in the schools main study areas. In addition, they also reported that *Acremonium* was found frequently in the investigated schools. Hyvärinen et al. (1993) found *Acremonium* in 32% of air samples in problem buildings and 12% in reference buildings. In our study *Acremonium* was found in most of the studied buildings and the concentrations were relatively high, in average 160 cfu/m^3 in indoor air. The most common fungal genera were *Penicillium*, *Cladosporium* and *Acremonium*. Furthermore a relationship between the concentration of *Acremonium* indoors and in crawl spaces (Pearson coefficient 0.89) was found in our study. This will indicate that when there were high counts in crawl spaces the same was also the case in indoor air. As *Acremonium* does not have typical sources indoors, it most probably originates from a contaminated crawl space via leakage through the base floor.

Yeasts particles indoors were clearly bigger in size. Yeasts may have sources indoors, which seem to produce yeast particles in bigger size fractions. Also, the species of yeast might be different indoors and in the crawl space. There were only a few non-sporulating microbes, and their size distributions differed in the different environments. This may indicate different species growing on the plates.

There are many factors affecting the size of fungal spores, such as age, dehydration, agglomeration, and the relative humidity of the surrounding air. In an earlier study (Reponen 1994), it was found out that the most common fungal spores, such as *Penicillium, Cladosporium, Aspergillus,* and yeasts, have their maximum concentrations in the size range 2.1–3.3 µm. In our study, the maximum counts were observed in smaller fungal spores, between 1.4–2.6 µm, indicating that the fungal spores are mainly detected as single spores and not as aggregates. This size range is interesting, as the alveolar deposition of particles above 0.5 µm has a maximum at about 3 µm. Therefore, even small changes in particle size around this maximum value have an effect on the deposition pattern of particles (Reponen 1994).

The transport of inert particles through cracks has been studied in many studies. Vette et al. (2001) report penetration factors of 0.5-0.8 for particles in a size range of 0.5-2.5 µm. Mosley et al. (2001) found that at a pressure of 5 Pa 40% of 2-µm particles and <1% of 5-µm particles penetrate through horizontal slits of a height of 0.508 mm. In a study (Liu and Nazaroff 2001) particles of 0.1-1.0 µm are predicted to have the highest penetration efficiency, nearly unity for crack heights of 0.25 mm or larger at a pressure difference of ≥4 Pa. Raunemaa et al. (1989) had found Sulfur-containing particles of sizes below 1.5 µm to penetrate a filter unit easily, elemental removal efficiency being only 7%, in a ventilation system of a office building. These results are important and support the findings of study (V); most of the fungal spores were impacted at the stage corresponding to a mean aerodynamic diameter of 1.4 µm, which makes them very suitable for penetration through a base floor.

6.5 Penetration of particles and fungal spores through a structure

The experiments in the laboratory in (VI) were intended to simulate the entry of particles and fungal spores through building envelopes when all windows and doors are closed. The equation used to calculate the penetration factor (Eq 16) applies for inert particles and a possible source of uncertainty is the assumption that the penetration through all the other parts of the envelope except the floor under study is zero. However, the error is probably minor since the chambers were carefully rendered airtight and the leakage rate was measured. The estimation of the penetration of fungal spores is more complicated, since they can agglomerate and some of them are sticky on their surfaces, and additionally the shape of microbes is not always spherical. Furthermore, a steady state was not achieved and therefore the measured results were only indicative for fungal spores.

The penetration factor is strongly dependent on deposition velocity. Recent studies on particle deposition on indoor surfaces, e.g. Lai (2002), make it clear that the deposition rate varies broadly across conditions. Particle size is undoubtedly important. However, other factors can also influence the deposition rate significantly, including interior furnishings (quantity and type of surface) and indoor air movement. According to Thatcher et al. (2002), air movement from zero to 0.142 m/s (which is a typical air velocity indoors) increased the deposition rate by 15% for 1-μm particles and by 24% for 1.9-μm particles. Furnishings had a great impact on the deposition rate, which increased by over 100% for 1-μm particles at an air velocity of 0.054 m/s and 78% for 2.5-μm particles if the bare room was furnished (Thatcher et al. 2002). The highest deposition rates were mainly found in field settings (Abt et al. 2000, Long et al. 2001, Vette et al. 2001), where the control of experimental settings is limited. Even in the best conditions it is difficult to isolate deposition from the many competing factors that can influence airborne particle concentrations. In (VI) the deposition velocity used was a combination of measurements and theoretical assumptions from studies (Xu et al. 1994, Thatcher et al. 2002, Lai and Nazaroff 2000). The penetration factor was also calculated with other deposition velocities measured in similar chambers. Although the penetration factor in (VI) varied greatly, depending on deposition velocity, it still clearly demonstrated the fact that the penetration occurred even at lower pressure differences and that the penetration was highly dependent on pressure difference.

