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# Crawl space air change, heat and moisture behaviour

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**Abstract**

The effect of ventilation on moisture behaviour in the traditional outdoor-air ventilated crawl space of blocks of flats with uncovered and moist ground surface is discussed in this paper. The objectives were to compare in real conditions the mechanical supply and mechanical extract ventilation to natural ventilation, to determine the rate of ground moisture evaporation, and to test the reduction of humidity with plastic sheet cover. The study was made between April 1997 and October 1998 when the conditions in naturally and mechanically ventilated crawl spaces of the test building were monitored. The air change rate in the crawl space was monitored continuously, as were temperature and humidity. This made it possible to assess moisture evaporation rate from the ground soil. Additionally, evaporation from some types of soil, crushed stone, gravel and granulated clay was measured in laboratory tests. The reported results account for the behaviour of air change and moisture balance, and give certain validity to arguments for optimum ventilation and the reduction of ground moisture evaporation. It was demonstrated that air change is only one important parameter affecting humidity in crawl spaces. Ground moisture evaporation was related to air change rate and pressure conditions: a higher air change led to higher moisture evaporation. Pressure conditions in the crawl space affected humidity notably; these were varied by using supply and extract fans and were monitored continuously during the measurements. Supply ventilation led to the lowest relative humidity, and extract ventilation brought about even higher humidity than did natural ventilation. No high relative humidity values were measured in summertime, and only brief condensation peaks over a few days were detected. During the summer, the relative humidity level with natural ventilation and uncovered ground was less than 85%, and with ground cover or with balanced ventilation it did not exceed 80%. It seems that with supply or balanced ventilation at 1-3 ach and with ground cover applied it is possible to maintain the relative humidity level under 80% in the outdoor-air ventilated crawl spaces of blocks of flats. 

*Keywords:* Crawl space; Air change; Humidity; Pressure conditions; Moisture evaporation; Ground covers

## 1. Introduction

### *1.1. The crawl space foundation*

The crawl space foundation is one of the most commonly used ground constructions in Finland. Over the last years, a remarkable amount of crawl space repairs has been made. Mould and moisture problems, appearing mostly as mould smell in apartments, are typical. In the repairs, crawl spaces are cleared of the organic materials (usually present in the crawl space since construction phase) and ventilation is increased. To solve moisture problems, not only air change and a ground covers should be considered, but also rain water sewerage and drainage should be made to function, because in some modern buildings, the floor level in crawl space is lower than the outside ground level. Such a building method using a low ground floor level was not known in the old building tradition, and has mainly come about through cost-effectiveness. This is also one explanation for the high incidence of moisture problems.

A crawl space can be ventilated by using outdoor air, exhaust air from the ventilation system, or it can be left unventilated. Unventilated crawl space needs almost perfect moisture insulation, and when exhaust air is used, the heat insulation level should also be relatively high to avoid condensation during the heating season. In Finland, the foregoing solutions are not used on a large-scale; traditional crawl space ventilated with outdoor air is most common (Fig. 1). Ventilation is mostly natural and designed for wind pressure differences, but mechanical extract ventilation is used as well in some scale.

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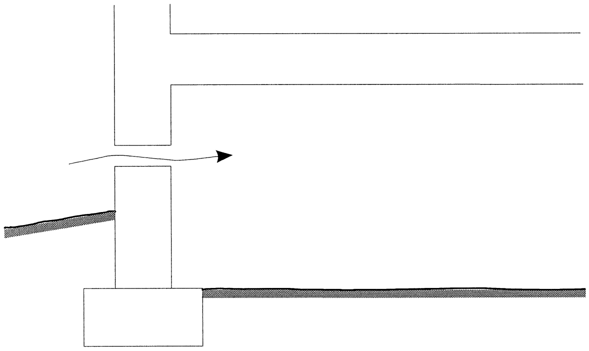


Fig. 1. An outdoor-air ventilated crawl space foundation.

