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# HUMIDITY CONTROL IN OUTDOOR-AIR-VENTILATED CRAWL SPACES IN COLD CLIMATE BY MEANS OF VENTILATION, GROUND COVERS AND DEHUMIDIFICATION

**REPORT A3**

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Doctoral dissertation

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# ABSTRACT

This study shows that acceptable moisture conditions in cold climate outdoor-air-ventilated crawl spaces may be achieved by the optimal selection of ground covers and ventilation. The objectives were to find out which ground covers are suitable to use in relatively warm or cold crawl spaces of buildings and houses, which material properties of the ground covers are important for the reduction of crawl space relative humidity and for increasing temperature, to determine optimum air change rates, and to test dehumidification.

The field measurements were carried out in five crawl spaces, where alternative ventilation solutions, ground covers and dehumidification were tested. The measured data were used to develop a new crawl space model in a modular simulation environment, which was used for parametric simulations, where air change rates and ground covers were varied in relatively warm or cold crawl spaces. The model took into account ground moisture evaporation, moisture flows carried by ventilation and moisture transfer in the base floor and ground cover. The acceptability of moisture conditions was assessed by mould growth analyses based on the cumulative time of wetness and the time needed to start mould growth.

The results show that the ventilation system and air change rate are not the key issues in the crawl space moisture balance. Ventilation cannot compensate ground moisture evaporation, since increasing the air change rate will increase moisture evaporation if the ground is uncovered and therefore, crawl space relative humidity cannot be significantly decreased. Nevertheless, ventilation is always necessary if any moisture evaporation occurs. The crawl space may be left unventilated only when evaporation and other possible moisture sources are entirely prevented. The most important issue is the effective insulation of the cold ground with a sufficiently thick ground cover which makes it possible to increase the crawl space temperature and to reduce relative humidity during the most critical time in the summer.

In the relatively warm crawl spaces of apartment buildings moisture problems may easily be prevented by use of ground covers, which decreased relative humidity to a 60–70% level. The only one important property of a ground cover in these crawl spaces is moisture resistance. In cold crawl spaces the moisture conditions become much more critical in the summer. When relative humidity is higher than 75%, the acceptability of moisture conditions has to be assessed with mould growth analyses. The method developed is probably basically correct, but the details of the calculation of the time of wetness and the equations for mould growth in unstable conditions need further research. Ground covers need special properties in cold crawl spaces. High thermal insulation and low thermal capacity are evidently beneficial because they insulate the cold ground and decrease the thermal lag, and thereby increase the crawl space temperature. In the summer, the direction of the ground moisture flow is quite often reversed – the moisture flow is from air to ground cover. Therefore, the moisture capacity of the ground cover plays an important role as well. The importance of these properties is demonstrated by the behaviour of the plastic sheet cover which gave as high (90–100%) relative humidity as uncovered ground in the summer.

In cold crawl spaces appropriate ground covers and air change rates have to be used to achieve acceptable moisture conditions. A 15–30 cm lightweight aggregate and 5–10 cm EPS covers can be recommended for any crawl space. A plastic sheet cover should not be used in cold crawl spaces and uncovered ground should never be used in any crawl space. A cold crawl space with the above mentioned ground covers needs a two-step air change: 0.5–1 ach in the heating season and 2–3 ach in the warm season from May to October.

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# LIST OF ORIGINAL PUBLICATIONS

I Kurnitski J. Crawl space air change, heat and moisture behaviour. Energy and Buildings, 2000, **32**, 1, 19–39.

II Kurnitski J. Ground moisture evaporation in crawl spaces. Building and Environment, 2000, **36**, 3, 359–373.

III Kurnitski J, 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.

IV Kurnitski J, Vuolle M. Simultaneous calculation of heat, moisture, and air transport in a modular simulation environment. Engineering, Proceedings of the Estonian Academy of Sciences, 2000, **6**, 1, 25–47.

V Kurnitski J, Kalamees T. Moisture convection around a crack by pressurization. Engineering, Proceedings of the Estonian Academy of Sciences, 2000, **6**, 1, 48–60.

VI The following conference papers:

Kurnitski J, Matilainen M. Crawl space ground covers, air change and dehumidification to reduce humidity. In Proc. International Building Physics Conference, September 18–21, 2000, Eindhoven, The Netherlands.

Kurnitski J, Pasanen P. Crawl space moisture and microbes. In Proc. Healthy Buildings 2000, August 6–10, 2000, Espoo, Finland.

Kurnitski J, Pöysti M. Lightweight expanded clay aggregate ground cover moisture behavior in crawl spaces. In Proc. Healthy Buildings 2000, August 6–10, 2000, Espoo, Finland.

VII Matilainen M, Kurnitski J. Crawl space moisture control by means of the moisture capacity and thermal insulation of the ground cover, and ventilation. Building and Environment, submitted for publication, 2000.

The author is the main author of six publications (I–VI). In (III) the computer simulations were carried out by co-author Miimu Matilainen who also participated in the model development. A selection of studied cases and analyses were carried out by the author. In (IV) the calculation model was first developed and used in the simulation environment as a single component by the author. Co-author Mika Vuolle rewrote the code to be compatible with the existing model library making it possible to use the model as a component of a large model system. During this process, certain developments to the model were made by the authors. In addition, Vuolle gave his support for computer simulations also in (III), (VI) and (VII). In (V) co-author Targo Kalamees performed the laboratory measurements, the results of which were analysed by both authors. The test was designed and the computer simulations were performed and analysed by the author. In (VI) co-authors Miimu Matilainen, Pertti Pasanen and Mikko Pöysti carried out the computer simulations, microbial studies and worked out an example of structural solution respectively. In (VII) the first author was Miimu Matilainen. The model developments were performed by both authors and the calculated cases were mainly chosen by the author. The concept for assessing the acceptability of moisture conditions in crawl spaces was developed by the author. The computer simulations were carried out and analysed by Matilainen.

# 1 INTRODUCTION

## 1.1 Background

The crawl space foundation is a commonly used ground construction. In recent years a significant amount of crawl space repairs has been made in Finland. Mould and moisture problems, appearing mostly as mould smell in apartments, have been typical. In the repairs, crawl spaces are usually cleared of organic materials (which have been usually present in the crawl space since construction phase) and ventilation is increased. In some cases the repairs have been successful, but in others they have not. This has depended naturally on the measures applied, but the nature of the problems may also be different.

Some of the problems, such as surface water in the crawl space on the ground, are trivial and can be solved by rainwater sewerage and drainage. The key problem is high relative humidity during summer in "properly" constructed crawl spaces caused by a low temperature in the crawl spaces. Low temperature in the summer is the result of a time lag in thermal behaviour which appears particularly in crawl spaces with highly insulated base floors and is caused by the high heat capacity of the ground and foundations. To solve moisture problems, ground covers and proper ventilation can be used. In some cases heaters or dehumidifiers may be worth using in crawl spaces.

Another approach is not to use outdoor air ventilation. The crawl space may be left unventilated if the moisture insulation is perfect (Åberg 1990). The crawl space can also be warm (no insulation in the base floor, insulated crawl space) and mechanically ventilated by the exhaust air of the building (Anderson 1987, Lehtinen 1991, Hagentoft, Harderup 1993). As these applications are rather expensive due to high requirements for moisture and heat insulation, they have not been used on a large scale and therefore an outdoor-air-ventilated crawl space is the most common solution. In practice, the main question seems to be how the acceptable moisture conditions in outdoor-air-ventilated crawl spaces may be achieved.

In Finland two common types of outdoor-air-ventilated crawl spaces are used. The first is used mostly in non-wooden apartment, office and industrial buildings, built often from sandwich elements and hollow core slabs, Fig. 1.1. This construction is typical when foundations are on piles in clay ground soil. The second type is used in smaller buildings and houses often made of wood, Fig.1.2. These relatively cold crawl spaces with highly insulated wooden base floors are most problematic. They are the result of the development of foundations – energy saving and cost effectiveness has lead to highly insulated base floors and crawl space floor levels below ground level. The first type of crawl space is easier to make function well since the crawl space is usually warmer due to the lower insulation of the base floor and because there are no organic materials present in the crawl space.

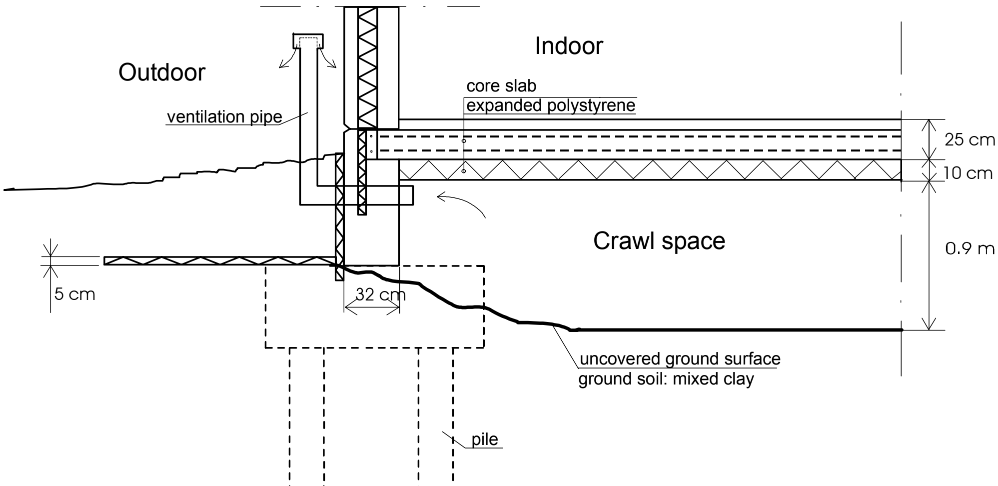



**Fig. 1.1.** An example of a crawl space used in non-wooden apartment, office or industrial buildings.

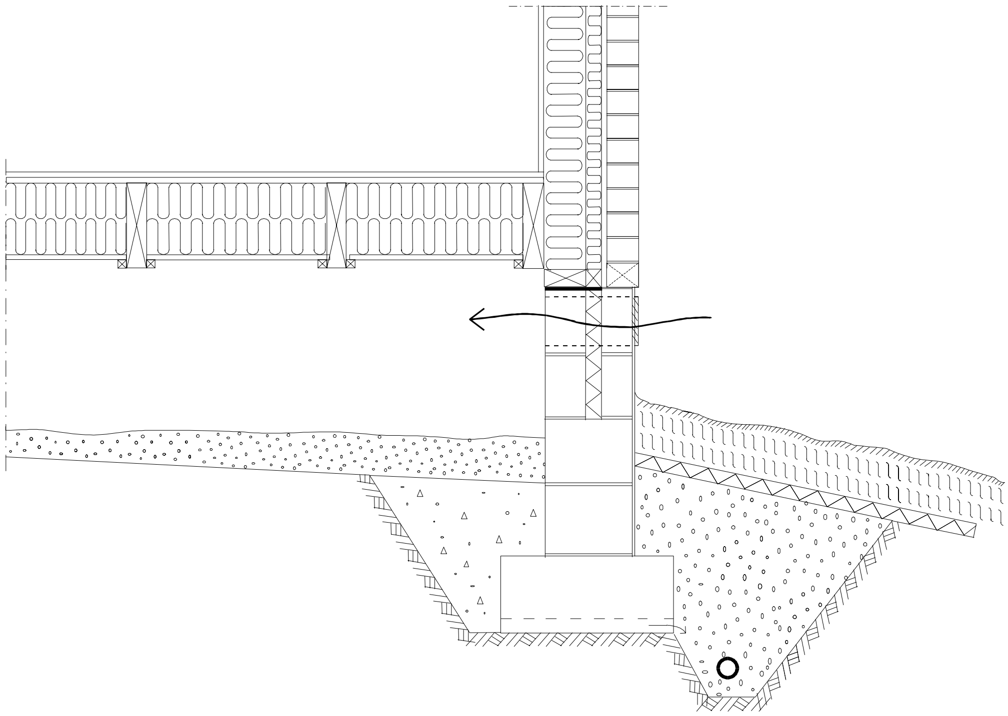


**Fig. 1.2.** An example of a crawl space used in wooden houses.

## 1.2 Objectives and contents of the thesis

The main objective is to find out the measures that can guarantee acceptable moisture conditions in outdoor-air-ventilated crawl spaces of buildings and houses. The working hypothesis is that at least the crawl spaces of non-wooden buildings may be made to function well by proper choice of ground covers and air change rate. In wooden houses, where conditions are more critical, additional requirements for ground cover heat insulation, heat and moisture capacity and a higher air change rate during the summer have to be specified. In addition, it is possible that in certain cases these measures are not sufficient and active measures, such as dehumidifiers or heaters, may be worth using.

The partial objectives of the study were the following:
1) To compare the behaviour of natural and mechanical extract, supply and balanced ventilation in crawl spaces
2) To evaluate the effect of the air change rate on crawl space relative humidity and to determine optimum air change rates with and without ground covers in the summer and heating season
3) To characterise ground moisture evaporation by determining evaporation rates and mass transfer coefficients from measured results and by using a convective heat transfer coefficient to calculate these values
4) To compare the effect of lightweight expanded clay aggregate (LWA), plastic sheet (PVC) and some other ground covers on relative humidity in crawl spaces
5) To determine the effects of thermal insulation and the thermal and moisture capacity of ground covers on crawl space temperature and relative humidity
6) To test the efficiency of dehumidification in crawl spaces
7) To analyse the moisture behaviour of wooden base floors and to assess the risk of condensation caused by under-pressure in the crawl space
8) To give some guidelines for the practical design of relatively warm and cold crawl spaces in the summer and heating season concerning the properties of ground covers, air change rates and acceptable values of relative humidity based on mould growth analyses.

The thesis consists of seven papers. The effect of ventilation on moisture behaviour in outdoor-air-ventilated crawl spaces of the apartment building with an uncovered and moist ground surface is studied in (I). Here, the mechanical supply and extract ventilation is compared in real conditions to natural ventilation. This is the most important novelty value of the study, in addition to continuous measurements of air change rates and pressure differences. The reduction of relative humidity using a plastic sheet cover is tested as well. The study consists of field measurements in which the conditions in naturally and mechanically ventilated crawl spaces of the test building are monitored during 1.5 years.

In (II) the ground moisture evaporation rates and mass transfer coefficients are determined in naturally and mechanically ventilated crawl spaces by using the results of field measurements carried out in (I). The correlations between air change and ground moisture evaporation rates, and air change rate and relative humidity are shown. Mass transfer coefficients are calculated from the convective heat transfer coefficient and compared with those derived from the results of the field measurements. As a part of this study, ground moisture evaporation measurements were carried out for certain materials in the laboratory by Kettunen (Kurnitski, Kettunen, et al. 1998). These results are briefly discussed. This study provides the first evaporation rates and mass transfer coefficients based on reliable measurements in situ, shows how they differ from laboratory measurements and calculated coefficients, and allows the detailed analyse of crawl space moisture balance.

A dynamic simulation of crawl space heat and moisture behaviour is carried out with an RC-network model in (III). An optimum air change rate with and without ground cover and the effect of thermal insulation on the ground in the outdoor-air-ventilated crawl space of the apartment building is determined by parametric simulation. The crawl space of the test building was modelled in an IDA-simulation environment, where the new module for crawl space calculations is developed. Moisture evaporation from the ground surface was included in the moisture balance, but moisture storage and flows in the constructions and the soil were not. The main novelty values of the study are the optimum air change rate values and the demonstration of the effects of the evaporation heat and thermal insulation calculated with the model validated against measured data.

In (IV) the new one-dimensional HAMWall-model for simultaneous heat, moisture and air transport calculations in a modular simulation environment is developed. This model is applied in (V, VI and VII) for crawl spaces' and base floors' moisture transfer calculations. It allows to take into account moisture transfer (moisture capacity) in base floors and ground covers. The model, which may be used as a single, independent model or as a component of a large model system, supplements the features of the indoor climate and energy model library (ICE) used for building simulation. The developed model adds an important feature to building simulation allowing to perform the simultaneous dynamic simulation of moisture transfer in addition to heat and air transport with real weather data.

A laboratory test and computer simulation to determine the effect of moisture convection caused by inside overpressure around the leakage in the wooden floor construction is carried out in (V). Here a new concept to characterise moisture convection is introduced. The accuracy with which moisture convection can be modelled with the one-dimensional HAMWall-model is tested and the limit value of inside overpressure for current construction is given. In modelling, the leakage airflow through a crack with known dimensions and glass fibre insulation is assumed to be divided on a certain area of permeable external wood fibreboard. This effective area is determined at the end of the laboratory test by measuring the area of the visibly wet surface where condensation has taken place.

The effects of LWA, expanded polystyrene (EPS), crushed stone and PVC ground covers, various air change rates, and dehumidification on crawl space relative humidity are compared in three crawl spaces of wooden houses and in two crawl spaces of the apartment building by means of one-year-long field measurements and computer simulations in (VI). In the wooden houses studied, the base floors were highly insulated and the crawl spaces were relatively cold compared to the crawl space of the apartment building which was significantly warmer. The crawl space model developed in (III) is improved here by the adoption of the HAMWall-model (IV) for moisture transfer in the base floor and ground cover. Therefore, the moisture capacities of the wooden base floor and ground covers are taken into account in the simulations because they play a significant role, particularly in the case of wooden buildings and certain ground covers. Parametric simulations are continued in (VII) where moisture storage effects are analysed and mould growth is evaluated by the calculation of the cumulative time of wetness which is then compared to the time needed to start mould growth. The last-mentioned is calculated with the equation that applies for wood and may be used in unstable conditions. Mould growth analysis made it possible to assess the acceptability of moisture conditions in critical cases (75–100% relative humidity), and to provide some guidelines for design. The novelty values of these studies are the demonstration of the effects of the moisture capacity and other properties of ground covers and base floors, the developed concept for assessment of the acceptability of moisture conditions and the results allowing to select ground covers and air change rates leading to acceptable moisture conditions in cold crawl spaces.

# 2 CRAWL SPACE HEAT AND MOISTURE BEHAVIOUR

Heat behaviour research in crawl spaces in respect to the controlling of heat consumption has a long tradition. A large amount of analytical heat transfer research has been carried out. A calculation model for the heat balance in a crawl space has been developed by Hagentoft (1986). Claesson has successfully applied dynamic thermal networks for the time dependent analytical calculation of crawl space temperatures and heat flows (Claesson 1999, Svensson, Claesson 1999). This allows the obtaining of a very compact model for the crawl space with any time-dependent air change and the accurate calculating of surface and air temperatures.

Moisture behaviour, especially the ground moisture evaporation, has a long research tradition as well. The first study was probably carried out by Britton in 1946 (Rose 1994). In this article he uses the term “crawl space” for the first time. Some soil evaporation experiments and research related to ventilation and vapour barrier requirements were carried out by Britton in 1947–1948. Moisture behaviour was analysed and recommendations for calculating ground moisture evaporation with constant moisture transfer coefficients were presented by Elmroth in 1975. These coefficients are used by many authors also today. Ground moisture evaporation rates were measured in situ with the lysimetry method by Abbot and Trethowen (1983, 1988) and in laboratory tests by Rantamäki (Nieminen, Rantamäki 1991). These results are not free of uncertainties; the handling of latent heat in field measurements and the controlling of the conditions on the surface of a sample in the laboratory tests were problematic. Evaporation rates were measured in the laboratory for certain soils and ground covers under controlled conditions by Kettunen (Kurnitski, Kettunen, et al. 1998).