The penetration factors of particles within the range of 0.5-2.5 μm were, in recent studies (Liu and Nazaroff 2001, Mosley et al. 2001, Vette et al. 2001), between 0.5 and 1, depending on the dimensions of the cracks studied. These results cover the size distribution of fungal spores, and the peak of spores of 1-2 μm seems to be very capable of penetration if the length of the crack is higher than 0.1 mm (Liu and Nazaroff 2003). Liu and Nazaroff (2001) have estimated that penetration through mineral wool insulation is negligible. In (VI) there was mineral wool inside the structure, and, as the results showed, penetration occurred, since the installation of mineral wool is seldom perfect, allowing some routes for particles. The penetration factors determined in (VI) were significantly different than in former studies, indicating that the surface contacts of mineral wool are likely to have an important effect on penetration. The importance of surface contacts seems to be confirmed by tests with holes in surface boards, which did not have any effect on penetration.

The results of (VI) address an important question for the design and construction of buildings, because even the determined small penetration factors of 0.05 to 0.2 at a moderate pressure difference will cause elevated concentrations indoors if the crawl space is contaminated. Additionally, Pessi et al. (2002) have found that fungal spores can penetrate structures used as external walls if mechanical exhaust ventilation is used. It seems that it is difficult to control the penetration of fungal spores by sealing the building envelope, leaving pressurising the building as the only way to prevent penetration. A significant difference in penetration, between a 6 and 20 Pa under-pressure, was shown in (VI). Although pressurising is an obvious way to block penetration it may cause condensation in structures in cold climates. Thus, balanced ventilation is recommendable for cold climates in order to decrease the risk of penetration.

6.6 Important factors in designing outdoor air-ventilated crawl spaces in a cold climate

The key problem in cold climate crawl spaces is high relative humidity during summer caused by a low temperature. Low temperatures in the summer are the result of a time lag in thermal behaviour which is caused by the high heat capacity of the ground soil and foundations. In principle, the time lag can be decreased by increasing the air change rate or by decreasing the heat capacity.

Outdoor air-ventilated crawl spaces in cold climates can roughly be divided into two categories; relatively warm and cold crawl spaces. Typically, buildings with a low level of thermal insulation in the base floor have relatively warm crawl spaces due to heat flow from indoors. A crawl space may also have some other heat source e.g. district heating pipes. In a relatively warm crawl space temperature in summer can even be 20°C. In these crawl spaces moisture problems are easy to avoid; ground soil should be covered so as to prevent moisture flow from the ground and an air change rate of at least 0.5 ach is enough to keep relative humidity at a low level. Even a PVC sheet is enough to keep relative humidity low provided that it is not insulating relatively cold ground soil. However, a PVC sheet is not recommended because of the risks of a possible water leak into the crawl space. For a relatively cold crawl space a highly insulating ground cover is recommended. A highly insulated crawl space is not sensitive to the air change rate, and, thus, natural ventilation can be used. If a traditional thin layer on the ground is used, a higher ventilation rate is needed in the summer to warm up the crawl space and to decrease relative humidity. A safer way to construct a cold crawl space is to use a thick ground cover with a thermal insulation, e.g. 30-cm LWA, and a constant air change rate of 0.5 ach. In addition to thermal insulation, an LWA ground cover has moisture capacity and is able to decrease the highest peaks in relative humidity.

The use of ground covers with thermal insulation to prevent an increase in relative humidity is recommended in studies (I)-(III). These studies also stress the limited effect of air change rate on moisture control. However, these measures may not be sufficient to keep relative humidity below its critical value in respect of mould growth, especially during critical weather conditions. Weather conditions vary considerably during the year and, due to the high thermal capacity of a crawl space, the weather conditions of the previous year will affect the conditions as well. Microclimates too play an important role in crawl space conditions (Svensson 2001). It seems that during summers with high humidity a rise in relative humidity cannot be avoided in outdoor air-ventilated crawl spaces. Heating a crawl space is not often considered to be a solution for moisture control, due to the energy consumption involved. However, (IV) shows that with reasonable ground insulation and air change rate the annual specific energy consumption of heating is low, only about 2-3 kWh/m^2, which is, for example, usually about 1% of the energy consumption of a typical residential building (Aho et al. 1998).