It is known that the behaviour of crawl spaces becomes problematic in the summer when in the daytime outdoor air is usually warmer and with higher moisture content than the air of the crawl space. This means that outdoor air can transport moisture into the crawl space and the relative humidity will rise. Samuelson [1] reports a relative humidity of 85–95% during summer, and under extreme conditions 100% over a period of several weeks. This has been the main reason why new innovative solutions are being worked out for crawl space. Unventilated crawl space, crawl space heated by exhaust air and a radiant barrier for raising temperature of wooden joists are reported by Hagentoft and Harderup [2], Åberg [3], Lehtinen and Viljanen [4], Elmroth and Fredlund [5] and Salonvaara [6]. On the other hand, a traditional crawl space is also in need of improvement, at least when the present building stock is considered, where new solutions are usually not competitive and in some cases even not achievable. What the optimum ventilation rate and appropriate ventilating strategy might be for maintaining acceptably low relative humidity, how the ventilation and moisture reduction should be established, and what effects can be achieved by mechanical ventilation, are the main questions asked by designers and others over the last decades. Rose concludes in Ref. [7] that there is general agreement in previous literature that ground covers are effective in reducing humidity, but there is no convincing technical basis for current building code requirements for ventilation. When the relevant section of the Finnish building code was being revised, it was noticed as well that providing guidelines about traditionally ventilated crawl space is problematic because of a lack of scientifically-based data.

### *1.2. Heat and moisture transfer in crawl space*

Thermal and moisture behaviour of crawl space is affected by air change in opposite ways. In the heating season, the crawl space is warmer than the outdoor air, and the outdoor air with its low moisture content effectively removes the moisture from the crawl space. At the same time, ventilation decreases the temperature of the crawl space, and if air change is too high this will cause a rise in relative humidity. In summer, outdoor air is at times warmer than the crawl space and ventilation works inefficiently. Outdoor air with a high moisture content even transports some moisture into crawl space on certain days in the summer. At the same time, ventilation warms up the crawl space and this decreases the relative humidity.

Important heat, moisture and airflows determining the conditions in a crawl space are shown in Fig. 2. High heat capacity of the ground (and foundations) causes continuously unsteady state in the crawl space. As moisture behaviour is related to thermal behaviour, it is important to determine heat transfer with sufficient accuracy.

In a general state, we have to write energy balance for the air in the crawl space and heat balance for the base floor, walls and ground. Humidity balance should be written in a similar way for the air in crawl space. The only considered moisture flow is evaporation from the ground surface. If evaporation is remarkable, the evaporation heat $Q_{\mathrm{EVAP}}$. should be considered. The energy balance of crawl space air is

$$C\frac{\partial T}{\partial t} = Q^{C}_{\mathrm{FLOOR}} + Q^{C}_{\mathrm{GROUND}} + Q^{C}_{\mathrm{WALL}} + Q^{\mathrm{IN}}_{\mathrm{VENT}} - Q^{\mathrm{OUT}}_{\mathrm{VENT}} \tag{1}$$

where $C$ denotes heat capacity of air (J/K) and $T$ is the air temperature in crawl space. Heat balance equations for surfaces (radiation heat transfer is considered only between base floor and ground) are

$$Q_{\mathrm{FLOOR}} = Q^{C}_{\mathrm{FLOOR}} + Q^{\mathrm{RAD}}$$
$$Q_{\mathrm{WALL}} = Q^{C}_{\mathrm{WALL}}$$
$$Q_{\mathrm{GROUND}} = Q^{C}_{\mathrm{GROUND}} - Q^{\mathrm{RAD}} + Q_{\mathrm{EVAP}}. \tag{2}$$

and moisture balance of crawl space air in steady state is

$$g^{\mathrm{OUT}}_{\mathrm{VENT}} = g^{\mathrm{IN}}_{\mathrm{VENT}} + g \tag{3}$$

Ground moisture evaporation $g$ (kg/s) can be written by using humidity by volume as potential and boundary layer theory assumptions for laminar flow as follows

$$g = \beta(v_{\mathrm{ground}} - v_{\mathrm{air}})A_{\mathrm{evap.}} \tag{4}$$

where $\beta$ is mass transfer coefficient (m/s); $\beta = \alpha/(\rho c_{\mathrm{p}})$, $\alpha$ is convective heat transfer coefficient (W m$^{-2}$ K$^{-1}$),