Crawl space researches give an impression that moisture problems were relatively easy to avoid “in the good old days” by using ground covers and an air change. High relative humidity during the summer caused by a low crawl space temperature has not been reported as an unsolved problem in outdoor-air-ventilated crawl spaces built in the sixties or seventies. It seems that the changes in building tradition, particularly highly insulated base floors and crawl space floor levels lower than the surrounding ground level, have made crawl spaces more problematic.

## 2.1 Crawl space relative humidity

It is known that the behaviour of crawl spaces becomes problematic in the summer when, at least in the daytime, outdoor air is usually warmer and has a higher moisture content than the crawl space air. This means that outdoor air can transport net moisture into the crawl space and its relative humidity (RH) will rise. Samuelson (1994) reports a RH of 85–95% during the summer and 100% under extreme conditions over a period of several weeks. This has been the main reason why innovative solutions are being worked out for crawl spaces. The unventilated crawl space application introduces the perfect moisture insulation (Åberg 1990): if there is no moisture source, there is no need for ventilation. In a crawl space heated with indoor air (Hagentoft, Harderup 1993), the heat insulation level should also be relatively high to avoid condensation during the heating season. Can acceptable moisture conditions be achieved by the proper choice of the ground cover and air change rate or not is the main question for outdoor-air-ventilated crawl spaces. If these measures are not sufficient, dehumidifiers or heaters or, alternatively, unventilated or warm crawl space applications can be used.

Despite of the rather long tradition of crawl space research, the lack of information is evident in practical design. What the optimum ventilation rate is and how the moisture reduction should be established are the main questions being asked by designers and builders over the past decades. Rose (1994) concludes that there is general agreement in the literature that ground covers are effective in reducing humidity, but there is no convincing technical basis for current building code requirements for ventilation. In addition, there is no clear criterion available for crawl space RH. It is known that high RH causes mould growth and at least a period of several weeks is needed to start mould growth. However, the process is temperature and humidity dependent and probably air change has also a certain effect. It is possible to estimate mould growth risk on wood by calculating the time needed to start mould growth as a function of RH and temperature (Viitanen 1996).

Relative humidity in the crawl space is the result of ground moisture evaporation, the air change rate and thermal behaviour which are all strongly linked. The air change affects hygrothermal behaviour in opposing ways. In the heating season, the crawl space is warmer than outdoor air, and outdoor air with its low moisture content effectively removes moisture from the crawl space. At the same time, ventilation decreases the temperature of the crawl space, and if the air change is excessively high, this will increase RH. In the summer, outdoor air is periodically warmer than the crawl space and therefore ventilation works inefficiently. Outdoor air with a high moisture content even transports some net moisture into the crawl space on certain days in the summer. At the same time, ventilation warms up the crawl space and this decreases RH.

In the summer, thermal behaviour is the key issue in the crawl space moisture balance. It is evident that there is a time lag between outdoor air and crawl space temperatures caused by the high heat capacity of ground soil and foundations. In principle, the time lag can be decreased by increasing the air change rate or decreasing the heat capacity.

## 2.2 Limit values for acceptable relative humidity

Almost saturated conditions (RH > 95%) during weeks or months and temperature over 5ºC are needed to start rotting in wood (Viitanen, Bjurman 1995). Unfortunately a similar, clear criterion cannot be stated for mould growth. There is always a risk of mould growth if RH is over 75% and the temperature is in the range of 5–35°C (Viitanen, Ritschkoff 1991, Pasanen et al. 1998, Kokko 1999). In some references a slightly higher limit value for mould growth, RH of 80%, is given (Viitanen et al. 2000). There are moulds and their spore everywhere in our environment. To grow, mould fungi need appropriate nutrition and a suitable temperature, RH and pH. Most building materials have sufficient nutrients for mould growth, and usually pH is not a limiting factor (excluding new concrete). In crawl spaces the temperature is not the limiting factor either whereas RH over 75% and its impact time will determine mould growth.

A high RH can be accepted for short periods. There is no risk of mould growth if the period is shorter than the time needed to start mould growth in the conditions in question. Defining the time needed for harmful mould growth is a very complicated question; it does not only depend on time, temperature, RH and air change, but it depends also strongly on the material, it's surface and the foreign matter (usually dust which contains a great deal of nutrition) on the surface of it.

In (Hallenberg, Gilert 1993, Nevander, Elmarsson 1991) mould growth has been estimated with a risk factor having values between 0-1. This factor is a function of temperature and RH, but the duration time has not been taken into account. The equation of the time needed to start mould growth in wood (actually, only for pine and birch) is given by Viitanen (1996)

$$t_m = \exp\left(-0.68 \ln T - 13.9 \ln RH + 0.14W - 0.33SQ + 66.02\right) \tag{1a}$$

where $t_m$ is the time needed for mould growth to reach the microscopic stage in <u>weeks</u>, $T$ temperature (0.1–40°C), $RH$ relative humidity [%], $W$ wood species (pine = 0, birch = 1) and $SQ$ a factor describing nutrients on the wooden surface (a sawed surface after drying = 0 and the original surface after drying = 1). The higher the RH, the shorter the time needed to start mould growth. In the worst case (RH ≈ 95%, T = 20°C) it takes only 2 weeks to start mould growth in pine. Eq. 1a is valid only for wood. For other materials the equations will be different and they are not currently available for the crawl space temperature and humidity range.

For varying humidity and temperature conditions Viitanen interprets Eq. 1a as a differential equation (Viitanen et al. 2000)

$$\frac{dM}{dt} = \frac{1}{7 \cdot \exp\left(-0.68 \ln T - 13.9 \ln RH + 0.14W - 0.33SQ + 66.02\right)} \tag{1b}$$

where $M$ is mould growth index [-] and the time $t$ is given in <u>days</u>. The mould growth index represents the growth rate, $M$ = 0 corresponds to no growth, $M$ = 1 to some growth detected only with a microscope, $M$ = 3 some growth detected visually and $M$ = 6 very heavy and tight growth with coverage around 100%. When conditions become unfavourable, the mould growth will slow down and index $M$ will decrease. The delay of the mould growth when RH drops below the critical RH value is given by Viitanen by using the time (in days) passed from the beginning of the dry period ($t - t_1$)

$$\frac{dM}{dt} = \begin{cases} -0.032, \text{ when } t - t_1 \le 6 \text{ h} \\ 0, \text{ when } 6 \text{ h} < t - t_1 \le 24 \text{ h} \\ -0.016, \text{ when } t - t_1 > 24 \text{ h} \end{cases} \tag{1c}$$

80% RH is given as the critical RH value in (Viitanen 2000), which means that Eq. (1c) has to be applied when RH < 80%.

In practice, it is rather complicated to assess mould growth by taking material samples. There is always some mould growth in constructions in contact with outdoor air caused by outdoor air RH that often exceeds 75%. The construction functions well if the drying periods are long enough to reset contamination. Mould growth on wood progressed to a microscopic discern stage needs a roughly two-month drying period (RH < 75%) to reset contamination (Kokko et al. 1999). If drying periods are shorter than the time needed to reset contamination, the risk of mould growth should be estimated by cumulative calculation of the time of wetness.

To estimate the mould risk, the average RH values of two-week periods are chosen in this study since two weeks is the shortest possible period that can start mould growth (Viitanen 1996) and is long enough to perform manual calculations of cumulative time of wetness (TOW). In this work TOW is defined as the time when RH is above 75% (or 80% or 85%) and it is compared to $t_m$ to estimate the mould risk. Alternatively the dynamic model (Eqs. 1b and 1c) with hourly data is used for the prediction of mould growth.

## 2.3 Heat and moisture balance

To understand processes in crawl spaces and to model heat and moisture behaviour, the important heat and moisture flows determining conditions in a crawl space should be known. In general, an energy balance should be stated for crawl space air and a heat balance for the base floor, walls and ground. This is shown in (III). Radiation heat transfer can usually be considered only between the base floor and ground. When the evaporation from ground is calculated, the convective heat transfer coefficient on the ground surface has to be calculated. For other surfaces constant values may be used.

The moisture balance consists of moisture flows carried by air change and ground moisture evaporation, Fig. 2.1. With the notations used in Fig. 2.1, we have in a steady state

$$q_v v_{out} + g = q_v v_{air} + m \tag{2}$$

where $v_{out}$ is humidity by volume in supply air, i.e. outdoor air [kg/m$^3$], $q_v$ is the air change in the crawl space [m$^3$/s], $g$ is the ground moisture evaporation rate [kg/s], $v_{air}$ is humidity by volume in extract air, with complete mixing it is the same everywhere in the crawl space air [kg/m$^3$], and $m$ is the effect of dehumidification [kg/s] which is normally equal to zero.

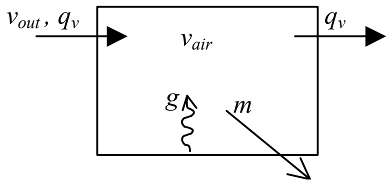



**Fig. 2.1.** Schematic air and moisture flows in a crawl space. *m* represents a dehumidifier and it is equal to zero without dehumidification.

Ground moisture evaporation depends on mass transfer on the surface and moisture transfer in the ground. Normally we have evaporation, but in the summer when the crawl space air temperature is higher than the ground surface temperature (due to high outdoor temperature), the direction may be reversed, Fig 2.2.

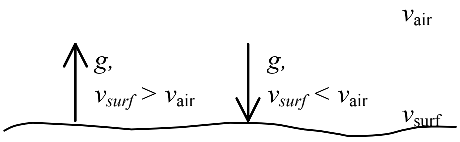
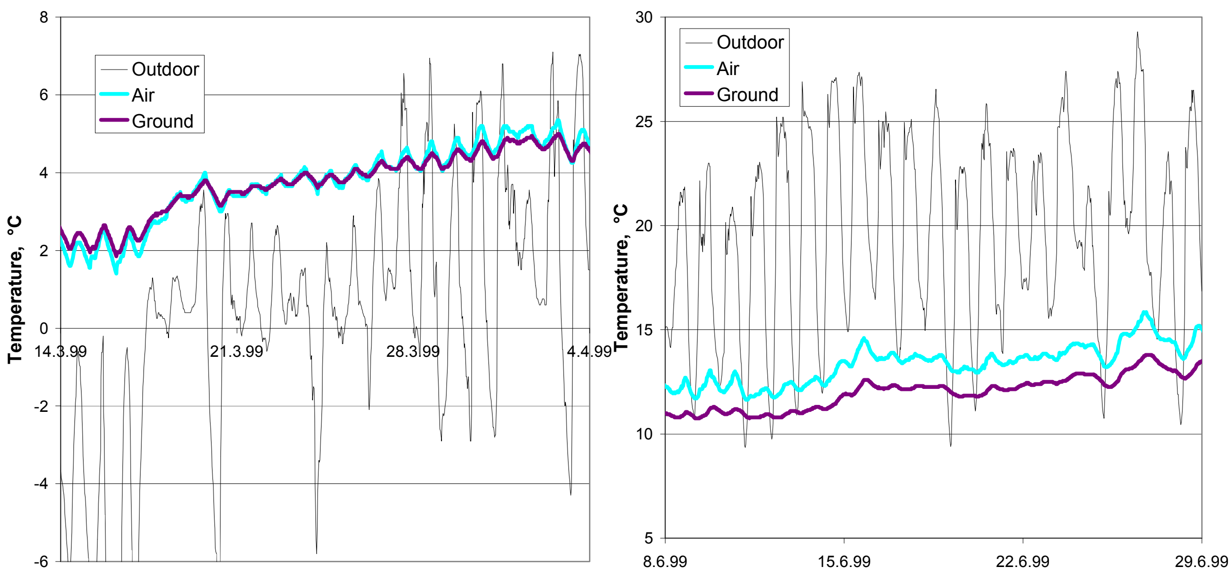



**Fig. 2.2.** Ground moisture evaporation or reversed moisture flow in a crawl space.

An example of crawl space thermal behaviour explaining possible directions of the ground moisture flow is shown in Fig. 2.3. In the heating season temperature differences between crawl space air and the ground surface are rather small; the ground might be slightly colder or warmer than the air. In the summer the air is often significantly warmer than the ground. If one considers 90% RH and 12ºC on the ground, the same moisture content of the air corresponds to 80% RH at 14ºC or 82% at 13.5ºC temperature.




a) b)

**Fig. 2.3.** An example of thermal behaviour in a cold crawl space (measured results) during three weeks in the spring a) and in the summer b). The base floor is highly insulated (U = 0.2 W/m$^2$ K), the ground (sand) is covered with 15 cm crushed stone and the air change is ≈1 ach.

When the ground surface is moist and the evaporation capacity is equal or lower than the moisture transport in the soil, the mass transfer determines the evaporation, Fig. 2.4. This situation is typical in the case of clay ground. The ground soil is saturated and $g$ can be directly calculated from the surface

$$g = \beta\left(v_{surf} - v_{air}\right)A_{eva} \tag{3}$$

where $\beta$ is the mass transfer coefficient [m/s], $v_{\mathrm{surf}}$ is humidity by volume on the ground surface [kg/m$^3$] and $A_{\mathrm{eva}}$ is the area of the evaporation surface [m$^2$]. In the case of an uncovered moist ground surface, the evaporation rate is often high and the evaporation heat affects crawl space thermal behaviour by decreasing the surface temperature. To take this into account the evaporation heat has to be included into the heat balance as is done in (III).

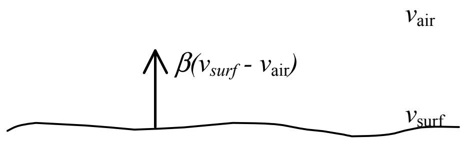



**Fig. 2.4.** The use of the mass transfer coefficient to calculate ground moisture evaporation from a moist ground surface.

When the very thin surface layer of the ground surface is not saturated, and if the drop of RH (and $v$) on the ground surface is taken into account ($\mathrm{RH}_{\mathrm{surf}} < 100$ %), the mass transfer coefficient may still be used to calculate evaporation with sufficient accuracy. If the unsaturated surface layer has a significant moisture resistance (with a magnitude of $1/\beta$) it begins to reduce evaporation and Eq. 3 will overestimate the evaporation rate. In practice, the evaporation rate is often calculated with Eq. 3, but the result is multiplied by a reduction factor to avoid overestimation. Some values of the reduction factors are given in (Elmroth 1975, Nieminen, Rantamäki 1991, Kurnitski, Kettunen et al. 1998). Rantamäki and Kettunen provide a moisture transport coefficient, which is a product of a reduction factor and a mass transfer coefficient, for various ground soils; the values are discussed in (II). It is evident that the use of reduction factors is a very approximate approach without any physical justification. It is based on the assumption that the moisture resistance of the unsaturated layer is constant – if the reduction factor has a constant value, it can only describe one resistance. In practice, the thickness of the unsaturated ground layer and the moisture permeability of the soil varies.

To calculate evaporation when the evaporation capacity is larger than the moisture transport in the soil or ground cover (the ground or ground cover is not saturated and has a remarkable moisture resistance), the moisture transfer in the ground or ground cover has to be taken into account. In the case of a ground cover of a thickness $d$ and known moisture permeability, the moisture flow $g$ can be calculated using the notations in Fig. 2.5

$$g = \frac{\left(v_{ground} - v_{air}\right)}{\frac{d}{\delta_v} + \frac{1}{\beta}} A_{eva} \tag{4}$$

where $\delta_v$ is the moisture permeability of the ground cover [m$^2$/s]. Since moisture transfer in vapour-resistant ground covers determines $g$, i.e. $1/\beta << d/\delta_v$, $1/\beta$ may be often omitted. For example, with 5 cm EPS-insulation the significance of $1/\beta$ is less than 1%. RH under the ground cover is usually assumed to be 100%. Eq. 4 may be applied for ground soil as well, if a surface layer with constant thickness is assumed. Alternatively, Fick's law may be used for moisture transfer inside the ground soil

$$g'' = -\delta_w \nabla w \tag{5}$$

where $\delta_w$ is the moisture transport coefficient [m$^2$/s] and $w$ is the moisture content in the ground soil [kg/m$^3$].

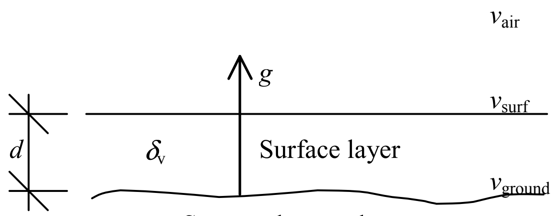



**Fig. 2.5.** Ground moisture evaporation when the surface layer has a significant moisture resistance

To determine the mass transfer coefficient, the convective heat transfer coefficient is usually used in engineering applications. The mass transfer coefficient based on the boundary layer theory can be stated as follows (Lampinen, 1996)

$$\beta = \frac{\alpha}{\rho c_p} \frac{\rho}{\rho_{BM}} Le^{1-n} \cong \frac{\alpha}{\rho c_p} \tag{6}$$

where $\alpha$ is the convective heat transfer coefficient [W/m$^2$ K ], $\rho$ is the density of air [kg/m$^3$] and $c_p$ is the specific heat capacity of air [J/kg K], $\rho/\rho_{BM}$ is the logarithmic density term [-] and $Le$ is Lewis' number [-]. The right-hand side of Eq. 6 is the most common expression for the mass transfer coefficient and it can successfully be used for crawl spaces because in the humidity and temperature range present in crawl spaces, the values of Lewis' number and the logarithmic density term are constant and close to 1. Still, it has to be noted that Eq. 6 is valid with the assumption of a laminar boundary layer, and theoretically it cannot be transformed into turbulent flow (Lampinen, 1996). However, in practice, Eq. 6 is widely used for turbulent flow as well.

To calculate the convective heat transfer coefficient, a lot of equations are available in handbooks. In crawl spaces free convection is usually in question since air velocities have relatively low values. Small temperature differences lead to low convective heat transfer coefficient values; in (II and VI) 0.5–2 W/m$^2$ K were obtained. The equations are different for heat transfer from a cold or a warm horizontal surface. During the heating season the ground surface is usually warmer than the crawl space air and in (II) reasonable results were obtained with equation

$$\alpha = 2.2\Delta T^{1/3} \tag{7}$$

where $\Delta T$ is the absolute value of the temperature difference between the crawl space air and the ground surface. In the summer, crawl space air, which is usually warmer than the ground surface, decreases heat transfer. In (VI), the following equation was used for the summer period

$$\alpha = 0.6\Delta T^{1/3} \tag{8}$$

The air velocity in the crawl space may be significant in the case of mechanical ventilation when forced convection might be useful to be taken into account [discussed in (II)].

The moisture capacity of building materials and ground in contact with the crawl space air affects RH in the crawl space in a similar way as the heat capacity affects the temperature. Moisture storage in the summer during moist periods may decrease RH in the crawl space air. Especially wooden base floors and some ground covers (such as LWA) can store and release a significant amount of moisture. To take into account the effects caused by the moisture capacity, the moisture transfer has to be calculated at least in the base floor and ground cover. This is possible when numerical calculations are carried out (VI, VII). Diffusive moisture transfer in structures and the corresponding moisture balance in one dimension according to Fick's law are

$$g'' = -\delta_v \frac{\partial v}{\partial x} \tag{9}$$

$$\frac{\partial w}{\partial t} = -\frac{\partial g''}{\partial x} \tag{10}$$

where $v$ is humidity by volume [kg/m$^3$] inside the material and $w$ is the moisture content of the material [kg/m$^3$]. It is also easy to apply Eq. 9 for a ground cover when a certain humidity boundary condition is assumed under the ground cover and the moisture transfer in ground soil is not calculated. This boundary condition can be for example humidity by volume corresponding to 100% RH. For numerical calculations, the time dependent moisture balance for crawl space air becomes from Eq. 2 (when dehumidification is not included)

$$V\frac{\partial v_{air}}{\partial t} = q_v v_{out} + g_c + g_f - q_v v_{air} \tag{11}$$

where $V$ is the air volume in the crawl space [m$^3$], $g_c$ and $g_f$ moisture flows from the ground cover and base floor [kg/s].