In addition to thermal and moisture behaviour, an important factor in designing a crawl space is the pressure difference between crawl space air and that indoors. Residential buildings in Finland often have mechanical exhaust ventilation, where intake air comes through inlets and cracks. In cold climates, inlets may cause draughts in winter and consequently are often closed, resulting in a higher under-pressure indoors and increased infiltration through cracks. In most buildings the base floor between the first floor apartments and the crawl space is not air-tight. As the apartments have lower pressure than the crawl space due to mechanical exhaust ventilation, crawl space air may flow into the apartments. Field measurements in (V) showed that concentrations in a crawl space could be several orders of magnitude greater than indoors, and a correlation between concentrations of *Acremonium* spores indoors and in crawl spaces was established. Thus, a crawl space may be a possible source of indoor air contamination. Basically, the pressure difference between crawl spaces and indoors can be eliminated by causing an under-pressure in the crawl space. However, in Kurnitski's study (2000) it was demonstrated that mechanical extract ventilation in the crawl space could not remove the pressure difference at any realistic air change rate. Tightening the leakages in the base floor decreases the air flow, but, as the results in (VI) showed, even very small penetration factors can cause elevated concentrations indoors if the crawl space is contaminated. It is an open question whether crawl spaces can be made sufficiently clean for intake air to be taken from them. Obviously, the use of a balanced ventilation system in apartments and the careful sealing of leakages in the base floor are recommended.

Demands for further research

Moisture conditions in crawl spaces can be predicted with relatively good accuracy. However, it is still unclear how the results should be interpreted. Microbial growth is a complicated question, since significant differences exist among various species. It is also unclear what the causal agents of exposure and the mechanisms of the health effects are. Usually, in indoor environments the concentration of fungal spores in indoor air is measured. Elevated concentrations of fungi in residences have been associated with several health effects, such as respiratory symptoms and asthma, or even an outbreak of occupational diseases. On the other hand, many studies have shown no correlation between fungal levels and symptoms. The mould index used in this study to evaluate the acceptability of moisture conditions is a good measure for the durability of structures. However, the mould index is not a limit value for conditions indoors and it should be noted that even if the mould index shows a low risk of microbial growth, sensitive inhabitants may have symptoms. Criteria for microbiologically clean buildings are still an open question and further research is needed.

In the case of damage caused by moisture, a significant amount of contaminated materials can remain in structures even after repairs. Therefore, the potential transport of pollutants from and through structures has great importance in respect of the design and construction of buildings. An important topic for future research is to study which factors affect the release and penetration of pollutants and possible measures, such as sealing and pressurising, that can be taken to avoid these.

The possible danger for the occupants of dwellings lies in the production and spreading of disease-causing agents, i.e. pathogens. However, even though existing fungi may not spread pathogens, they may still become particulate matter. The studies published to date have focused on the penetration of nonvolatile particles. Fine particles often contain significant proportions of volatile constituents, such as water, organic compounds, and nitrates. The behaviour of such particles and their constituents in air leakage pathways could be considerably different from that of purely nonvolatile particles. Continued developments in this area would improve our understanding of how ambient particle sources might affect health. This might also lead to improvements in building design and operation that would reduce human exposure to outdoor particulate matter and fungal spores.

7. CONCLUSION

In this work outdoor air-ventilated crawl spaces in a cold climate were studied. The crawl spaces studied had either a wooden or concrete base floor (U value 0.2-0.4 W/m^{2}K). The results should not be generalised to other climates or other types of crawl spaces.

The most important factors causing mould growth in a crawl space are relative humidity, temperature, nutrition, and pH. In practice, relative humidity is the most significant factor causing mould growth in crawl spaces. Moisture control in an outdoor air-ventilated crawl space is problematic due to time lags in the thermal behaviour of the crawl space. Especially in the summer, the moisture conditions become problematic because the crawl space remains cold and outdoor air is usually warmer and has a higher moisture content than the air in the crawl space. Thus, in such conditions outdoor air can transport net moisture into the crawl space. This can be prevented by reducing the time lag between the outdoor air temperature and the crawl space temperature. The time lag is caused by the high heat capacity of the ground soil and foundations, and it can be decreased by increasing the air change rate or decreasing the heat capacity.