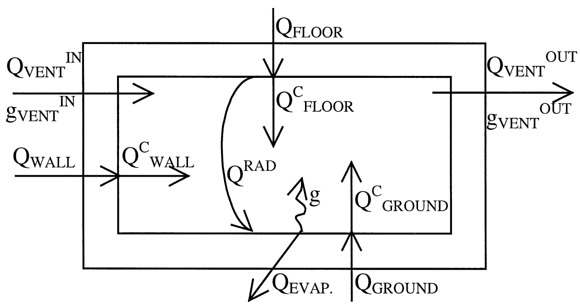



Fig. 2. Important heat ($Q$) and moisture ($g$) flows in crawl space. Superscript ''c'' marks convection.

$v_{ground}$ is humidity by volume on the ground surface (kg/m$^3$) and $v_{air}$ in crawl space air (kg/m$^3$), $A_{evap.}$ is the area of the evaporation surface (m$^2$), $\rho$ is density of air (kg/m$^3$) and $c_p$ is specific heat capacity of air (J kg$^{-1}$ K$^{-1}$). Often vapour pressure is used in moisture evaporation equation as potential. If one considers universal gas law, i.e., the relation between vapour pressure and humidity by volume, the Eq. (4) can be expressed alternatively

$$g = \beta(p_{ground} - p_{air})\frac{M_w}{RT}A_{evap.} \quad (5)$$

where $p_{ground}$ is vapour pressure on the ground surface (Pa) and $p_{air}$ in crawl space air (Pa), $M_w$ is molecular weight of water 0.018 kg/mol, $R$ universal gas constant 8.31 J mol$^{-1}$ K$^{-1}$ and $T$ absolute temperature (K).

Moisture behaviour of crawl space was analysed by Elmroth in 1975 [8]. Recommendations for calculating ground moisture evaporation with constant moisture transfer coefficients, given by Elmroth, are applied by many authors today also. Evaporation was measured with laboratory tests by Nieminen and Rantamäki [9] and in situ by Trethowen [10]. These results are not free of uncertainties, for example, handling the latent heat causes some problems.

Complicated behaviour and the high heat and moisture capacity of the ground soil means that also successful modelling needs data from field measurements and laboratory tests. Such data are the heat and moisture transfer parameters of ground soil and air change rate. If the air change rate is measured, the ground soil parameters can be estimated with certain accuracy from the results of humidity and temperature measurements. In modelling, the results of previous research can be used, where a lot of work with analytical solutions and calculation methods has been carried out by Hagentoft [11], Åberg [12], Anderlind [13] and others.

High relative humidity (usually considered over 80–85%) is the most important parameter for mould growth in crawl space, where temperature is usually over 5°C. In addition to high humidity, the presence of cold surfaces for condensation is also an important parameter for mould growth. For analysing the effect of ventilation on relative humidity, the results given in Refs. [8–10] cannot be successfully used because air change is not only affecting moisture behaviour of a crawl space, but also the thermal behaviour. Since the moisture transfer process is strongly temperature-dependent, the effect of air change rate on resulting relative humidity of crawl space air cannot be directly estimated. Thus, the best way to study the issue of air change rate is to carry out field measurements with real boundary conditions.

## 2. Methods

### 2.1. The test building

Field measurements were made in one middle block of a 4-story apartment building. A section of the foundation is shown in Fig. 3 and the plan of the block investigated in Fig. 4. The height of the crawl space is 0.9 m and the bottom of the crawl space is roughly 1 m beneath the outside ground level. The foundations and base floor are typical for clay ground soil. The building foundations are on piles and the base floor hollow-core slabs are borne by base rockers (all of concrete). Thermal insulation of 50 mm and 100 mm EPS (expanded polystyrene) can be seen