# 3 METHODS

In (I and II) 1.5-year-long field measurements on air change, RH and temperature, and pressure variations between two crawl spaces and apartments were carried out in the crawl space of a four-storey apartment building. The test building represents a typical apartment building, built from precast concrete elements in 1979. The crawl space was relatively warm due to the high U-value of the base floor (0.38 W/m$^2$ K), and the ground surface (mixed clay) was moist and uncovered. The aim of measurements was to compare the behaviour of natural ventilation to mechanical ventilation, to determine the ground moisture evaporation rate and mass transfer coefficients on the ground and to test the effect of the air change rate on RH and ground moisture evaporation. To compare natural and mechanical ventilation, the crawl space was divided into two parts. Natural ventilation was maintained in the first part and mechanical extract, supply or balance ventilation was arranged in the second part by the use of duct fans. The air change rate was measured continuously by monitoring the pressure loss in all ventilation pipes. This made it possible to evaluate the ground moisture evaporation rate from the steady state moisture balance (Eq. 2). The measurement technique of the air change rate was tested with instant tracer gas measurements. The age of the air at different locations in the crawl space, which indicates the air-mixing rate, was measured with tracer gas as well. During the measurements it became apparent that pressure conditions may strongly affect natural ventilation and crawl space RH. Due to this reason, balanced mechanical ventilation was tested, and the pressure differences between the crawl spaces and between the naturally ventilated crawl space and a ground floor apartment were monitored.

Relative humidity and temperature were measured with Vaisala HMP44 humidity and temperature probes with a given accuracy of ±2% RH and stability of 1%RH/year. The probes were checked before and after the measurement period. The two point calibration at 75% RH (NaCl) and 100% RH (overheated water) was carried out. If necessary, the calibration coefficients of the sensors – offset and gain – were shifted. This was usually not necessary since the sensors were new and the calibration certificates proved to be valid. Still, there were some probes which did not remain stable – the calibration measurement before and after the measurement period showed a larger than 5% difference in RH. It was possible not to use the results measured with these probes as they were not located at the main measurement points.

The crawl space of the test building of (I, II) was modelled in (III). The RC-network model was developed in an IDA simulation environment (Sahlin 1996). IDA is a modular simulation environment that consists of a NMF-translator, solver and modeller. In modular simulation environment, the modules and solver are separated and the modules are handled as data, i.e. for the same component completely different mathematical formulations may be used without any changes in a model description file. The module system may be hierarchical; modules are linked and boundary conditions given in a model description file. Several module libraries concerning building and HVAC-components are available for building simulation. The modules are written in Neutral Model Format (NMF), serving at the same time as a readable document and computer code. Every module consists of equations as well as link, variable and parameter definitions. The model uses the steady state moisture balance (Eq. 2) and evaporation is calculated from the convective heat transfer coefficient which is determined from temperature differences. In heat transfer modelling the main simplification is the heat transfer in ground soil. This is modelled by means of three semicircular heat flow patterns – one of these describes heat conduction through the foundation and the rest in ground soil, Fig. 3.1.

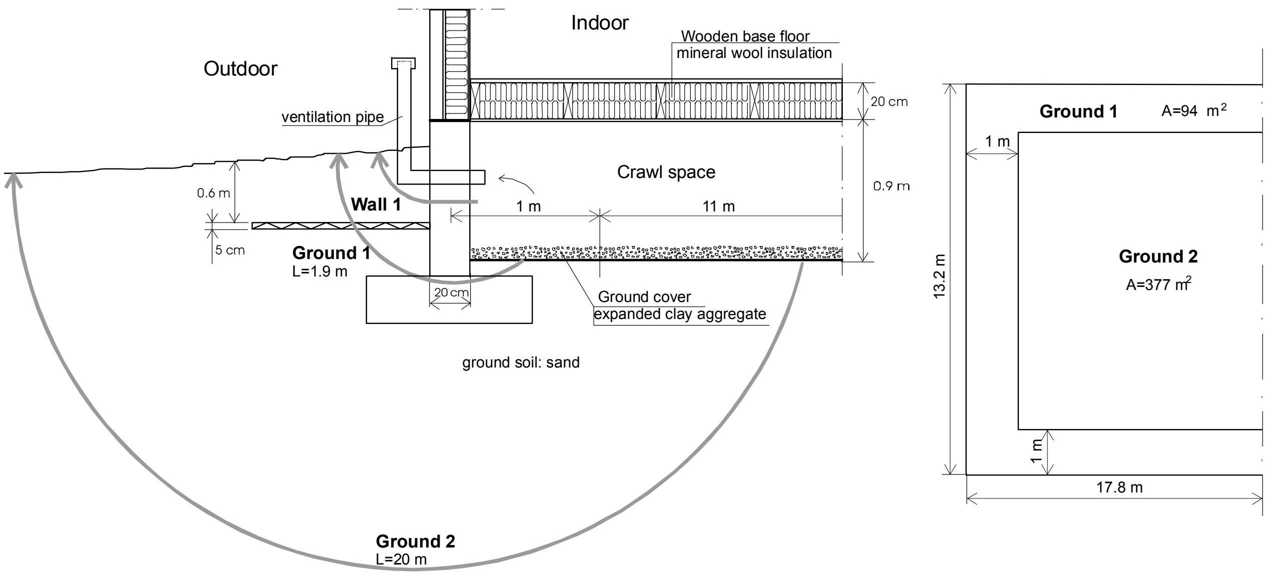



**Fig. 3.1.** Semicircular heat flow patterns in ground and floor area division in the crawl space of the wooden building (VII). The same heat flow patterns are used in (III).

To study moisture convection effects in the base floor and moisture capacity effects in the crawl space, the moisture transfer model HAMWall for an IDA simulation environment was developed in (IV). The model calculates simultaneous heat, moisture and air transport in the modular simulation environment and it supplements the features of the indoor climate and energy model library (ICE) that is used for building simulation. The model may be used as a single, independent model or as a component of a large model system, where all the features of the used modular simulation environment can be utilised. Humidity by volume $v$ is used as a moisture transfer potential, the enthalpy is calculated, condensation is taken into account and all equations are solved simultaneously. The moisture flow and moisture balance equations are the following

$$g'' = -\delta_v \frac{\partial v}{\partial x} + \frac{M_a''}{\rho_a}\left(v - v_{ref}\right) \tag{12}$$

$$\frac{\partial w}{\partial t} = -\frac{\partial g''}{\partial x} = -\frac{\partial}{\partial x}\left(-\delta_v \frac{\partial v}{\partial x} + \frac{M_a''}{\rho_a} v\right) \tag{13}$$

where $M_a''$ is the air mass flow [kg/s m$^2$], $\delta_v$ moisture permeability [m$^2$/s], $\rho_a$ density of air [kg/m$^3$], $v_{ref}$ an arbitrary reference humidity by volume [kg/m$^3$] and $w$ the moisture content of the material [kg/m$^3$]. Moisture permeability may be given as a function of RH. Sorption isotherms can be given by a linear fit (in two parts) or by logarithmic equation.

The HAMWall-model is applied to the wooden base floor in (V). Here the laboratory test and computer simulation to determine the effect of moisture convection caused by inside overpressure around the leakage in the wooden floor construction was carried out. The purpose of the study was to test with which accuracy moisture convection can be modelled with a one-dimensional model. In the modelling, it was assumed that the leakage airflow through a crack with known dimensions and glass fibre insulation is divided over a certain area of permeable external wood fibreboard. This effective area was determined at the end of the laboratory test by measuring the area of the visibly wet surface where condensation took place. The simulation was carried out with the HAMWall using the effective area and airflow through the crack.

The HAMWall-model was used to calculate moisture transfer in the base floor and ground cover in (VI and VII). This made it possible to take the moisture capacity of structures into account in crawl space calculations. The crawl space model developed in (III) was used here as a starting point. The RCWall-module used for heat transfer in the base floor was replaced by HAMWall. HAMWall module was added for the ground cover as well. It calculates heat and moisture transfer in the ground cover only. For moisture transfer a constant boundary condition (humidity by volume corresponding to 100% RH) was used on the lower surface of the ground cover. Moisture transfer in ground soil was not calculated and the heat transfer was calculated with the RCWall-module as in (III). The behaviour of several ground covers and the wooden base floor was analysed. In (VII) mould growth was evaluated by calculating the cumulative time of wetness and comparing it to the time needed to start mould growth (Eq. 1).

The behaviour of a lightweight expanded clay aggregate (LWA) ground cover and a dehumidifier was tested by carrying out field measurements in the relatively warm and cold crawl spaces in (VI). The measurements of RH, temperature and air change were carried out in three test buildings. The first building was the same which was studied in (I, II), there only the LWA ground cover was added. This building was a typical apartment building with a relatively warm crawl space (U-value of the base floor 0.38 W/m$^2$ K). The second building was an 11 years old one-storey wooden day care centre which represents building technology used in detached houses. In this building the crawl space was rather cold due to a highly insulated base floor (U = 0.2 W/m$^2$ K). In both the buildings, the air change in crawl spaces was between 0.5–1 ach. In the apartment building, it was possible to evaluate the ground moisture evaporation rate and the drying effect of the dehumidifier from the moisture balance because the air change rate was monitored. In the wooden building this was not possible due to only approximate instant measurement of air change from extract fans. The third building was a wooden two-storey apartment building with constructions similar to the wooden day care center, and with moist sand on the ground. In this building the air change rate in the crawl space was very low and dehumidification was tested to reduce the high RH.

# 4 RESULTS

## 4.1 The effect of ventilation on moisture behaviour

The effect of the air change rate on RH in crawl spaces was a highly pressing question when the current study was begun. Typically, many crawl spaces have been repaired by increasing the air change rate by adding ventilation pipes, openings or extract fans, and by cleaning crawl spaces from organic materials and other rubbish. Quite often uncovered ground surface is maintained in crawl spaces. In (I, II) the effects of the ventilation system and the air change rate on RH and ground moisture evaporation are studied in relatively warm crawl spaces, where there are good chances to avoid moisture problems. Natural, extract, balanced and supply ventilation with air change rates up to 4 ach (1 ach ≈ 1 $m^3/h\ m^2$ as the height of the crawl space is ≈ 1m) are tested. The ground soil in the studied crawl spaces was mixed clay with a moist and uncovered surface.

Mechanical extract ventilation surprisingly showed a significantly higher RH than natural ventilation with a lower air change rate did. RH is shown in Fig. 4.1, where at the beginning, natural ventilation was applied in both crawl spaces. At 1) extract ventilation was started in the mechanically ventilated crawl space. To decrease RH with ventilation, it was necessary to change extract ventilation to balanced ventilation; supply ventilation showed the same behaviour as balanced ventilation – RH was lower compared to natural ventilation.

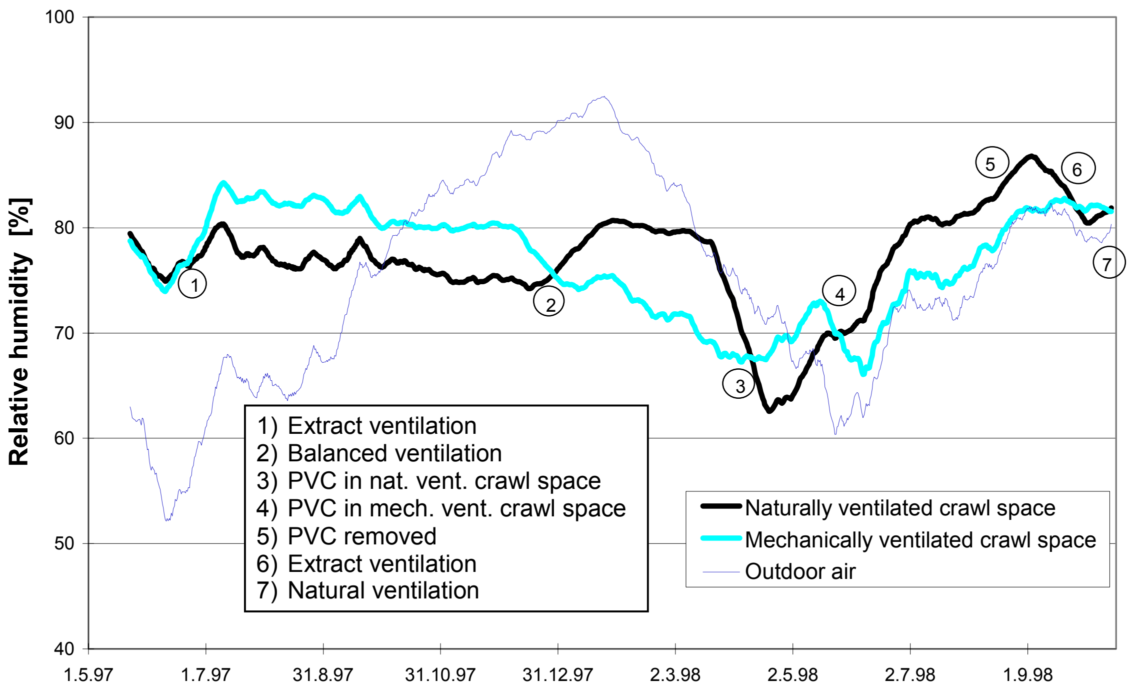



**Fig. 4.1.** Monthly moving average of RH in naturally and mechanically ventilated crawl spaces of the apartment building.

High RH during extract ventilation can be explained by under-pressure causing flows through drainage pipes and gravel, permeable soil and possibly by some direct leakage from adjacent sections of the crawl space. These air flows transport moisture and raise RH in the crawl space. To what extent the phenomenon was caused by ground flows and to what extent by direct leakage from the adjacent sections of the crawl space did not become completely clear. (Possible leakage points were sealed with polyurethane foam, but there was a possible flow path between two adjacent sections of the crawl space, through drainage gravel and pipes installed in the crawl space side along the external walls.) Still, the effect of higher RH was noticed also during the period with one supply and two extract fans when under-pressure was only about 0.5 Pa.

The pressure difference between the crawl space and apartments strongly affected the air change rate in the naturally ventilated crawl space. This was easy to notice because two-speed fans were used in the exhaust ventilation system of the building. Full speed increased under-pressure in apartments as well as the pressure difference between the crawl space and the apartments. This change can clearly be seen at the supply air flow rate through ventilation pipes to the crawl space, Fig 4.2. The zero value of extract flow through ventilation pipes indicates that almost all of the extract air flows through the base floor to the apartments (extract flow through ventilation pipes has only some peaks in windy weather). Thus, a significant amount of the intake air of the base floor apartments came from the crawl space. In order to be acceptable, crawl space air should have the same quality as outdoor air.

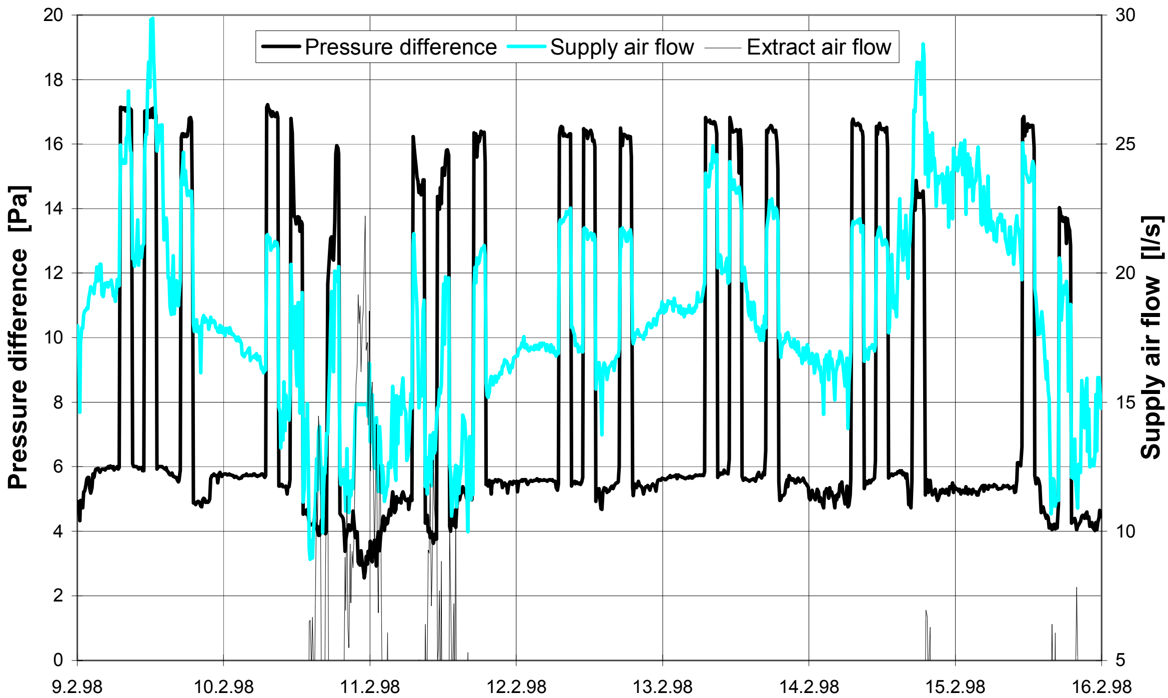
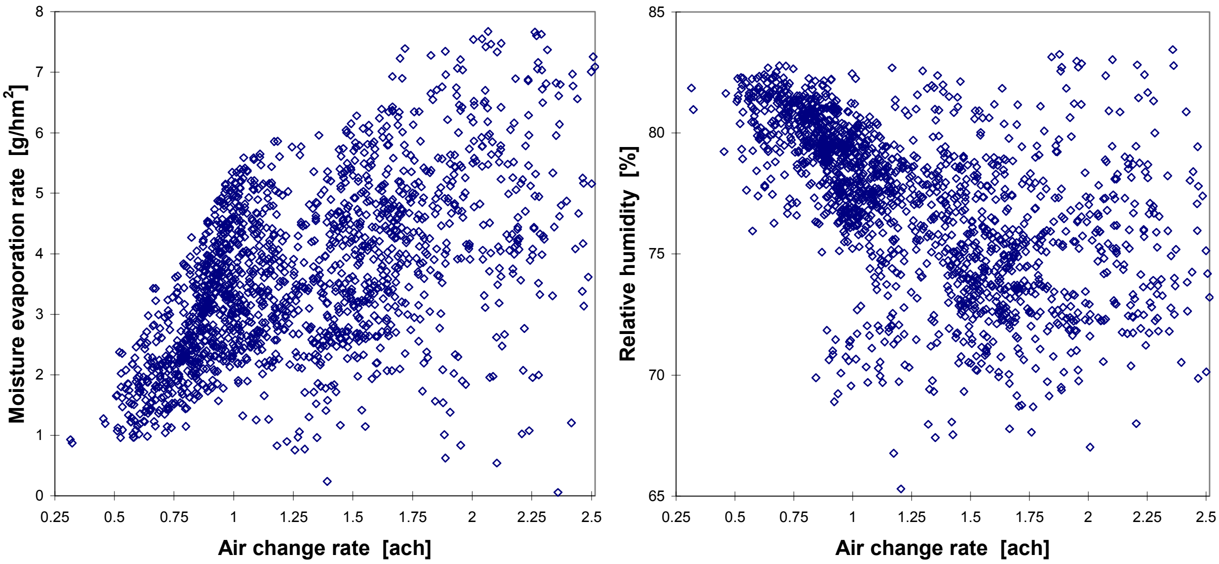



**Fig. 4.2.** Pressure difference between the crawl space and apartments (under-pressure in apartments) and crawl space air flows through ventilation pipes (20 l/s corresponds to 1 ach) during a typical week.