Moisture performance

Important factors in controlling moisture and, thus, mould growth in crawl spaces are the ground cover and heat losses to the crawl space. An ideal ground cover has a low thermal capacity and a high moisture capacity, as well as thermal resistance. A ground cover and other surface materials with a high moisture capacity decrease the peaks and level of relative humidity in a crawl space and therefore decrease the risk of mould growth. In a relatively cold crawl space lightweight clay aggregate and expanded polystyrene showed good moisture performance and in a relatively warm crawl space crushed stone and PVC sheets performed well. However, a PVC sheet is not recommended because of the risks of a possible water leak into the crawl space. The effect of ventilation rate was smaller than expected, as air change rates between 0.5–2.0 ach had only a minor effect on moisture performance in most cases. Only if PVC or crushed stone ground cover is used does the higher air change rate clearly warm up the crawl space in the summer and, thus, decrease relative humidity. However, a higher ventilation rate in the summer is also recommended in crawl spaces with thin layers of ground cover.

Satisfactory conditions in a relatively warm crawl space can be achieved if the ground is covered and the air change rate is between 0.5–1.0 ach. A relatively cold crawl space needs either 1) a ground cover with a moderate thermal resistance, e.g. 15-cm lightweight clay aggregate, and a higher air change rate in the summer, at least 2.0 ach, or 2) a ground cover with a high thermal resistance, e.g. 30-cm lightweight aggregate, and an air change rate of 0.5 ach, so that natural ventilation can be used.

In principle, relative humidity and temperature in a crawl space can be very close to outdoor humidity and temperature if the air change rate is very high and the entire thermal mass present in the crawl space is highly insulated. Heat losses through the base floor have an effect on crawl space temperature and, thus, moisture conditions. If the base floor U-value is reduced by half (U=0.4$\rightarrow$0.2 W/m^{2}K), the temperature in the crawl space is, on average, 2°C lower, and the relative humidity nearly 10% higher.

Insulation of the foundations and the location of the base floor insulation had minor effects on crawl space conditions. Temperature and relative humidity were nearly the same, regardless of whether the insulation was on or under the base floor slab. The insulation of the foundations had some effect on temperature and relative humidity when the ground was covered with LWA and the crawl space was small, i.e. the area of the crawl space was the same as that of the foundations. In the summer a crawl space without insulation in the foundations was slightly warmer and thus had lower relative humidity, since the heat flow from outside warmed the crawl space.

Heating a crawl space in summer is an excellent way to control relative humidity when the evaporation rate from the ground is low. If significant ground evaporation is suspected, it should be reduced by means of an appropriate ground cover. The advantage of heating is greatest if the ground cover has a high level of thermal conductivity; a lightweight clay aggregate ground cover performs well even without heating. Heating is best suited to renovation cases or those in which it is essential to avoid all mould growth.

The specific annual energy consumption for heating a crawl space is generally low, within a range of 1.4–3.6 kWh/m^2, if the controller set point value and ventilation rate are kept reasonable. The results may be formulated as a design guideline for cold climate crawl space design; a heated crawl space needs a heat output rate $\geq 2.5\ W/m^2$, a controller with a set point of 75% RH, and an air change rate of 0.5 $m^3/h,m^2$.

Transport of fungal spores

In mechanical exhaust ventilation, if the base floor has some leaks, pressure measurements show that air flows through leaks in the base floor into the apartment. The change of ventilation rate in the dwelling directly reflects that in the crawl space. In the worst cases, all the extract air from the crawl space may flow through the base floor to the apartment.

A comparison of fungal spore concentrations indoors, in crawl spaces, and outdoors usually demonstrates that the highest concentration is in the crawl spaces. In the buildings that were studied the size distribution of spores of fungal species was mainly similar in shape in the crawl space and indoors. The shape of the size distribution varied between fungal species.

In the field measurements the extent of the correlation between the fungal spores in the crawl space and indoors depended on the microbial species. The concentration of the most abundant species, *Penicillium*, did not correlate between crawl spaces and indoors. The concentration of *Acremonium*, which do not have a natural source indoors, correlated to the indoor concentration, indicating air leakage and fungal spore transport from crawl space air to that indoors.

In the full-scale laboratory measurements it was established that inert particles and fungal spores in the size range 0.6-2.5 μm penetrate a wooden structure at moderate pressure differences of 6-20 Pa. Measurements showed that the penetration was highly dependent on pressure difference and not dependent on holes in the surface boards of the structure. The results seem to show that the surface contacts of mineral wool with other building elements may play an important role in the penetration.

Laboratory and field measurements indicated that it is difficult to control the penetration of fungal spores by sealing the building envelope. The only effective way to avoid penetration seems to be balancing the building. However, in cold climates the moisture condensation risk should be taken into account. The penetration factors determined were highly dependent on pressure difference, being roughly twice as high, at 20 Pa, in relation to 6 Pa. This indicates that mechanical exhaust ventilation causing an underpressure in the building may cause health risks if some contamination exists in the building envelope.

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