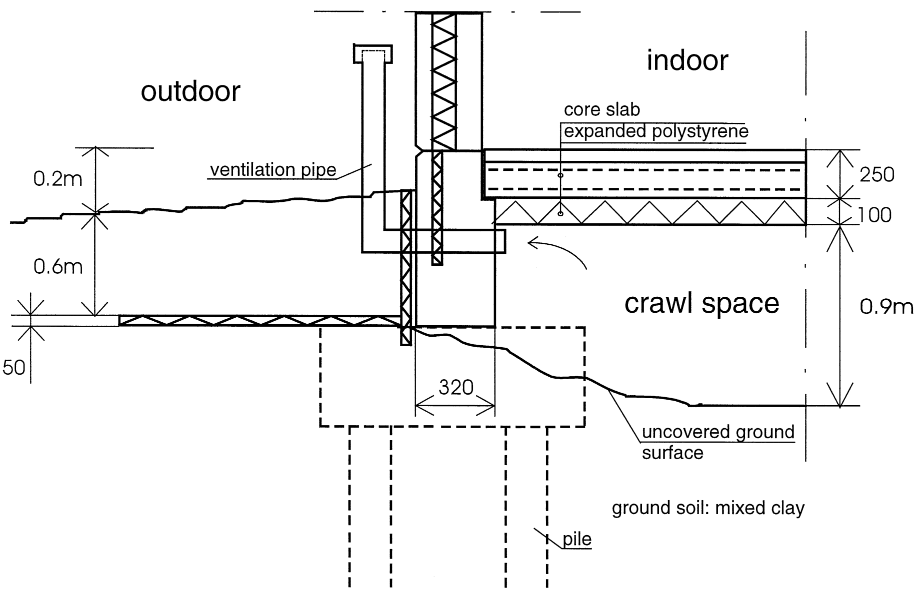



Fig. 3. Section of the foundations of the test building.