The results of the measurement of RH, air change rate and calculated ground moisture evaporation indicate that higher air change rates have led not only to a slightly lower RH, but also to higher moisture evaporation. This can clearly be seen from the correlation shown in Fig. 4.3. The correlations between the moisture evaporation rate and air change, and between RH and air change are depicted during the period before the plastic sheet was laid on the ground in the naturally ventilated crawl space. The R-squared value is about 0.4 in the whole range for both correlations. For the mechanically ventilated crawl space a corresponding correlation cannot be drawn because the air change rate was constant. The moisture evaporation rates and RH are studied in (II), but, in general, air change effects were overrun by the effect of pressure conditions in the mechanically ventilated crawl space (i.e. extract or supply ventilation had a greater effect on the RH and evaporation rate than the air change rate had).




a) b)

**Fig. 4.3.** The correlation between the calculated moisture evaporation rate and air change a) and between measured RH and air change b) in the naturally ventilated crawl space. (2.5-h averages)

## 4.2 Ground moisture evaporation from uncovered surface

The ground moisture evaporation rate from an uncovered ground surface is determined in (II) from the steady state moisture balance (Eq. 2), Fig. 4.4. The evaporation rate was clearly higher when a significant under-pressure (caused by extract ventilation) occurred in the crawl space. Thus, during these periods the evaporation rate includes some moisture convection flows, as under-pressure cannot affect pure evaporation. In the summer, some negative values indicate condensation. The strong fluctuation of the evaporation rate may be caused by the assumption of a steady state: the moisture capacity is not taken into account. However, the numerically calculated values that are discussed afterwards show also high fluctuation. The average value of moisture evaporation from an uncovered ground was 3.6 g/h m$^2$ in the naturally ventilated and 5.7 g/h m$^2$ in the mechanically ventilated crawl space, when the periods with extract ventilation are not considered. These values can be considered very high because the ground surface was almost saturated and the crawl space was rather warm.

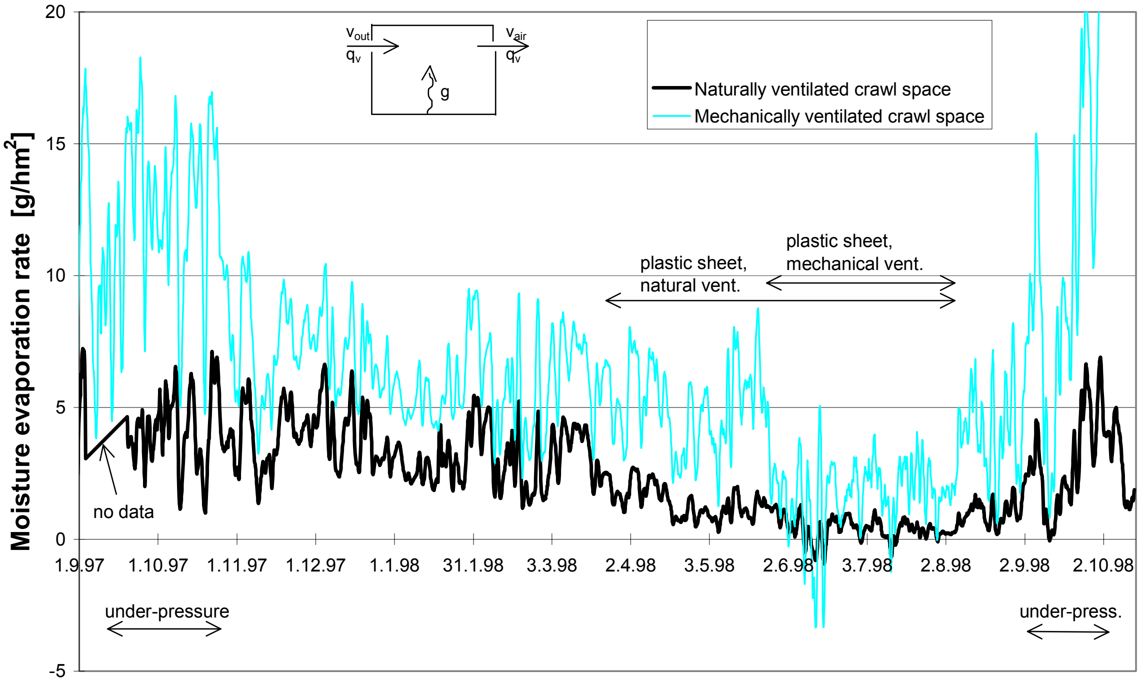



**Fig. 4.4.** Calculated ground moisture evaporation rate (24-h moving averages).

RH on the ground surface depended on the moisture evaporation rate. In the naturally ventilated crawl space a clear negative correlation was found, Fig. 4.5. High evaporation rates caused slight drying of the surface in both crawl spaces.

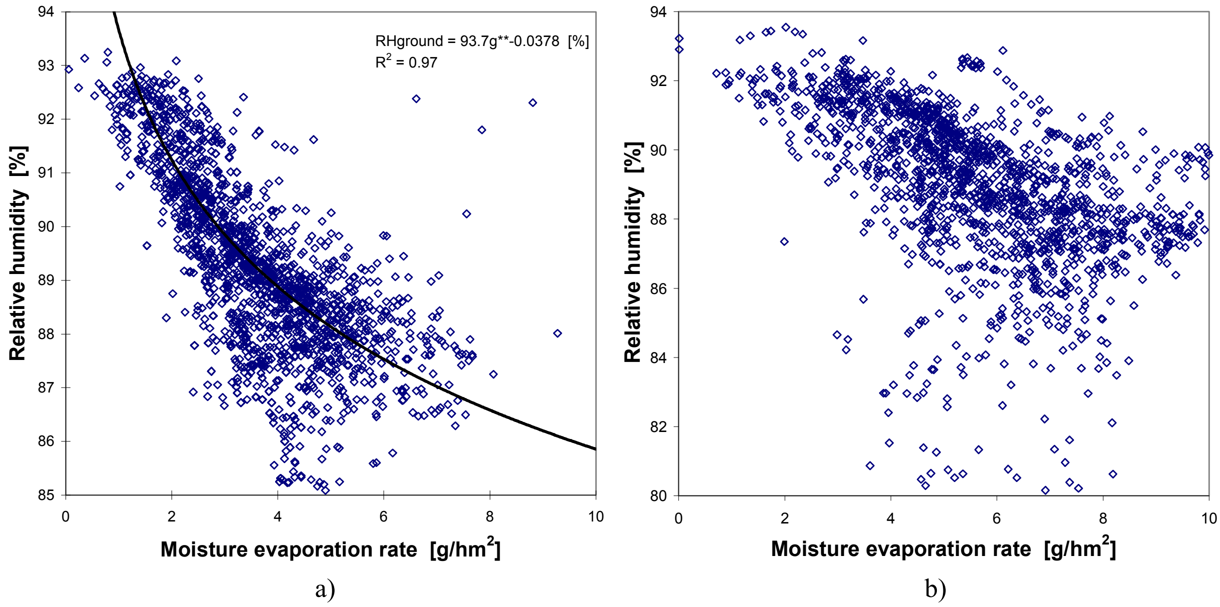



**Fig. 4.5.** The correlation between measured RH on ground and calculated moisture evaporation in the naturally ventilated crawl space a) and in the mechanically ventilated crawl space b). (2.5-h averages)

Mass transfer coefficients were determined from moisture evaporation Eq. (3) by using the calculated ground moisture evaporation rate. In order to operate with more convenient values, the mass transfer coefficients were expressed as convective heat transfer coefficients

(Eq. 6), i.e. multiplied by $\rho c_p$ (1250 J/m$^3$ K). The results are shown in Fig. 4.6 and 4.7 for naturally and mechanically ventilated crawl spaces, where the values determined from Eq. (3) are compared to values calculated from the temperature differences. The coefficients are not defined when ($v_{surf} - v_{air}$) in Eq. (3) approaches zero, and this can be seen as a sharp fluctuation from time to time in Figs. 4.6 and 4.7. Significantly, the values of the naturally ventilated crawl space agree reasonable without using any reduction factor for ground moisture evaporation. The values of the plastic sheet periods are not correct because ($v_{surf} - v_{air}$) is measured under the plastic. It is also notable that after removing the plastic sheet it took some time before the values reached the previous level.

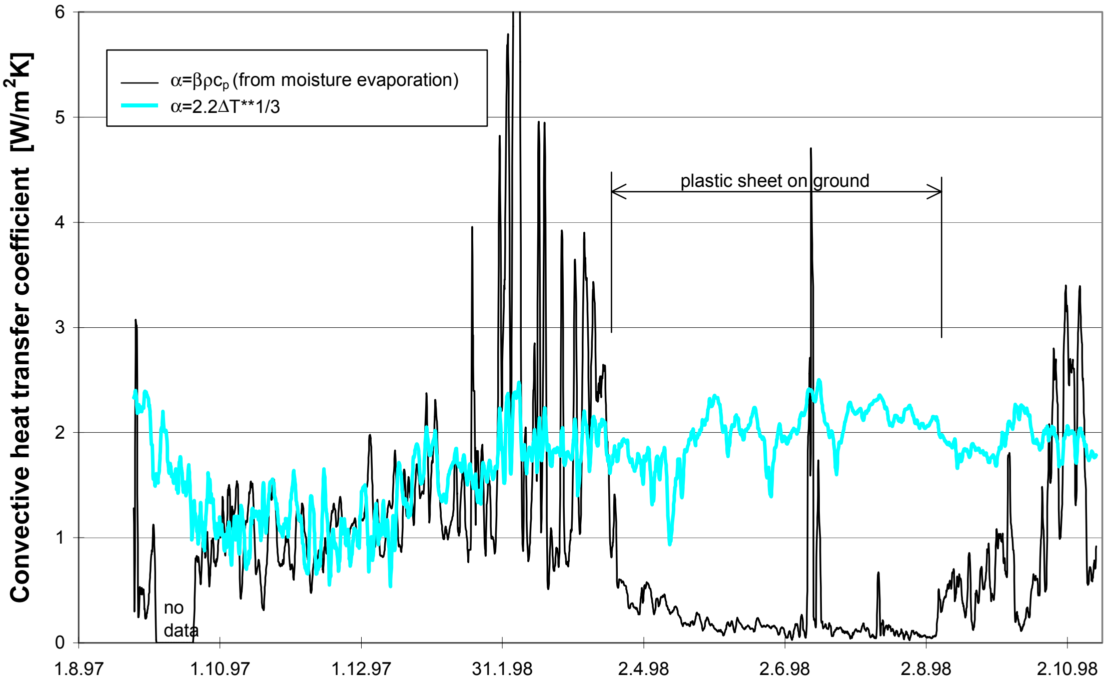



**Fig. 4.6.** The convective heat transfer coefficient in the **naturally ventilated** crawl space calculated from moisture evaporation and the corresponding coefficient calculated from temperature difference. (24-h moving averages)

For the mechanically ventilated crawl space, Eq. (7) underestimated the mass transfer coefficient, because the air change rate was high (2.3–4.4 ach) and the air movement on the ground was significant. With the addition of the velocity term to the equation, known from equations of forced convection, the results were closer to the coefficient calculated from moisture evaporation.

The high values of the mass transfer coefficients during extract ventilation periods are caused by moisture convection flows that are included in the moisture evaporation rate value calculated with Eq. (3). Such moisture convection flows through permeable soil and drainage gravel, and possible direct leakages from adjacent sections of the crawl space were caused by under-pressure in the crawl space and could not be quantified from the measured results. Thus, the moisture balance Eq. (2) is incorrect during extract ventilation periods because there is no convection term that must be kept separate from evaporation. Therefore, the mass transfer coefficients calculated with Eq. (3) are overestimated.

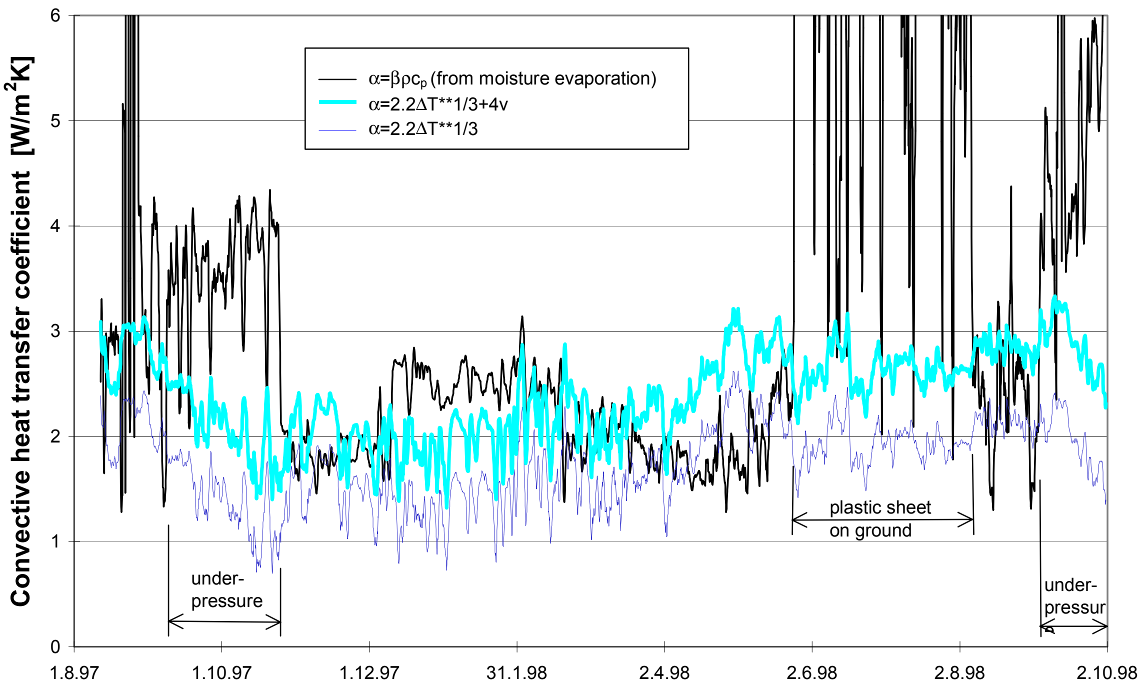



**Fig. 4.7.** The convective heat transfer coefficient in the **mechanically ventilated** crawl space calculated from the moisture evaporation and the corresponding coefficient calculated from temperature difference. (24-h moving averages)

In the naturally ventilated crawl space the average value of the convective heat transfer coefficient was 1.5 W/m$^2$ K (Eq. 3), and the corresponding value calculated from the temperature difference (Eq. 7) was 1.4 W/m$^2$K. These correspond to mass transfer coefficients 0.0012 m/s. In the mechanically ventilated crawl space the average value was 2.2 W/m$^2$K (0.0018 m/s) and the value calculated from temperature difference 1.7 W/m$^2$ K (0.0013 m/s). This value increased to 2.3 W/m$^2$ K when the velocity term was added to Eq. (7). The determined mass transfer coefficients were compared in (II) to the results reported in previous studies. In general, the results were satisfactorily congruent with the laboratory measurements carried out by Rantamäki and Kettunen.

## 4.3 The effect of air change rate on RH and evaporation rate in relatively warm crawl space

In (III) the measured data from the test building of (I, II) was used to develop the crawl space model that was then used to carry out parametric simulations. The air change rate was varied between 0–10 ach (1 ach ≈ 1 m$^3$/h m$^2$, as the height of the crawl space is ≈ 1 m) to study moisture behaviour with a covered and uncovered ground. First, the crawl space temperature was calculated as a function of the air change rate with an uncovered ground. The crawl space was clearly the warmest all year round with no ventilation. 0.5 ach gave an already significantly lower (by 3–6ºC) temperature in the crawl space. This can be explained by evaporation that in addition to outdoor air cools the crawl space down. When RH in the crawl space was calculated with a zero ground moisture evaporation rate, no ventilation at all gave the lowest RH, but 0,5–1 ach air change caused only small differences in RH. In these cases RH was less than 60% all year round. These results demonstrate the principle of an unventilated crawl space application – the unventilated crawl space is warmest and driest in a cold climate if the moisture insulation is perfect.

RH in a crawl space with an uncovered ground is shown in Fig. 4.8. With an uncovered ground zero ventilation has brought about almost a saturated state. In the summer there is no upper limit for optimum ventilation: the higher the air change, the lower the RH, and in winter, 2–3 ach gives the lowest RH. The corresponding moisture evaporation rates with an uncovered ground surface are shown in Fig. 4.9. The relation between the air change rate and evaporation rate is not linear; there is certain flexibility in moisture evaporation, i.e. higher air change rates have clearly increased the evaporation rate.

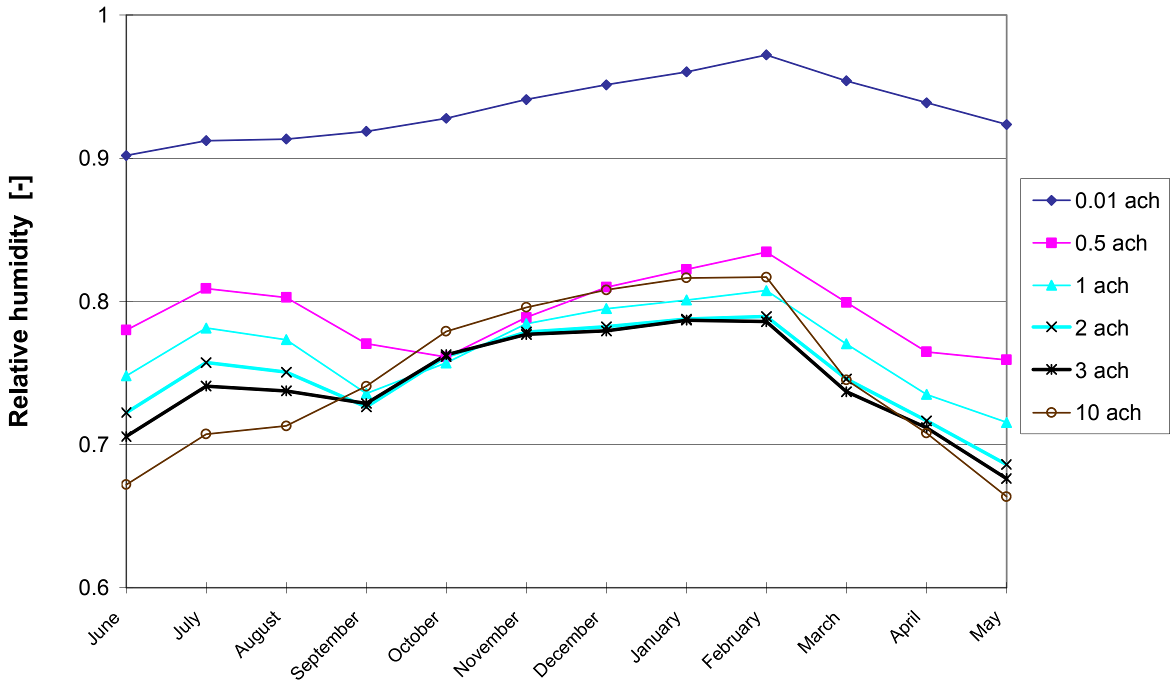



**Fig. 4.8.** The effect of the air change rate on RH of crawl space air when the ground surface is uncovered.

The moisture resistance of a ground cover affects both the moisture and thermal behaviour in a crawl space, because the reduced moisture evaporation will raise the crawl space temperature due to the reduced heat of evaporation. The thermal insulation of the ground cover will bring about extra effects in thermal behaviour. Temperatures in the crawl space with and without ground cover at an air change rate of 1 ach are shown in Fig. 4.10. Notably higher temperatures can be seen, especially in the summer, when the insulation is applied. However, the temperature rise is caused mainly by reduced moisture evaporation, which was 0.34 $g/m^2\,h$ with insulation and 3.4 $g/m^2\,h$ with uncovered ground. The effect of evaporation heat on the air temperature can be seen when the PVC-sheet (no evaporation) is compared to uncovered ground. The air temperature with a PVC-sheet is lower in the summer and higher in the winter compared to EPS-insulation. Thus, the insulated heat capacity of the ground will increase the temperature in the summer and in the winter the temperature will correspondingly decrease.

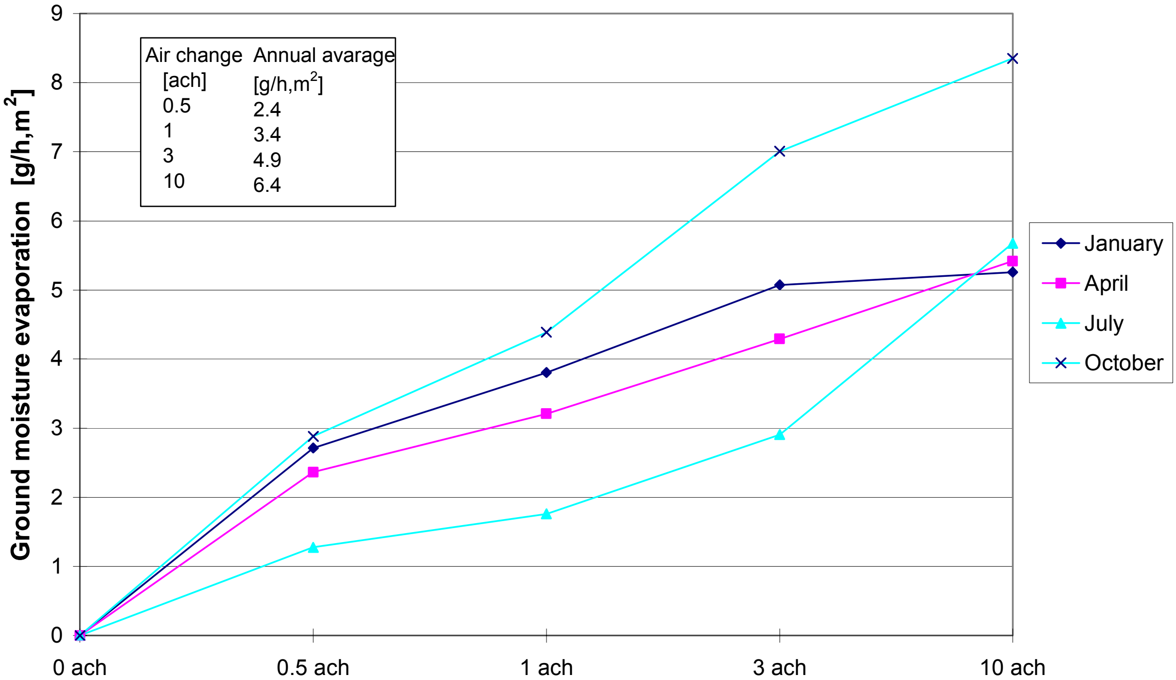



**Fig. 4.9.** Ground moisture evaporation rate as a function of air change rate for uncovered moist ground.

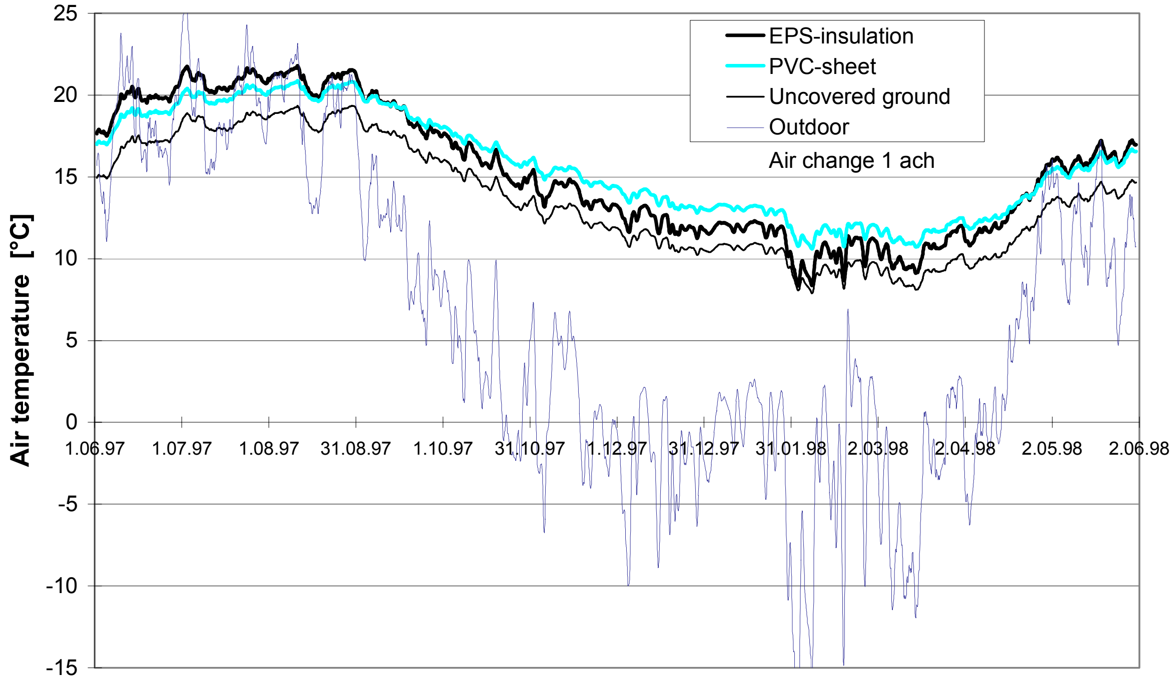



**Fig. 4.10.** The effect of thermal insulation and evaporation heat on air temperature in the crawl space. Air change is constant, 1 ach. (24-h moving averages.)

Relative humidity in the crawl space air is shown in Fig. 4.11. RH with insulation or PVC on the ground is very low in the heating season because of effectively reduced moisture evaporation. In the summer, when outdoor air is moist and warm, the effect is smaller, but still significant as RH remains clearly under 80%. In the summer, EPS-insulation gives slightly lower RH than PVC-sheet.

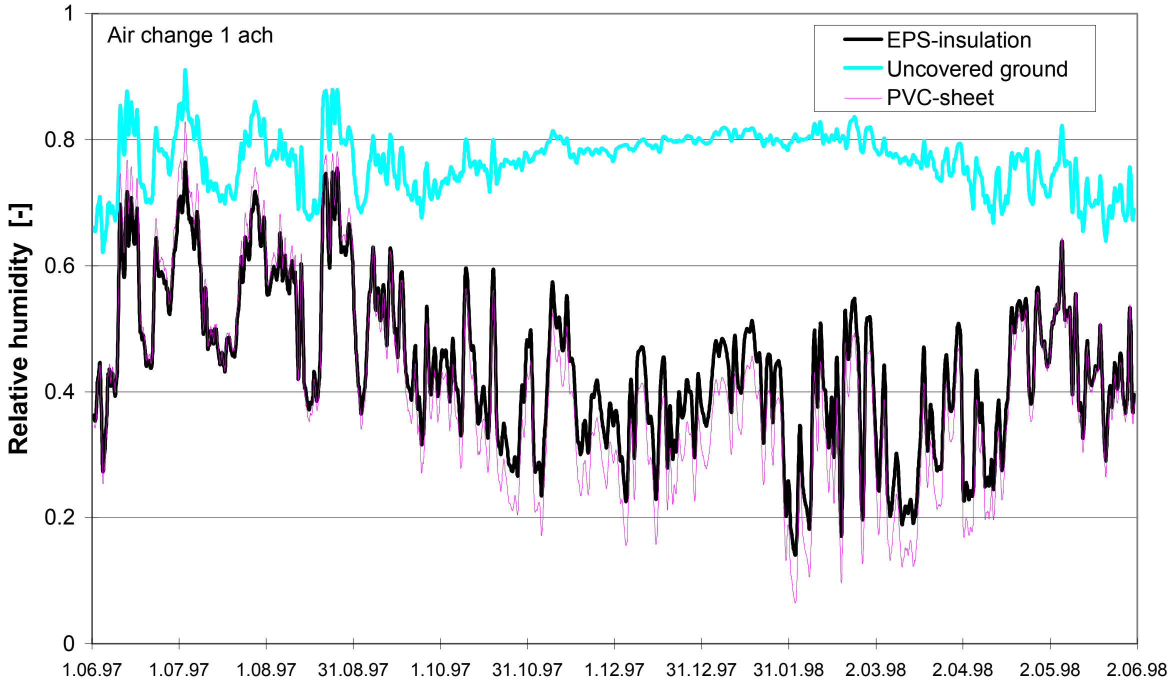



**Fig. 4.11.** Relative humidity in the crawl space air when ground covers (5 cm EPS and PVC) are applied. Air change is constant, 1 ach. (24-h moving averages.)

The effect of air change rate on RH with EPS-insulation on the ground is shown in Fig. 4.12. The optimum air change rate is about 0.5 ach and RH remains almost the same within the range 0.2–1 ach. Within this range monthly averages are less than 60%. High air change rates brought about slightly higher RH because the crawl space was cooled down. Unventilated crawl space shows the highest RH because the used EPS-insulation is not completely vapour-tight. Still, the ground moisture evaporation rate is by about 90% lower compared to uncovered ground, the average value is 0.4 g/h m$^2$ with 0.5 ach, 0.34 g/h m$^2$ with 1 ach, and about 0.3 g/h m$^2$ with 3 and 10 ach.

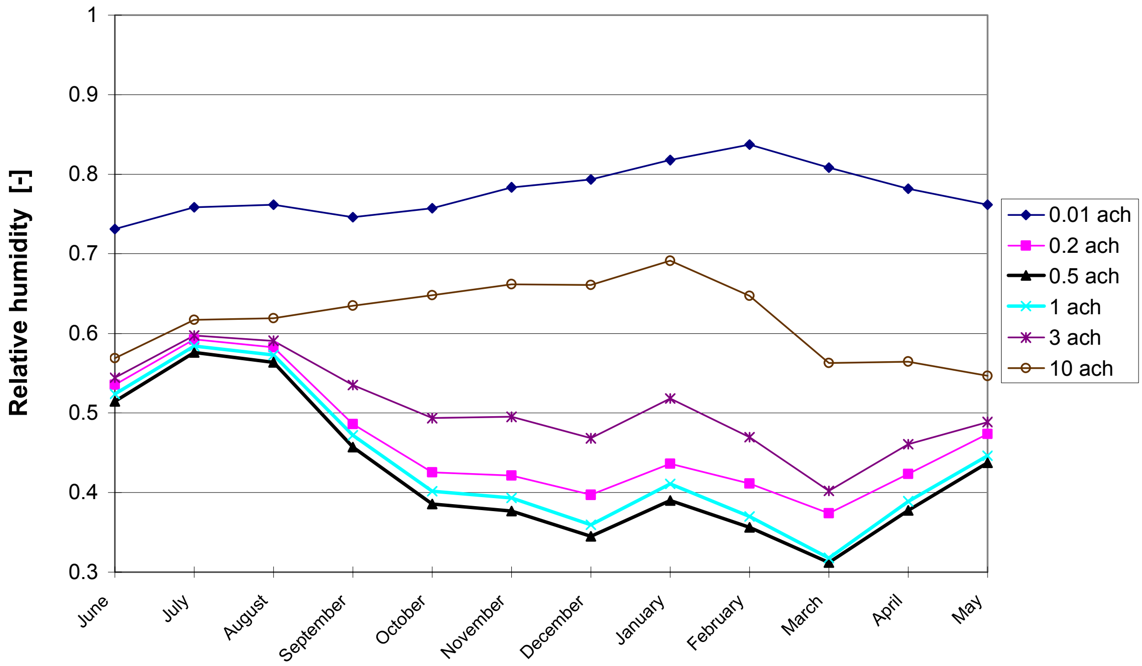



**Fig. 4.12.** The effect of air change rate on RH with 5 cm EPS-insulation on the ground.

## 4.4 Moisture conditions in relatively cold crawl spaces

The moisture behaviour of LWA and crushed stone ground covers were compared in five crawl spaces of two wooden buildings and an apartment building during one-year-long field measurements in (VI). The effect of the air change rate on RH with a LWA ground cover was studied by means of computer simulation in (VII).

The measured RH in both relatively warm and cold crawl spaces is shown in Fig. 4.13. In these crawl spaces the air change rate was between 0.5–1 ach and the thickness of the ground covers about 15 cm. RH is very low in the "warm" crawl space (apartment building, U-value of base floor 0.38 W/m$^2$ K). In the cold crawl space (wooden building, U-value of base floor 0.2 W/m$^2$ K) the temperature was continuously about 5ºC lower than in the "warm" crawl space and therefore RH reaches a critical level. LWA shows slightly lower RH than crushed stone, but no visible mould growth was noticed in either cold crawl space.

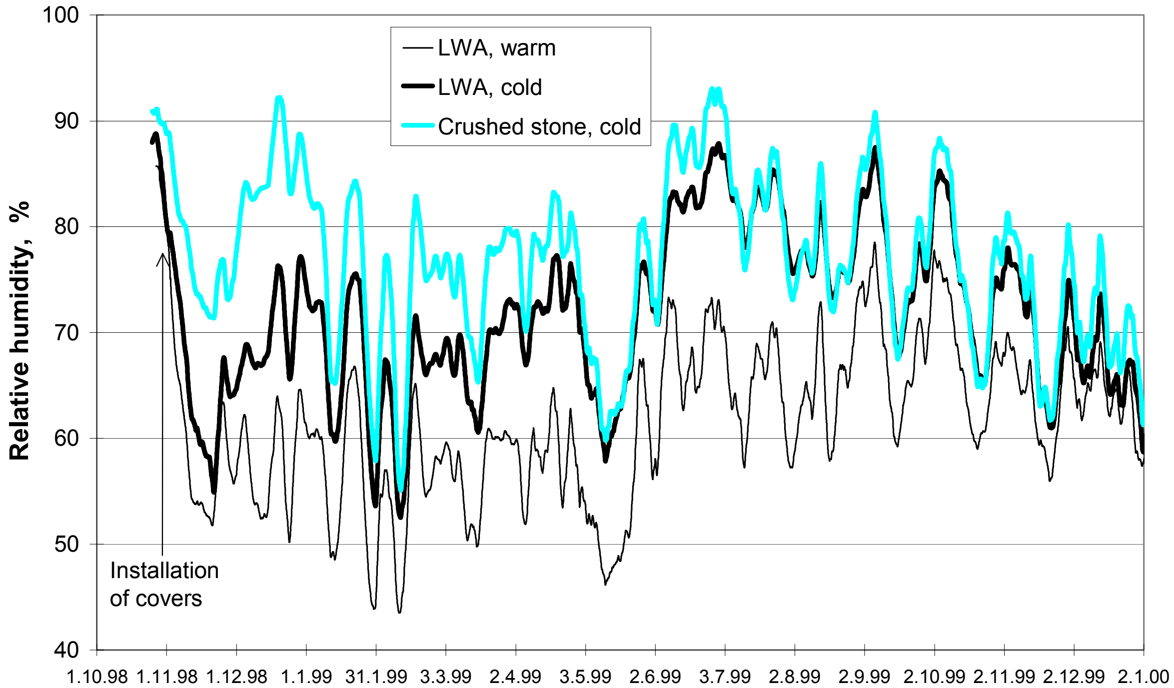



**Fig. 4.13.** Measured RH in three crawl spaces where LWA or crushed stone cover is used (96-h moving averages).

The effect of the air change rate on RH is shown in Fig. 4.14. where the parametric simulation is carried out for the "cold" crawl space with a 15 cm LWA-cover. Air change 1 ach corresponds ≈1 m$^3$/h m$^2$ as the height of the crawl space is about 1 m. The simulations use the weather data of 1998 (notice the different weather data in Fig. 4.13). High air change rates, such as 2 and 5 ach, have clearly reduced RH in the summer. Since 0.5–1 ach shows the lowest RH in the heating season, an air change rate of 0.5 ach is used in "2" and "5" ach cases during October 1 to April 30. Compared to a constant air change rate all the year round this decreases RH significantly in the heating season, but also slightly in the summer, as the crawl space keeps slightly warmer.

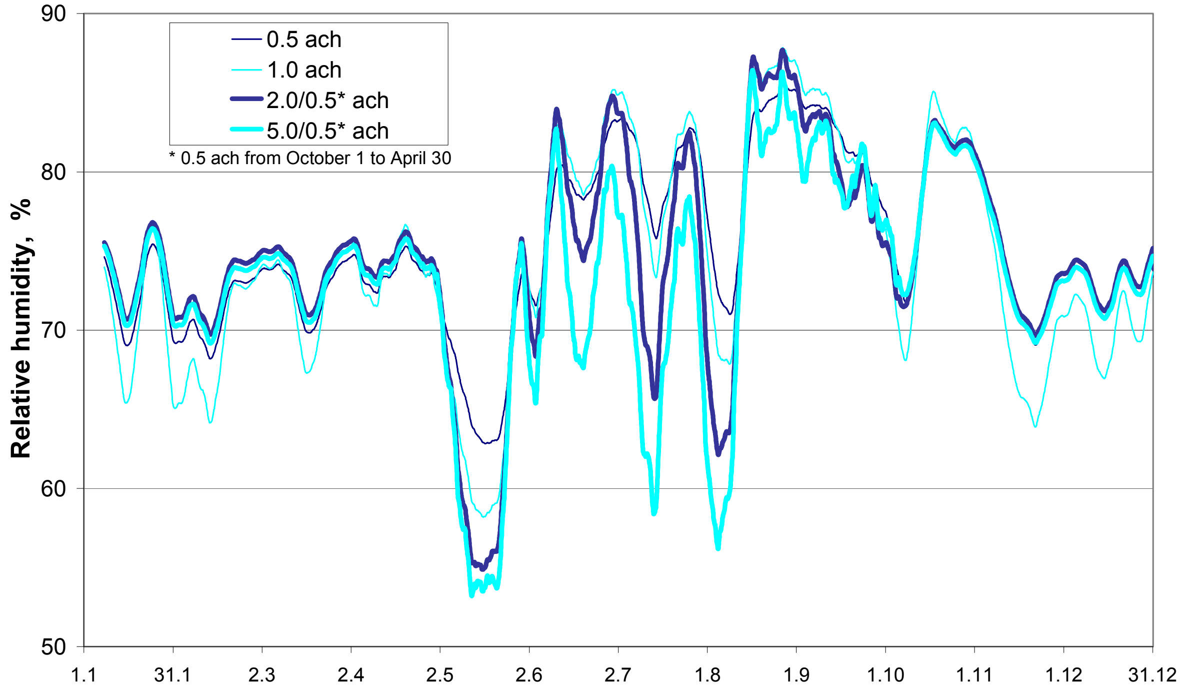



**Fig. 4.14.** Calculated RH in the "cold" crawl space with a 15 cm LWA-cover at various air change rates (weekly moving averages).