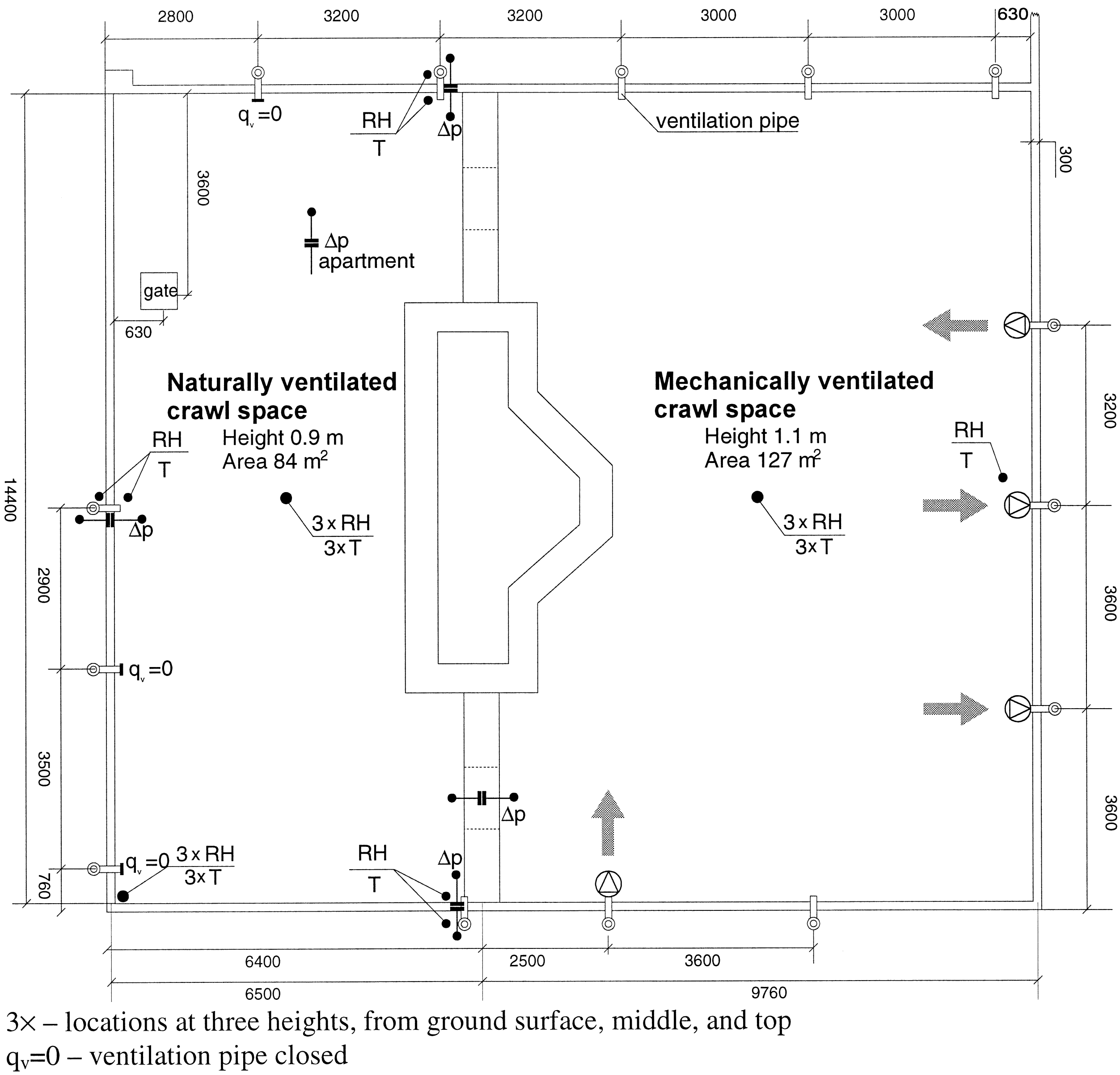



Fig. 4. Plan of the foundations. The area of natural and mechanical ventilation, measurement points of RH, $T$ and $\Delta P$, ventilation pipe and fan locations in the case of balanced ventilation.

from the section. The crawl space is naturally ventilated with outdoor air that flows through L-pipes with a 125-mm diameter. The building is equipped with a mechanical extract ventilation system with two-speed fans. Normally the extract fans run at half-speed, but there are a few short periods during the day when they run at full speed. There are no air intakes in the apartments.

The crawl space of the selected block was divided into two rectangular sectors with areas of 84 m$^2$ and 127 m$^2$ as shown in Fig. 4. In practice, this division by base rocker already existed, only the openings for passage were closed and made air-tight. According to this choice, the geometry, the ground soil and climate conditions are possibly similar in both crawl spaces, as these are in the middle of the building, inside the same block, and thus it is possible to compare natural and mechanical ventilation. Natural ventilation was maintained without any changes in the left part and mechanical ventilation was installed in the right one. For mechanical ventilation, the duct fans (125-mm size) were directly connected to L-pipes inside the crawl space. The fan directions were changed to establish extract and supply ventilation.

### 2.2. Measurements

Measurements were carried out between April 1997 and October 1998. The following quantities were monitored continuously:

- air velocity and pressure drop in ventilation pipes (natural ventilation)

- pressure variation between crawl space and chosen apartment
- pressure variation between crawl spaces and between crawl space and outdoor air
- relative humidity in crawl space and outdoor
- temperature in crawl space and outdoor
- wind velocity and direction provided by weather station on the roof of the building

The locations of the measurement points are shown in Fig. 4. Humidity and temperature were measured at several heights and locations. Moisture content of soil was observed by taking samples once a month. Pressure variation between the crawl space and outdoor air were measured across three walls of the naturally ventilated crawl space. These values indicate also pressure drops in ventilation pipes and can be used for determining the airflow in pipes.

### 2.3. Air change measurements

Air change in mechanically ventilated crawl space can be determined with sufficient accuracy from the flow through fans if these depressurise or over-pressurise the crawl space. Only in the case of balanced ventilation, the wind-induced airflows (that are not measured) might cause inaccuracy. Monitoring the air change in naturally ventilated crawl space is much more problematic. It is still necessary for comparing ventilation systems and analysing moisture behaviour. Possible measuring techniques are active or passive tracer gas [10] or airflow measurements from ventilation openings/pipes that are based on air velocity or pressure drop measurement. The passive tracer gas technique is suitable for long-term measurements, but it gives only the average value for the measured period. Also, unstable airflows without a fixed direction make passive tracer gas measurements quite complex. Active tracer gas is more suitable for instant measurements with a typical duration of two time constants of the space. However, achieving the needed mixing is not easy in low and extensive crawl space; additionally, mixing by fans disturbs the airflow patterns and can even affect the ventilation rate. Airflow measurements from ventilation openings/pipes lay on pseudo-steady flow assumption and can be made only if flow patterns are well-defined and flow characteristics are known.