In the summer, when crawl space air is usually warmer than the ground surface in cold crawl spaces, the direction of moisture flow from the ground is reversed – quite often we have a moisture flow from air to ground. This means that the moisture capacity of the ground cover plays a significant role as well. There is a moisture uptake during the summer that reduces RH, whereas during the heating season the moisture will dry out. This can be seen in Fig. 4.15 where the RH measured inside the LWA-cover is higher from June to October.

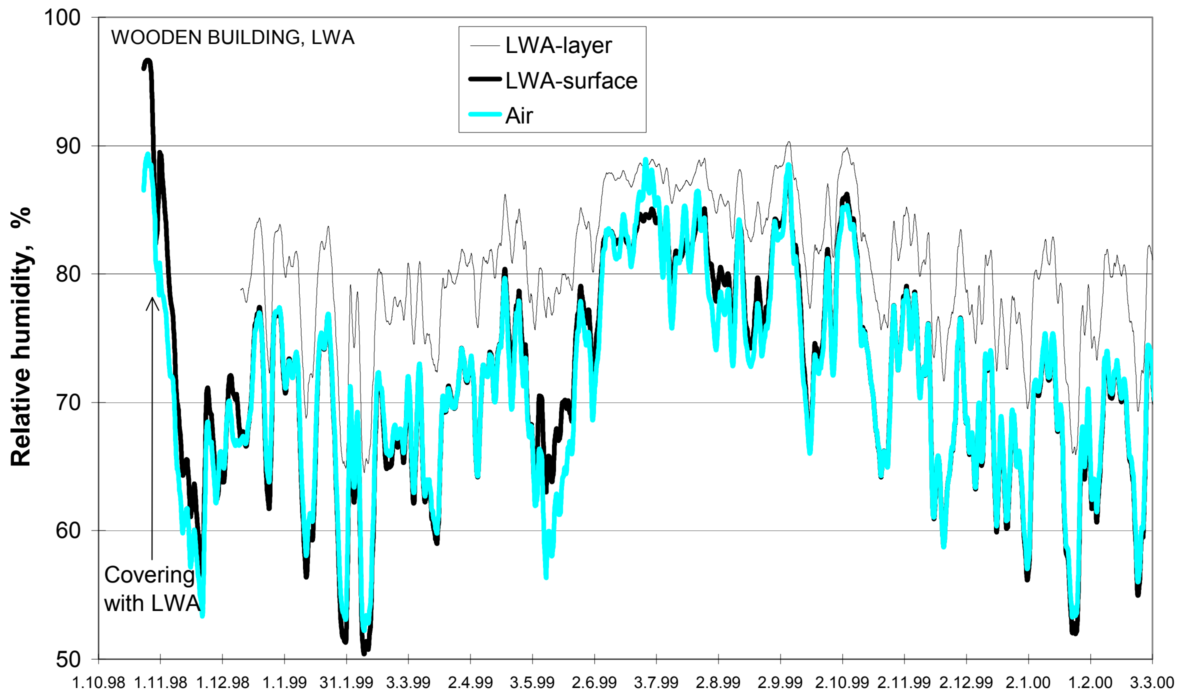



**Fig. 4.15.** Measured RH in the cold crawl space with a 15 cm LWA-cover (48-h moving averages). "Air" is the same as "LWA, cold" in Fig. 4.13.

Moisture uptake during the summer can be seen from the simulated results, Fig. 4.16. These results correspond to Fig. 4.14. At the air change rates of 0.5–2 ach during some periods in the summer, LWA stores a significant amount of moisture and the moisture content reaches close to the hygroscopic limit value (2.0 kg/m$^3$). At 5 ach the rise in the moisture content is smaller as RH is lower as well.

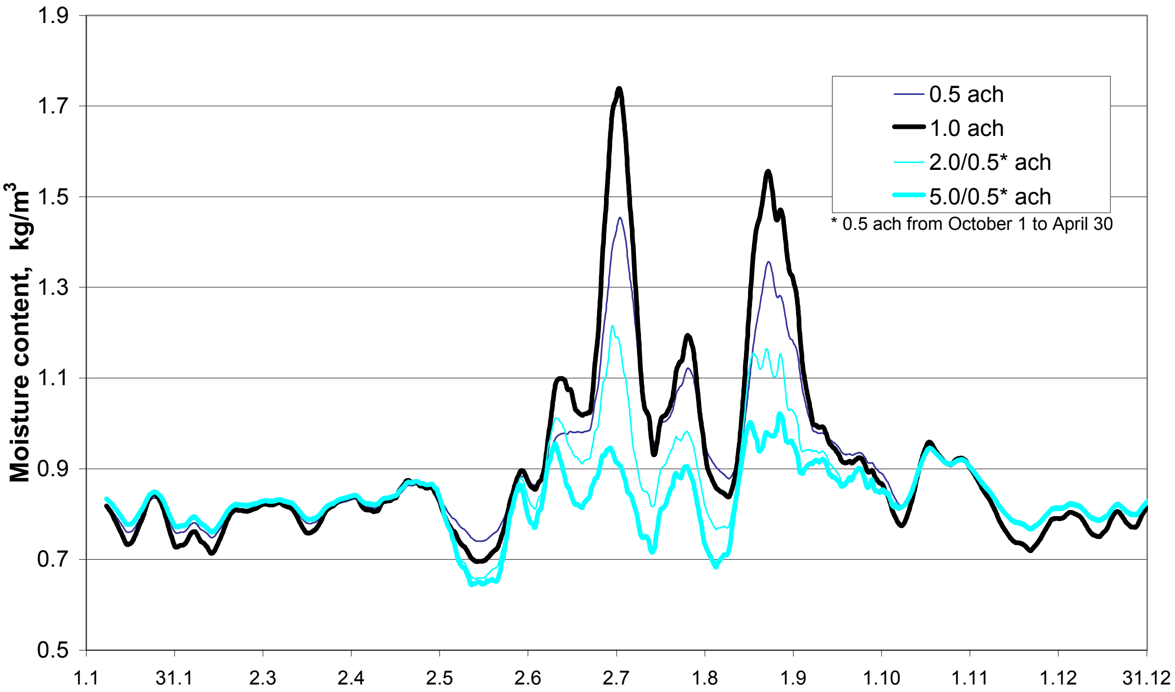



**Fig. 4.16.** Calculated moisture content inside LWA at 5 cm depth (weekly moving averages).

## 4.5 The effect of dehumidification on RH and evaporation rate

Dehumidification was tested in the cold crawl space of the wooden building and the relatively warm crawl space of the apartment building. The wooden building had constructions similar to the wooden building in Ch. 4.4. and the apartment building was the one discussed in Ch. 4.4, but the dehumidifier was used in another crawl space with clay ground (no ground cover). In the wooden building the ground soil was sand which was rather wet (6–7% moisture content by mass) and there was clearly visible mould growth on the wooden surfaces (on fibreboard and wooden joists) of the base floor. The air change in the crawl space was very low.

In the 130 m$^2$ crawl space of the apartment building, the dehumidifier with a drying effect of 0.5–0.8 kg/h decreased RH from about a level of 85% to slightly below a level of 70%. The RH was almost the same everywhere in the crawl space air since the shape of the crawl space was close to a square. On the ground surface the RH remained the same, it was continuously close to 100%. In the wooden building a similar dehumidifier was used. Here the crawl space with dimensions of 7.3 by 30 m was divided with a foundation beam into two parts, leaving only a 10 cm air gap below the beam and therefore the RH was not the same everywhere in the crawl space, Fig. 4.17. In spite of this, RH is at a safe level everywhere in the crawl space at the end of the dehumidification period. At this point the ground surface has become clearly drier than before; RH on the ground is less than 90% and it remains at this level after removing the dehumidifier. In December 1999 some surface water flowed into the crawl space and the ground surface became wet again.

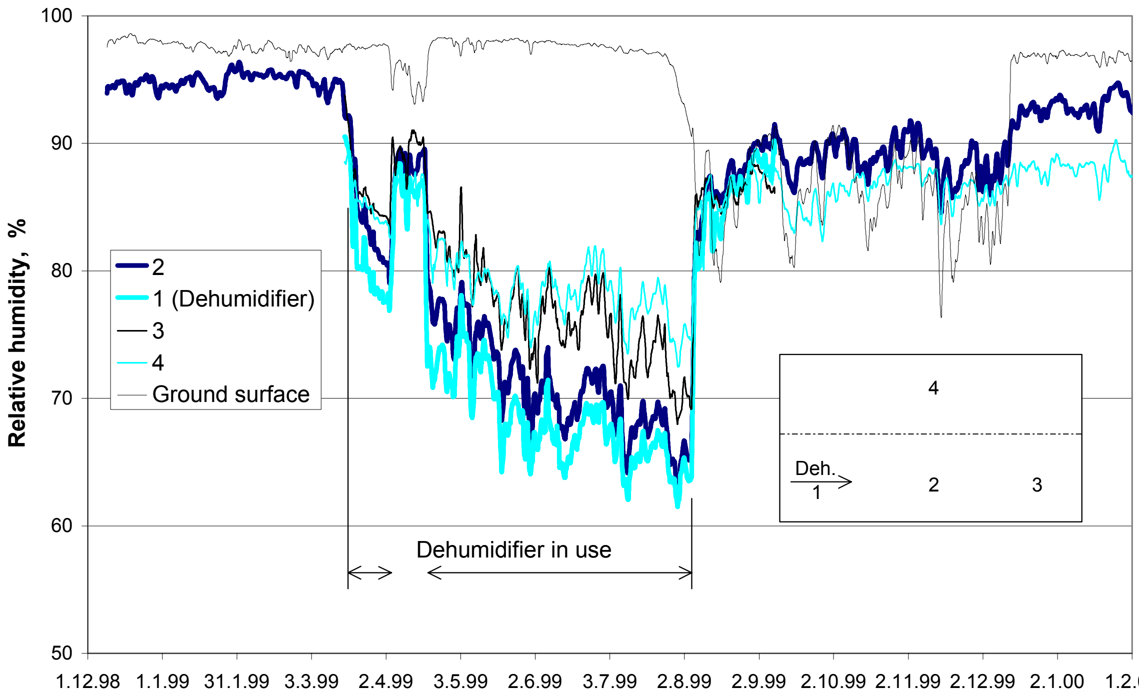



**Fig. 4.17.** RH at various locations in the crawl space of the wooden building, where dehumidification was used (24-h moving averages).

The effect of dehumidification on ground moisture evaporation and the drying effect were possible to assess in the crawl space of the apartment building where air change was measured, Fig 4.18. Since the drying effect depends on temperature and humidity conditions, the dehumidifier means a second unknown in the moisture balance (Eq. 2). To determine the drying effect [kg/h], the mass transfer coefficient should be calculated from the convective heat transfer coefficient. This was calculated from Eq. (8), where the multiplier 0.6 is used instead of 2.2 of Eq. (7), because in the summer the crawl space air is usually warmer than the ground surface which decreases heat transfer. (Eq. 7 was used in II for the heating season.) The average value of the convective heat transfer coefficient was close to 0.5 $W/m^2 K$ during the calculation period. The accuracy of the calculation can be seen from the values of the drying effect after removing the dehumidifier – now there is no drying, but the calculated value is between -0.2–0.2 kg/h. Nevertheless, the calculated drying effect corresponds well to the value of the used device (0.5–0.8 kg/h). The dehumidifier has significantly increased the evaporation rate during its use. Evaporation from LWA is much lower; some negative values indicate net moisture transport by air change to crawl space, i.e. the moisture content of outdoor air is higher than that of the crawl space air.

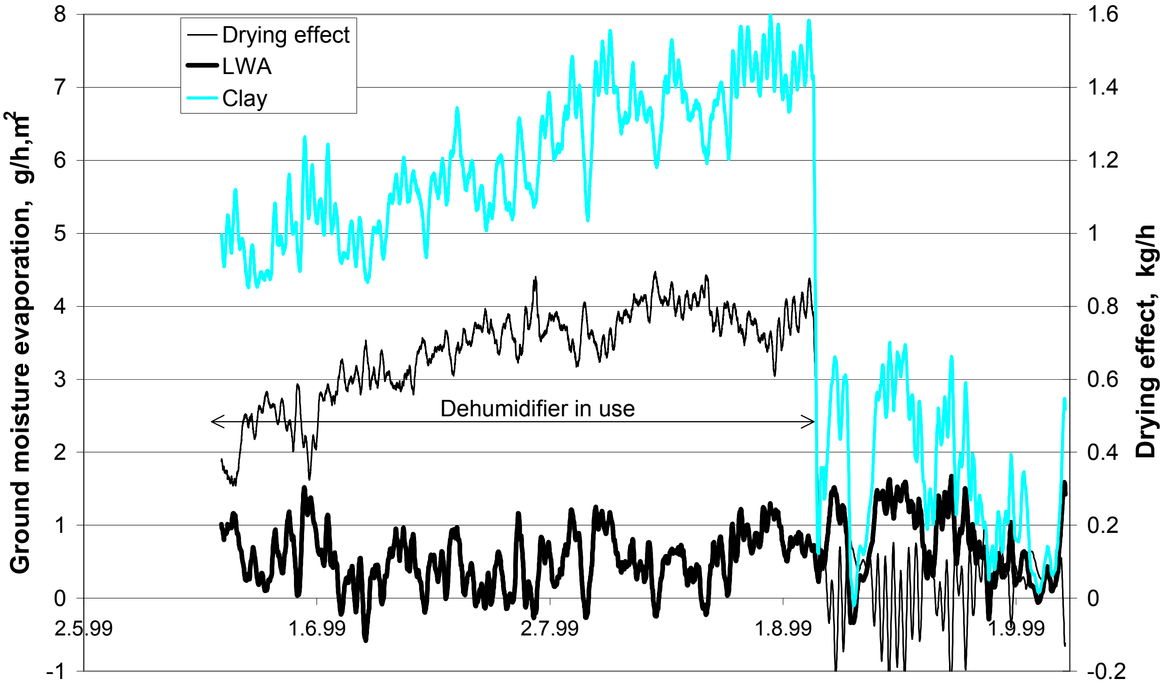



**Fig. 4.18.** Ground moisture evaporation in crawl spaces of the apartment building. Covered ground (LWA) and uncovered ground (clay). The dehumidifier was used only in the crawl space with uncovered ground.

## 4.6 The acceptability of moisture conditions in cold crawl spaces

Moisture conditions are acceptable when RH is lower than 75–80%, which can be taken as a threshold value for mould growth. Thus, the moisture conditions were evidently acceptable in the relatively warm crawl spaces (studied in Ch. 4.3) when a ground cover was applied and the crawl space was ventilated. In relatively cold crawl spaces, RH was higher than 75% during rather long periods (Ch. 4.4). This means that mould growth analyses are needed to assess the acceptability of the moisture conditions. In the following Eq. (1) is used in two ways for the prediction of mould growth. First, the time needed to start mould growth $t_m$ is calculated from Eq. (1a) as a function of RH and temperature, which are average values of defined cumulative time periods. Secondly, Eq. (1b) is used for dynamic mould growth prediction based on mould growth index $M$.

When $t_m$ is calculated with Eq. (1a) it has to be compared to the time of wetness (TOW). TOW is defined here as the cumulative time period when RH is higher than 75, 80 or 85%. If TOW $<$ $t_m$ the conditions are acceptable. Probably the cumulative time period when RH > 85% is the most crucial in respect of mould growth, but as mould growth is possible also at lower RH, the calculations had to be carried out for each RH range. Counting of TOW starts when RH exceeds 75% (or 80% or 85%). The periods when RH < 75% (or 80% or 85%) are not taken into account. The calculation ends when the duration of the dry period (RH < 75%) has been at least two months – this is the time needed to reset the contamination. Then TOW of each RH range has to be compared to $t_m$ which is calculated as a function of average RH and temperature of the corresponding cumulative TOW-period (i.e.

RH and T values when RH is lower than 75, 80 or 85% are not taken into account). In principle TOW and $t_m$ have to be studied all year round, but in crawl spaces the critical period starts definitely in the spring or summer and ends in the autumn.

In (VII) the average values of two-week periods were used for the cumulative calculation of TOW. The two-week period was chosen because it is the shortest time that can start mould growth and is long enough for performing manual calculations. If RH > 75% (or 80% or 85%), the period was taken into account, otherwise not. TOW and $t_m$ were calculated for each RH range, since it is not known which range would give the most critical result. In Table 4.1, average RH values of the two-week periods are given for the critical time period (RH > 75%) in the crawl space. These values are calculated from the simulated data of the wooden building with a 15 cm LWA-cover shown in Fig. 4.14. The lowest RH values and the most critical TOW and $t_m$ values are marked with bold. (The cases there the difference between $t_m$ and TOW is 1–2 weeks are also considered to be critical because due to the logarithmic nature of Eq. (1a) even small changes in RH may cause a few weeks differences in $t_m$.)

**Table 4.1.** Average RH values of two-week periods [%], cumulative time of wetness (TOW) for RH > 75, 80 or 85% and the corresponding time needed to start mould growth $t_m$ [in weeks] at various air change rates in the "cold" crawl space with a 15 cm LWA-cover during the most critical time when RH > 75%. $RH_{avg}$ and $T_{avg}$ are the average values of the cumulative time periods used in Eq. (1) to calculate $t_m$.

| | **0.5 ach** | **1 ach** | **2 ach** | **2/0.5* ach** | **5 ach** | **5/0.5* ach** |
|---|---|---|---|---|---|---|
| May 24 – Jun 06 | 73.4 | 74.4 | 75.2 | 74.0 | 74.5 | **72.9** |
| Jun 07 – Jun 20 | 79.3 | 80.4 | 79.2 | 77.9 | 73.9 | **72.2** |
| Jun 21 – Jul 04 | 82.5 | 84.0 | 83.6 | 82.6 | 78.4 | **76.9** |
| Jul 05 – Jul 18 | 78.5 | 77.5 | 72.9 | 71.6 | 66.4 | **65.3** |
| Jul 18 – Aug 01 | 79.7 | 79.0 | 76.0 | 75.0 | 71.0 | **69.8** |
| Aug 02 – Aug 15 | 76.1 | 75.5 | 74.5 | 73.8 | 72.7 | **71.8** |
| Aug 16 – Aug 29 | 84.8 | 86.8 | 87.1 | 86.1 | 84.2 | **83.0** |
| Aug 30 – Sep 12 | 83.9 | 84.7 | 84.0 | 82.9 | 82.7 | **81.5** |
| Sep 13 – Sep 26 | 80.2 | 79.5 | 78.6 | **77.6** | 79.2 | 78.1 |
| Sep 27 – Oct 10 | 74.6 | 72.5 | **72.2** | 74.0 | 74.6 | 74.8 |
| Oct 11 – Oct 24 | **82.1** | 83.5 | 85.6 | 82.4 | 88.8 | **82.1** |
| Oct 25 – Nov 07 | 78.9 | 78.4 | 80.0 | 79.2 | 84.7 | **78.8** |
| $TOW_{RH>75\%}$ | **20** | **20** | **16** | 16 | **12** | 12 |
| $t_{m,\ RH>75\%}$ | **21** | **18** | **18** | 20 | **14** | 21 |
| ($RH_{avg}$[%]; $T_{avg}$[°C]) | (80; 12.7) | (81; 12.8) | (81; 12.3) | (80; 13.5) | (83; 11.5) | (80; 12.9) |
| $TOW_{RH>80\%}$ | 10 | **10** | 8 | 8 | **8** | 6 |
| $t_{m,\ RH>80\%}$ | 13 | **11** | 11 | 11 | **10** | 14 |
| ($RH_{avg}$[%]; $T_{avg}$[°C]) | (83; 12.6) | (84; 12.9) | (84; 11.9) | (84; 13.6) | (85; 10.5) | (82; 13.1) |
| $TOW_{RH>85\%}$ | 0 | 2 | 4 | 2 | 2 | 0 |
| $t_{m,\ RH>85\%}$ | >9 | 7 | 8 | 7 | 6 | >9 |
| ($RH_{avg}$[%]; $T_{avg}$[°C]) | (85; 12.6) | (87; 13.9) | (86; 12.1) | (86; 14.6) | (89; 9.0 ) | (85; 12.6) |

* 0.5 ach during heating season from October 1st to April 30th

There are two simplifications in the calculations shown in Table 4.1. The calculations are based on average conditions during the cumulative time period and the possible delay in mould growth when conditions are unfavourable is not taken into account. In principle, more accurate results can be obtained when Eq. (1) is used as a differential equation. In this case, the increase in mould growth index *M* is calculated with Eq. (1b). When RH is lower than the critical RH value, the drop in *M* is calculated with Eq. (1c). The value of *M* equal to 1, which corresponds to the microscopic stage of mould growth, is taken as the criterion. In the calculations the average values of three hours and the time period shown in Table 4.1 were used. Since the critical RH value, which determines when the calculation of the drop in *M* has to be started, had a significant effect on the maximum value of *M*, the calculations were performed with three critical RH values as shown in Table 4.2.