In naturally ventilated crawl space, air change was determined by measuring pressure difference across ventilation pipes or alternatively, by measuring velocity inside a 40-cm long duct component that was added to the ventilation pipe. The measured results were compared to a number of instant active tracer gas measurements. In mechanically ventilated crawl space, air change was determined from the flow through the fans. Tracer gas was used once for confirming the result.

The airflow characteristics of the L-type ventilation pipe with a diameter of 125 mm, used in the test building, were measured in a laboratory. The airflow rate can be stated as $q = 4.38\Delta p^{0.512}$, if the flow direction is from outside to the crawl space, and $q = 5.23\Delta p^{0.517}$, if the flow is from the crawl space to the outside. Here $q$ (l/s) and $\Delta p$ (Pa) denote the airflow and pressure difference.

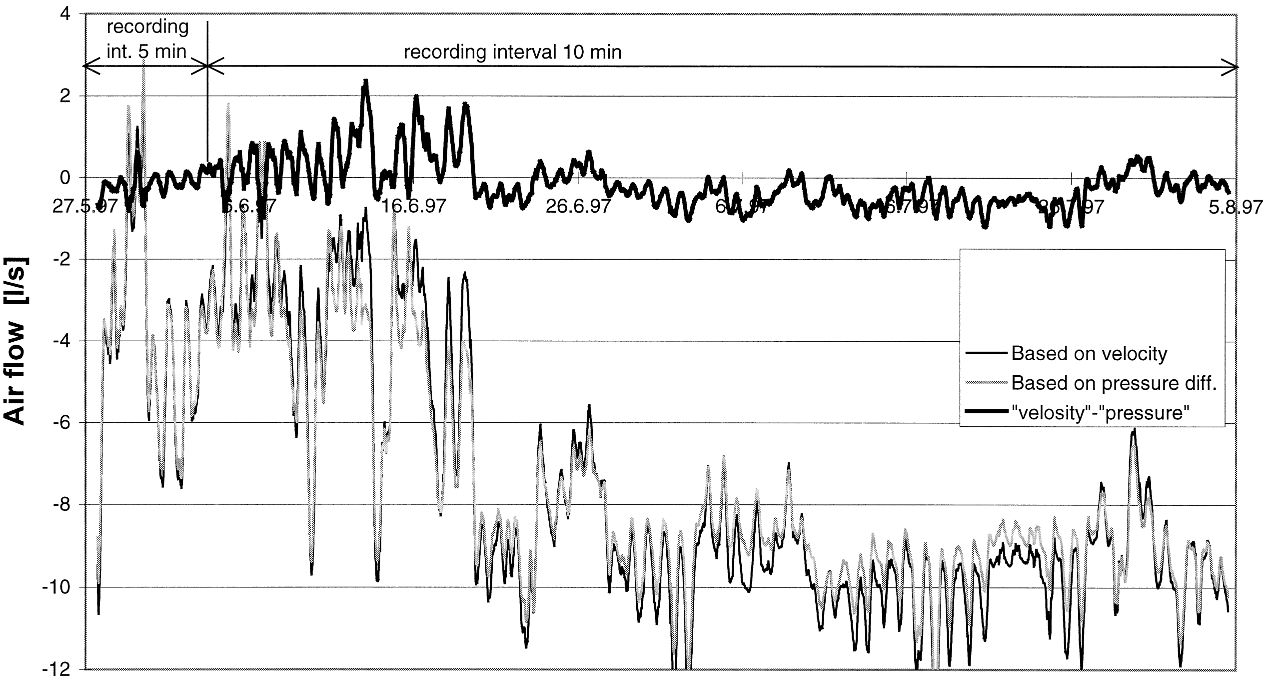



Fig. 5. An example of measured air change using methods based on pressure difference and velocity (values are moving averages with 6-h period).