**Table 4.2.** Prediction of mould development for the cases shown in Table 4.1. Maximum value of mould growth index *M* when critical RH has a value of 80%, 77% or 75%.

| | 0.5 ach | 1 ach | 2 ach | 2/0.5* ach | 5 ach | 5/0.5* ach |
|---|---|---|---|---|---|---|
| *M*, critical RH= 80% | 0.52 | 0.70 | 0.79 | 0.58 | 1.08 | 0.48 |
| *M*, critical RH= 77% | 0.76 | 0.98 | 1.06 | 0.66 | 1.22 | 0.61 |
| *M*, critical RH= 75% | 0.95 | 1.14 | 1.20 | 0.82 | 1.29 | 0.71 |

In Table 4.1 TOW is in every case except in the 1 ach case shorter than $t_m$, which indicates no risk of mould growth in these cases. Significantly, the 1 ach case shows worse behaviour than the 0.5 ach case. 2 and 5 ach give the shortest TOW for >75 and >80% RH ranges, but for the > 85% RH range, 0.5 ach gives TOW equal to zero. The last situation is natural since high air change rates (such as 2 and 5 ach) cool the crawl space down in the heating season. When the air change rate is reduced to 0.5 ach from October 1st to April 30th, the 5 and 2 ach cases show clearly the best performance. The results were almost the same when the air change was reduced from October 1st to May 31st.

Mould growth index *M* obtains notably low values (except in the 5 ach case) when 80% is used as the critical RH value (Table 4.2). When 77 or 75% is used as the critical RH value, the mould growth index shows reasonably good agreement with the results shown in Table 4.1.

An additional complication in the prediction of the acceptability of conditions is the use of correct weather data, since the weather data used may strongly affect the results. The calculations for the cold crawl space were carried out with weather data of 1998 which was considered to be a typical year in respect of weather. If the summer is cold and moist the results may be different. For example, the Finnish test-year for energy calculations (Tammelin, Erkiö 1987), which is modified from 1979, has an exceptionally cold and moist summer with RH near or over 90% during long periods. The results calculated with this test-year are shown in Table 4.3. Although the temperature is low, $t_m$ is due to high RH much shorter than TOW. The higher air change rates do not have a significant effect on the results.

Remarkably, even in outdoor conditions ($T_{avg}$ = 10.4°C, $RH_{avg}$ = 82.5%) the $t_m$ equal to 16 weeks is shorter than the $TOW_{RH>75\%}$ equal to 18 weeks. This means that in this year mould growth starts on any wood in contact with outdoor air, also in crawl spaces.

**Table 4.3.** Average RH [%] and T [ºC] during the critical period (Jun 6 – Nov 11) at various air change rates when the Finnish test year for energy calculations is used. Cumulative time of wetness (TOW) and time needed to start mould growth $t_m$ [in weeks].

| | $TOW_{RH>75\%}$ | $RH_{avg}$ | $T_{avg}$ | $t_m(T_{avg},RH_{avg})$ |
|---|---|---|---|---|
| 0.5 ach | 18 | 83.1 | 12.1 | 13 |
| 1.0 ach | 16 | 85.0 | 12.2 | 9 |
| 2.0 ach | 16 | 85.2 | 12.2 | 9 |
| 5.0 ach | 18 | 83.2 | 10.6 | 14 |

## 4.7 Optimal selection of ground covers

In relatively warm crawl spaces (high U-value of base floor) all ground covers show good behaviour. The one important property is moisture resistance, i.e. the reduction of ground moisture evaporation. In cold crawl spaces the other properties, such as thermal insulation and the thermal and moisture capacity, play a significant role. As demonstrated in the following, RH in the crawl space may be significantly reduced by the use of a proper ground cover.

In (VII) the behaviour of several ground covers was simulated. In the simulations the air change rate of 2 ach was used. RH in the case of 15 or 30 cm LWA, 5 cm expanded polystyrene (EPS), plastic sheet (PVC) and uncovered ground is shown in Fig. 4.19. Significantly, during the summer PVC shows as high RH as uncovered ground (moist sand). This is caused by the uninsulated thermal mass of the ground, which is the same in both cases. The same RH in these cases demonstrates that outdoor air is the only moisture source during the summer since no evaporation occurs from the cold ground surface (Fig. 4.20). Negative values in Fig. 4.20 indicate significant moisture flow from air to ground. In the case of sand, only evaporation from the ground surface was calculated and thus the amount of condensation cannot be seen (0-values indicate condensation). Moisture flow from air to ground cover is the highest in the case of 15 cm LWA. This is caused by a slightly lower temperature in the crawl space than with 30 cm LWA and 5 cm EPS.

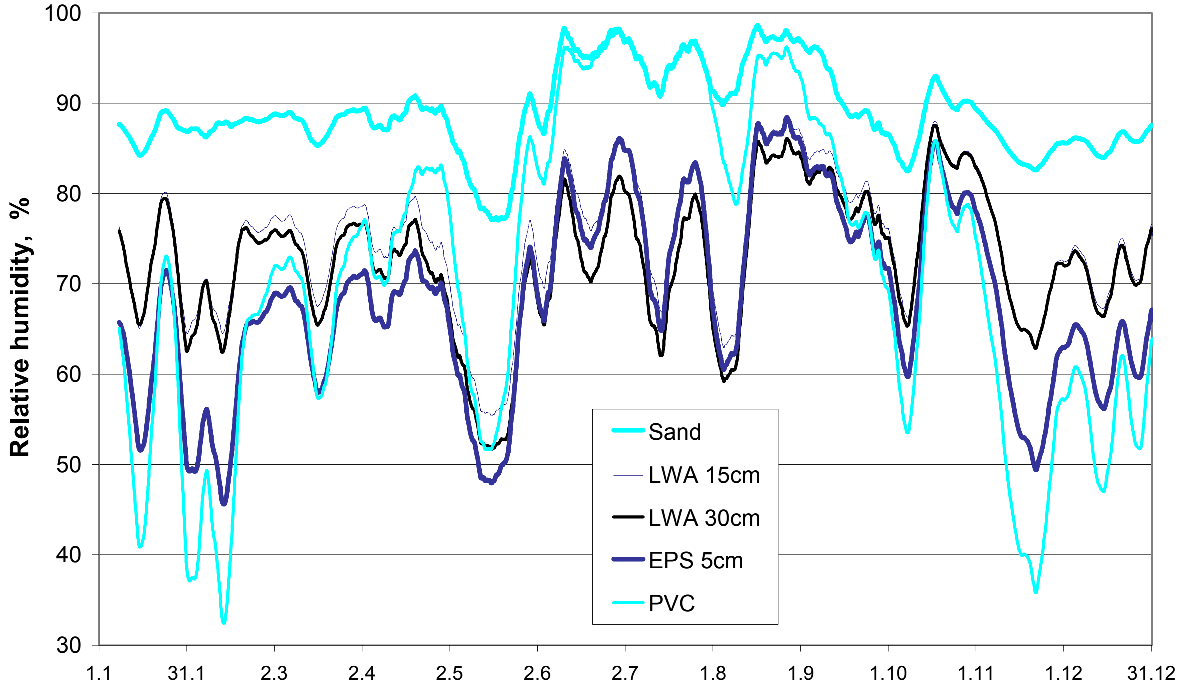



**Fig. 4.19.** RH in the "cold" crawl space with several ground covers at 2 ach air change (weekly moving averages).

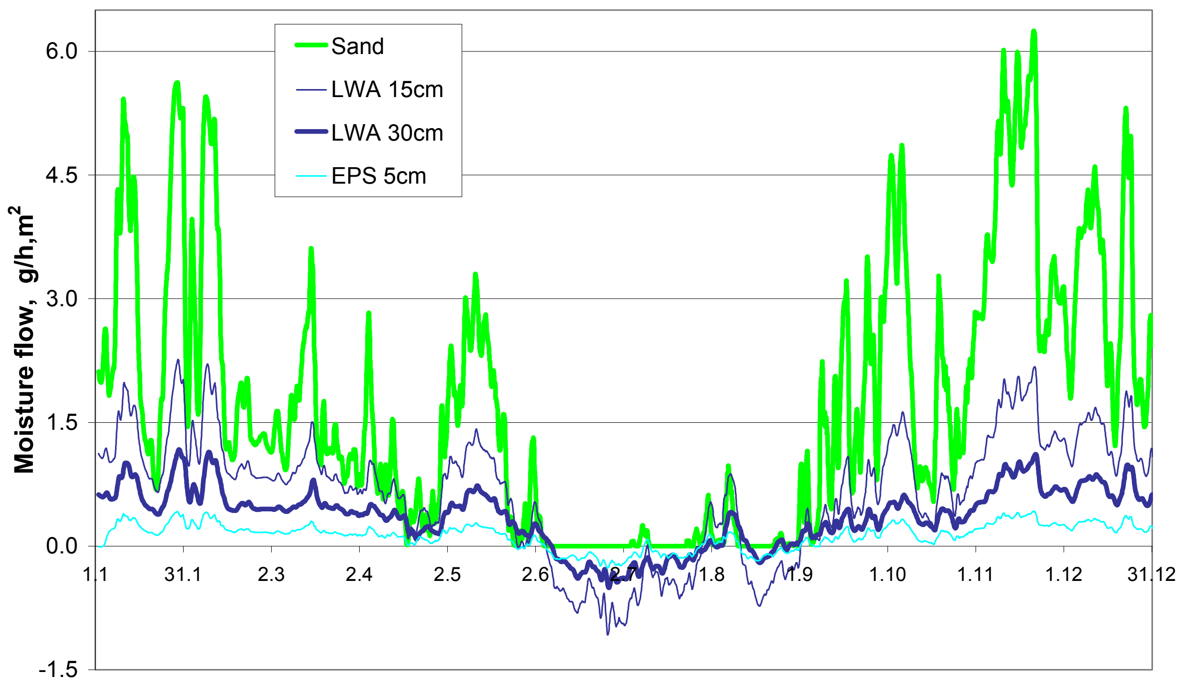



**Fig. 4.20.** Moisture flow from ground (evaporation rate in the case of sand). Positive values indicate evaporation and negative values moisture flow from air to ground (24-hour moving averages).

In the summer when outdoor air is the main moisture source, ground covers store a significant amount of moisture, Fig. 4.21. 15 cm LWA nearly reaches its hygroscopic limit value (2.0 kg/m$^3$). EPS stores clearly less moisture than LWA covers, but its maximum moisture content even slightly exceeds its hygroscopic limit value (0.6 kg/m$^3$).

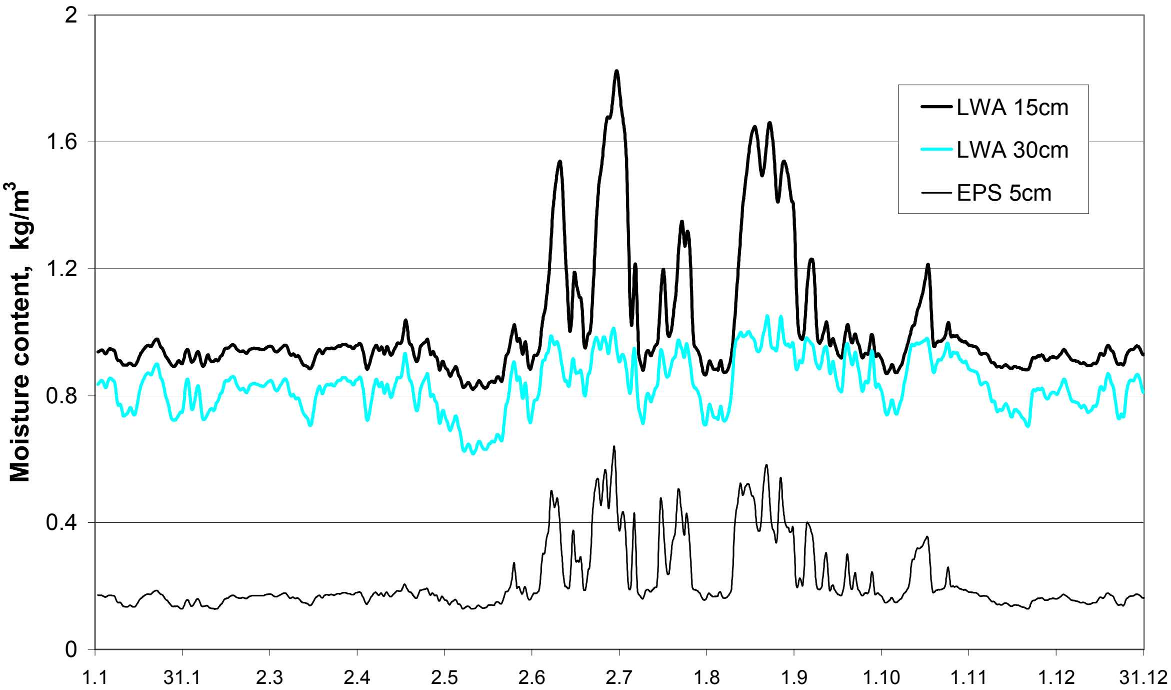



**Fig. 4.21.** Moisture content in EPS at 1.7 cm depth, and in 15 and 30 cm LWA at 5 and 10 cm depth.

Since 30 cm LWA and 5 cm EPS ground covers show slightly lower RH than 15 cm LWA, the mould growth analyses were carried out in the same way as shown in Ch. 4.6. The results are shown in Tables 4.4 and 4.5. The column "LWA 15 cm" in Table 4.4 should be the same as the column "2.0 ach" in Table 4.1. Since the two-week periods are shifted by one day, the average values of RH are not exactly the same and this has caused up to two-week differences in TOW and $t_m$. When in Table 4.1 TOW is 16 weeks and $t_m$ is 18 weeks, in Table 4.4 these values are vice versa. This demonstrates that the results are approximate and they depend to some extent on the choice of the calculation period.

Tables 4.4 and 4.5 clearly show that with PVC or uncovered ground mould growth would be obvious ($M$ = 6 is the maximum value for mould growth index). The performance is better with 15 cm LWA, yet $M$ is close to 1 and TOW is two weeks longer than $t_m$ for RH > 75% and as long as $t_m$ for RH > 80%, which means, in principle, unacceptable conditions. However, in the most critical range (RH > 85%) the conditions are clearly acceptable. 30 cm LWA shows the best performance as TOW is at least 5 weeks shorter than $t_m$ and $M$ is clearly lower than 1. Similarly, 5 cm EPS provides acceptable conditions in all studied RH ranges.

**Table 4.4.** Average RH values of two-week periods [%], cumulative time of wetness (TOW) for RH > 75, 80 or 85% and the corresponding time needed to start mould growth $t_m$ [in weeks] in the "cold" crawl space with several ground covers. Air change rate is 2 ach all the year round. The lowest RH values and the most critical TOW and $t_m$ values are marked with bold.

| | Sand | LWA 15 cm | LWA 30 cm | EPS 5 cm | PVC |
|---|---|---|---|---|---|
| Jun 06 – Jun 19 | 96.1 | 80.0 | **75.2** | 78.3 | 94.9 |
| Jun 20 – Jul 03 | 97.4 | 83.4 | **78.9** | 83.3 | 97.0 |
| Jul 04 – Jul 17 | 95.2 | 78.3 | **73.4** | 77.5 | 94.9 |
| Jul 18 – Jul 31 | 94.2 | 77.0 | **73.0** | 76.1 | 93.5 |
| Aug 01 – Aug 14 | 93.9 | 72.6 | **69.5** | 71.2 | 85.0 |
| Aug 15 – Aug 28 | 97.2 | 87.2 | **84.6** | 86.8 | 95.0 |
| Aug 29– Sep 11 | 94.6 | 84.3 | **82.1** | 82.2 | 87.3 |
| Sep 12 – Sep 25 | 88.2 | 79.1 | 77.7 | **74.9** | 75.7 |
| Sep 26 – Oct 09 | 84.7 | 71.6 | 70.6 | 66.0 | **61.6** |
| Oct 10 – Oct 23 | 91.0 | 85.4 | 85.0 | 81.7 | **80.6** |
| Oct 24 – Nov 06 | 88.6 | 81.0 | 80.7 | 75.1 | **70.1** |
| $TOW_{RH>75\%}$ | **22** | **18** | 14 | 16 | **16** |
| $t_{m,\ RH>75\%}$ | **3** | **16** | 19 | 20 | **5** |
| ($RH_{avg}$[%]; $T_{avg}$[°C]) | (93, 11.1) | (82; 12.8) | (81; 12.5) | (80; 13.5) | (89; 12.2) |
| $TOW_{RH>80\%}$ | **22** | **10** | 8 | 8 | **16** |
| $t_{m,\ RH>80\%}$ | **3** | **10** | 13 | 11 | **4** |
| ($RH_{avg}$[%]; $T_{avg}$[°C]) | (93; 11.1) | (84; 13.2) | (83; 11.4) | (84; 13.4) | (91; 12.2) |
| $TOW_{RH>85\%}$ | **20** | 4 | 2 | 2 | **14** |
| $t_{m,\ RH>85\%}$ | **3** | 8 | 11 | 6 | **3** |
| ($RH_{avg}$[%]; $T_{avg}$[°C]) | (94; 11.3) | (86; 12.1) | (85; 10.2) | (87; 14.8) | (93; 12.5) |

**Table 4.5.** Prediction of mould development for the cases shown in Table 4.4. Maximum value of mould growth index *M* when critical RH has a value of 80%, 77% or 75%.

| | Sand | LWA 15 cm | LWA 30 cm | EPS 5 cm | PVC |
|---|---|---|---|---|---|
| *M*, critical RH= 80% | 6 | 0.79 | 0.42 | 0.60 | 6 |
| *M*, critical RH= 77% | 6 | 1.04 | 0.60 | 0.73 | 6 |
| *M*, critical RH= 75% | 6 | 1.18 | 0.67 | 0.83 | 6 |

# 5 DISCUSSION

## 5.1 Crawl space ventilation system and air leakage to apartments

In (I) mechanical extract ventilation in the crawl space increased its RH up to 5% due to under-pressure in the crawl space which caused flows through ground soil, drainage pipes, etc. To what extent the phenomenon was caused by ground flows and to what extent by direct leakage from the adjacent sections of the crawl space did not become completely clear. Nevertheless, this effect was noticed also during the period when the under-pressure in studied crawl space was only about 0.5 Pa compared to the adjacent sections. Only when the under-pressure was removed by balanced or supply ventilation, the mechanically ventilated crawl space was drier than the naturally ventilated one. Still, it seems that the ventilation system of the crawl space does not play a very significant role because RH can be effectively reduced by a proper choice of ground covers and an air change rate provided by any ventilation system. Even more, slight under-pressure in crawl spaces (compared to outdoors) can be recommended since it prevents or reduces air leakage from the crawl space to the apartments. In the studied apartment building, a notable part of the intake air of the apartments was sucked through the leaky base floor from the crawl space as there was under-pressure in the apartments. Since this building was highly typical, equipped with common mechanical exhaust ventilation, it seems to be a general question about ventilation hygiene. It is an open question whether crawl spaces can be made clean enough for taking intake air from them. It was demonstrated that mechanical extract ventilation in the crawl space could not remove the pressure difference at any realistic air change rate. Thus, there is no easy solution that allows to prevent this leakage. Obviously, the use of balanced ventilation in apartments or/and the tightening of base floors is recommendable.

If the crawl space is notably airtight, the extraction ventilation may cause some under-pressure into the crawl space compared to indoors. In the case of a wooden base floor, this pressure difference leads to moisture convection in the base floor which may cause condensation on cold surfaces. However, this seems to be a rather theoretical risk since crawl spaces are warmer than outdoors and, as shown in (V), a pressure difference of a few pascals will not cause significant moisture convection.

## 5.2 Accuracy of the simulation model

The simulations were carried out with an RC-network model with about 70 calculation points. For moisture transfer two models were used. In (III) only evaporation and moisture flows carried by ventilation were taken into account. Good agreement with measured data can be explained with the very low moisture capacity of the materials present in the crawl space. In (III) measurements were carried out with uncovered clay ground, and other materials in the crawl space were concrete and EPS. In (VII) measurements were carried out in the same crawl space which was in the meantime covered with LWA. Now the calculation with a simplified model caused higher RH fluctuations than in the measured data. Therefore, in (VII) the improved moisture model was used which took moisture transfer in the base floor and in the ground cover into account. This was especially important in the case of the cold crawl space of the wooden building – the simplified model significantly overestimated RH fluctuations and even the RH level was overestimated during the summer. In general, the moisture models showed good performance in both (III) and (VII), the difference between measured and calculated data was less than 5% RH. However, the main simplification of the model concerned heat transfer; the floor area of the crawl space was divided into two sectors and heat conduction in the ground was calculated along two semicircular heat flow patterns. In order to achieve accurate results, it was necessary to use the parameter identification for the thermal properties of the ground and the U-value of the base floor.

## 5.3 Determining the acceptability of moisture conditions

How to determine the acceptability of moisture conditions is a very pressing question, especially in cold crawl spaces where RH is often higher than what is needed to start mould growth. This study defined the acceptability of the moisture conditions in regard to mould growth – when mould growth did not progress beyond the microscopic stage and there were sufficiently long dry periods to reset contamination, the conditions were considered to be acceptable. It is probably justified to use mould growth criteria in common situations for any crawl space because even in non-wooden crawl spaces, mould growth may occur, for example, on the ground, and leakage through the base floor may carry fungi and bacteria indoors. If the crawl space is under-pressurised, certain mould growth may be accepted in the case of inorganic materials.

To mention other possible criteria, the threshold RH value for mould growth (75% RH) determined in laboratory studies seems rather unrealistic to apply in practice. On the other hand, recommendations for a certain percentage of surface area allowed to be mouldy in the crawl space [5-10% in (Viitanen 2000)] seem to be slightly too risky because they may cause health hazards and regular inspection is needed to control the extension of the mould growth. (Probably the owners or users of the buildings neither expect such conditions in the crawl spaces as these are not considered to be a part of good building tradition.) However, it is evident that simplified guidelines are necessary for design, and inspection and maintenance of buildings. For example, guidelines for not allowing significant mould growth, significant condensation on the surfaces, and specified limit values for monthly average values of RH for different building types measured in summer, may be worth having further discussion.

The prediction of mould growth is complicated since it depends on RH, temperature and time. In this study the equations determined for wood by Viitanen was used. The weakness of such equations is that they have been determined mainly in stable laboratory conditions. However, (Kokko, et al. 1999) reports that Eq. (1a) can be used in unstable conditions when the conditions are favourable for mould growth. It is known that short dry periods do not affect the mould growth much – the progress stops but it will continue when RH exceeds the

75% level again. To reset the contamination, a dry period of two months at least (RH < 75%) is needed. In relation to the tests in fluctuated humidity conditions Viitanen has shown that the mould growth equation can be interpreted as a differential equation for the dynamic prediction of mould development (Viitanen et al. 2000). This method was also used despite of the very limited experience available on such dynamic prediction. Crawl spaces are usually dry during the heating season, and therefore, the most critical time in respect of mould growth is in the summer and possibly in the autumn. During this time RH in cold crawl spaces is periodically over 75% and during rather short drier periods RH is slightly lower than 75%. Therefore the question is, will the mould growth progress to the microscopic stage during the critical time period or not. During the heating season the conditions are dry enough, in any case, to reset the contamination.

To assess mould growth, the critical time when RH was over 75, 80 or 85% was divided into two-week periods. If the average RH of the current period was higher than the chosen criterion (75, 80 or 85%), the period was included in the cumulative time of wetness (TOW). Finally, the average RH and T of all two-week periods belonging to cumulative TOW was calculated. These were substituted to Eq. (1a) to calculate the time needed to start mould growth $t_m$. If the cumulative time of wetness was shorter than the time needed to start mould growth, the conditions were considered to be acceptable. Alternatively the differential form of Eq. (1) was used. In this case the increase or decrease in mould growth index $M$ was calculated based on hourly data (Eqs. 1b and 1c). $M$ increases when RH is higher than critical RH and if vice versa $M$ decreases.

It can be argued whether the used routines were correct for the prediction of mould growth and which routine should be preferred. In the first routine ($t_m$/TOW), the calculations are based on average conditions during the cumulative time period and the possible delay in mould growth when conditions are unfavourable is not taken into account. In principle, the second routine, which allows dynamic prediction, should give more accurate results. However, this routine was very sensitive to the critical RH value which determines when the drop in $M$ has to be started to calculate. When 80% was used as the critical RH value, as recommended by Viitanen, mould growth index $M$ remained very low in most cases. It seemed that the delay term of mould growth (Eq. 1c) is very approximate as it strongly decreased mould growth index $M$. The effect of the delay term was significantly less if 77 or 75% was used as the critical RH value, i.e. the decrease in $M$ was started to calculate later, in drier conditions. In this case there was reasonably good agreement with the first routine. In general, it is hard to say which routine should be preferred – there is certainly more experience available on the prediction of mould growth based on stable conditions, but the need for further research and experience in this field is evident.

In addition, Eq. (1) does not take the air movement or stagnant air into account. Mould fungi try to maintain saturated conditions on their surface as they do not have a “skin”. If they are surrounded by stagnant air, the conditions are more favourable for surviving even in lower RH. Respectively, moulds cannot usually survive in an air flow. For example, high air velocity may be the explanation why mould growth is not observed in filters used in air conditioning systems even in humid and warm conditions (Pasanen 1998, Torkki 1995). In crawl spaces air velocities are low, commonly 0–0,2 m/s, but they still may have a certain effect on mould growth. In practice, the highest contamination and damages are usually found from closed and moist crawl spaces. Many experienced builders and designers believe that stagnant air will speed up mould growth. Field measurements carried out in this study support the assumption that the air change has an effect on mould growth. In the well-ventilated crawl space of the wooden building, where RH was 80–90% during rather long periods (Fig. 4.13), visible mould growth was not found. In another wooden building (Fig. 4.17), where a dehumidifier was tested and RH was "normally" 90–95%, and the air change was very low, mould growth was clearly visible in large areas on the base floor and even some rot was seen.

The both routines used for determining the acceptability of the moisture conditions gave very realistic results (when critical RH of 77 or 75% was used for the second routine). The idea behind the first routine is simplified, but it would seem to be basically correct. It might be possible that Eq. (1a) is applicable in its current form with sufficient accuracy for the conditions present in crawl spaces where fluctuations are not very high and RH is rather high during the whole of the critical period. However, the empirical equations for the prediction of mould growth in unsteady conditions clearly need further research. Another problem is that the routines used are too complicated for practical calculations. All the same, it seems that there is no other concept available to evaluate the acceptability of the conditions in cold crawl spaces.

An additional complication in mould growth prediction is the used weather data which may have a significant effect on results. In this study, the calculations were mostly carried out with the weather data of 1998, which was considered to be a typical year in regard to weather. An exceptionally cold and humid summer will make the crawl space moist. If the outdoor air RH already causes mould growth, high RH cannot be avoided in a crawl space ventilated with outdoor air. This was the case in (VII) when the weather data of 1979 was used. Hyppel and Åberg have reported similar conditions (i.e. mould growth in all outdoor-air-ventilated crawls spaces) in 1988 (Hyppel 1990, Åberg 1993). Therefore, there are some exceptional years when mould growth occurs on any wood in contact with outdoor or crawl space air, and in this way the weather conditions force us to accept some mould growth. In the prediction of the acceptability of moisture conditions the prevalence of the weather data should be thus taken into account. In which way it has to be taken into account in design is a question open for discussion and it certainly needs further analyses.

## 5.4 Optimal selection of ground covers and air change in cold crawl spaces

The results calculated in (III) demonstrate that all ground covers will perform well in relatively warm crawl spaces if these are ventilated. When the crawl space temperature is close to outdoor temperature, the only one important property of the ground covers is moisture resistance. In the cold crawl spaces with highly insulated base floors, the temperature is during the critical time in the summer significantly lower than the outdoor temperature and this causes high RH. Here the task of the ground cover and air change rate is to raise the crawl space temperature during the summer as much as possible. As shown in (III, VI, VII) important properties of the ground cover are, in addition to high moisture resistance, high thermal insulation, moisture capacity and low thermal capacity. The high thermal insulation and low thermal capacity allow to insulate the thermal mass of the ground from crawl space air and thus the crawl space temperature will be closer to outdoor temperature. If the cover has a high moisture capacity, it can store a significant amount of moisture during the periods with high RH.

The air change affects the crawl space temperature as well; the optimum air change rate is that which provides the lowest RH in the crawl space or the greatest difference between the time of wetness and time needed to start mould growth. In (VII) the effect of the air change rate was studied by means of parametric simulation for a 15 cm LWA-cover. 2 and 5 ach gave very similar results; 5 ach showed lowest RH, but the difference between the time of wetness and the time needed to start mould growth was almost the same in these cases. Because 2 ach is closer to the air change rates commonly used in practice, it was chosen for the simulations in which the behaviour of several ground covers was compared. At 2 ach a 30 cm LWA and a 5 cm EPS covers showed the best performance, i.e. clearly acceptable conditions. Evidently, increasing the thickness of the ground cover produces better results. However, the optimum air change for the thicker cover has yet to be determined.

It is possible that some vapour and water tight ground covers may cause microbial risks. Especially, when a plastic sheet is laid on the ground, it might provide circumstances for microbial growth in the soil. This might apply also for a relatively vapour tight (high density) cell-plastic insulation, which was not studied in this work. However, there is no quantified information available on microbial effects in the soil. Nevertheless, it always seem more safe to use permeable ground covers such as LWA or common low density EPS.

In the most resent simulations carried out in (Matilainen, Kurnitski 2000[b]), an extreme thickness of the cover – 20 cm EPS – was tested. In this case all tested air change rates (0.5-10 ach) showed very similar results in the summer. At 0.5 ach the crawl space was even at its warmest and driest, the average RH in the summer was 73%. At 2 ach the average RH was 75% and at 10 ach 76%. Thus, if the ground is highly insulated, a low air change rate is sufficient to warm up the crawl space. Higher air change rates will not, however, change the situation much as all air change rates gave nearly the same RH in the summer. The results with a 20 cm EPS raise the question, what is the sufficient insulation of the ground cover which allows the use of a constant air change rate (0.5 or 1 ach) all year round. To answer this question and to produce exact guidelines, further parametric simulations are needed.

## 5.5 Alternative solutions for achieving acceptable moisture conditions

Dehumidification effectively decreased RH in the crawl space air in the studied cases. In respect of the prevention of mould growth it is, however, important that the ground surface dries out as well. When RH on the ground is 90–100%, which is common in the case of clay or silt, mould growth will start on the ground if any nutrients are present. This is a risk because the smell of mould (metabolic products or spores) may be transported indoors by air flows. Therefore, dehumidification will only be successful if the ground soil is coarse enough and no water can flow into the crawl space. Dehumidification can dry out only a rather small amount of moisture content and usually it cannot compensate poor rain water sewerage or drainage. If necessary and possible, a new ground cover may be laid to support the performance of dehumidification. It seems that dehumidification may be a very competitive solution, at least in some repairs. In repairs it is rather common that the working in the crawl space is very complicated due to limited space. In such cases, dehumidification may provide a good result with minimum working effort in the crawl space.

Despite of dehumidification, the heating of the crawl space can decrease its RH. For example, if there are any cooling devices in the building, condensers are useful to install in the crawl space. Heating is needed only in the summer when the crawl space temperature is lower than the outdoor temperature. In the case of a highly insulated base floor, a simple convector may be used for heating the crawl space. Because the heating need is only a few degrees during short periods, the necessary heating power and energy consumption are very low. One can calculate these by considering an RC-network with convective heat transfer from crawl space air to ground, i.e. the crawl space is heated by the heater and outdoor air and heat loss occurs to ground. For example, in crawl spaces of houses even 500 W heaters will be big enough to raise the temperature by a few degrees which will then decrease RH to a safe level.

# 6 CONCLUSIONS

Outdoor air ventilated crawl spaces of wooden and precast concrete buildings and houses with the base floor U-value of 0.2–0.4 $W/m^2K$ were studied in this work. The results apply for common crawl spaces in a cold climate only and they cannot be generalised to other climate types. The most important results are listed below:

1. No exact answer was found which ventilation system should be preferred in crawl spaces. Extraction ventilation with significant under-pressure may cause ground flows transporting moisture into the crawl space. Supply ventilation will force leakage flows through the base floor to indoor. A slight under-pressure in the crawl space may be recommended to control the leakage indoors. In general, the effect of the ventilation system is much smaller than the effect of ground covers or a proper air change rate provided by any ventilation system.
2. Ground moisture evaporation is the key element in the moisture balance. If any evaporation occurs, ventilation will always be needed to remove this moisture and to avoid equilibrium, i.e. almost saturated conditions in the crawl space. This is a risk in unventilated crawl spaces – the crawl space may be left unventilated only when evaporation and other moisture sources are entirely prevented.
3. When the ground surface is uncovered and moist, the relative humidity of the crawl space can not be significantly decreased by increasing the air change rate, because it increases evaporation which compensates the effect of air change. Evaporation rates and mass transfer coefficients showed large variation in the studied crawl spaces. For a moist ground surface, the mass transfer coefficient was possible to calculate with sufficient accuracy from the convective heat transfer coefficient determined from the temperature differences when different equations were used for the summer and heating season to take into account whether the ground surface is warmer or colder than the air. The average values of the convective heat transfer coefficients were close to 0.5 $W/m^2K$ in the summer and 1.5–2 $W/m^2K$ in the heating season.
4. Dehumidification decreased relative humidity in the studied crawl spaces to a safe level. When dehumidification is used, it is important that the ground surface also dries out, because the evaporation rate from the moist surface may be as high as 5–8 $g/m^2h$ and there is a risk of mould growth on the moist surface. Dehumidification may be a particularly effective measure, especially in repairs, as it allows the minimising of the work in the crawl space.
5. In the relatively warm crawl spaces of apartment buildings, moisture problems may be easily prevented by ground covers which decreased relative humidity to a 60–70% level. The only one important property of a ground cover is its moisture resistance; cutting the evaporation increased the crawl space temperature by 2 ºC in the summer. The optimum air change rate depends on the moisture resistance of the ground cover; with 5 cm expanded polystyrene without joints, 0.5 ach gave the lowest relative humidity all year round. In practice, an air change of 0.5–1 $m^3/h\ m^2$ can be recommended as it can effectively remove moisture flows through the ground cover, through its joints and other leakage points.

6. Moisture conditions in cold crawl spaces become critical in the summer when the temperature in the crawl space is significantly lower than outdoors. When relative humidity is higher than 75% for long periods, the acceptability of moisture conditions has to be assessed by mould growth analyses – the conditions are acceptable when the cumulative time of wetness is shorter than time needed to start mould growth. This method is probably basically correct, but the details in calculating the time of wetness and the equations for mould growth in unstable conditions need further research.
7. Extraordinary weather conditions may significantly affect the acceptability of the moisture conditions. During an exceptionally cold and moist summer the outdoor air relative humidity already caused mould growth on wood, and it was not possible to avoid high relative humidity in cold crawl spaces. Therefore, it seems that weather conditions force us to accept some mould growth during exceptionally cold and moist summers. This makes mould growth analyses more complicated as the prevalence of the weather data has to be taken into account as well.
8. In cold crawl spaces the moisture resistance of the ground cover exclusively is not a sufficient measure to decrease relative humidity. High thermal insulation and low thermal capacity are evidently beneficial as they insulate the cold ground, decrease the thermal lag and, thereby, increase the crawl space temperature. In the summer when crawl space air is usually warmer than the surface of the ground cover, the direction of moisture flow from the ground is reversed – quite often the moisture flow is from the air to the ground cover. Therefore, moisture capacity of the ground cover plays an important role because moisture uptake decreases crawl space relative humidity. The importance of these properties is demonstrated by the behaviour of the plastic sheet cover which showed in the summer as high (90–100%) relative humidity as uncovered ground.
9. The ground covers with appropriate properties for cold crawl spaces were found to be lightweight expanded clay aggregate (LWA) and expanded polystyrene (EPS). At a common thickness of ground covers, it was necessary to use the higher air change rate in the summer to warm up the crawl space. 2 ach air change was enough in the summer, however, 5 ach showed significantly better performance. At 2 ach air change, 30 cm LWA showed the lowest relative humidity, but the conditions were also clearly acceptable with 5 cm EPS. 15 cm LWA showed slightly higher relative humidity, but the conditions were still acceptable. When significantly thicker, highly insulating ground covers are used, the higher air change in the summer is probably not needed as the basic air change 0.5 ach is enough to warm up the crawl space. To find out at which thickness of the covers a constant air change rate can be used, further parametric simulations should be carried out.
10. In cold crawl spaces appropriate ground covers and air change rates have to be used to achieve acceptable moisture conditions. 15-30 cm LWA and 5-10 cm EPS covers can be recommended for any crawl space. A plastic sheet cover should not be used in cold crawl spaces and uncovered ground should never be used in any crawl space. A cold crawl space with the above mentioned ground covers needs a two-step air change: 0.5–1 $m^3/h\ m^2$ in the heating season and 2–3 $m^3/h\ m^2$ in the warm season (from May to October).

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