Which equation should be used can be seen from the sign of measured pressure value. The nonlinear relation between pressure drop and airflow rate (typical turbulent duct flow) means that quite fast sampling should be used. Five and 10 min recording intervals were tested. With both recording intervals each measurement was measured once every 30 s and averaged for a 10-or 5-min value. Shorter interval gave a better result, but still a 10-min interval was chosen to avoid huge amounts of measured data. An example of the measured data, compared to velocity measurements, is shown in Fig. 5. In velocity-based measurements, equipment consisting of a 40 cm duct and velocity sensor was calibrated in laboratory also. Here the relation between measured maximum velocity and average velocity was determined. It was 0.77 or 0.71 depending on the flow direction. This method worked, as did the measuring of pressure difference, but the reliability of the sensors used was not good, and it was applied only as a parallel method.

Air change measurements with active tracer gas were carried out mainly to find out how large differences in local mean age-of-air [14] would be at different points in crawl space. During the first measurements it was noticed that the mixing rate in crawl space was surprisingly good and the same sampling system can be used for determining local mean age-of-air and average air change rate. Measurements were made with a modified decay method [14] by sampling from twelve points in naturally ventilated crawl space. First, tracer gas was released into crawl space and mixed by using 2–3 fans. After achieving a stable concentration at all twelve points (it was occasionally problematic), the release of tracer gas was stopped, fans were switched off and sampling was started. The decay was recorded from every point and the local ages of air were calculated. Since the measured values were very close, the time constant was calculated as the average value for determining air change. In mechanically ventilated crawl space, air change was measured once in the traditional way by the decay method, i.e., mixing fans were running during the measurement, and only average concentration was recorded. The result was 2.4 ach when the air change determined from flows through the fans was 2.8 ach. The latter is an approximate result since determining the volume of a crawl space with varying height is more or less approximate. The measured air change values from a naturally ventilated crawl space are compared to airflow measurements from ventilation pipes in Table 1.

When comparing the results, it should be noted that some uncertainty in tracer gas measurements is caused by the difficulties in mixing, which was not always complete (mostly during first measurements). The results measured from ventilation pipes do not include a leakage that is notable if the pressure difference between naturally and mechanically ventilated crawl space is high, as shown in Section 3. Measurements 5–10 represent a situation where there was strong under-pressure in mechanically ventilated crawl space and, thus, they demonstrate that smaller air change values measured from ventilation pipes are showing considerable leakage. The last three measurements that show a much better agreement represent balanced ventilation.

## 3. Results

### 3.1. Measuring periods during the research

The effect of air change rate, the influence of under- or overpressure on crawl space heat and moisture behaviour, and the reduction of ground moisture evaporation with a plastic sheet were studied by field measurements. It should be noted that the number of cases that can be studied by field measurements is quite limited because of the long duration of the measurement periods. Moreover, analysing the results of field measurements is complicated because almost everything is in interaction. Therefore, the computer simulation was carried out for adding the number of cases studied and for analysing the effects of some parameters. The results of computer simulation are not discussed in this paper. In addition, the results of the laboratory tests where the moisture evaporation was measured for various types of soil, gravel, crushed stone, expanded clay and other materials will be discussed briefly only. The periods of the research are shown in Table 2.

### 3.2. Air change, pressure conditions and air distribution in crawl space

Air change rate in mechanically ventilated crawl space is shown in Table 3. The air change is determined from the flow through the fans. Wind-induced ventilation caused uncertainty only in the case of balanced ventilation (Period 6, two supply and two extract fans). However, it can be seen from the extract airflow in naturally ventilated crawl space (that was measured, see Fig. 6) that the rate of this

Table 1
Air change in naturally ventilated crawl space

| No. of measurement | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Air flow (l/s) from tracer gas | 41.1 | 30.7 | 37.8 | 38.3 | 64.6 | 59.9 | 42.2 | 28.2 | 47.3 | 52.3 | 21.3 | 19.3 | 10.7 |
| Air flow (l/s) from pressure difference | 47.2 | 44.2 | 45.8 | 47.4 | 39.1 | 38.6 | 32.5 | 19.7 | 30.6 | 30.3 | 16.6 | 19.9 | 12.4 |

Results from tracer gas measurements and from ventilation pipe measurements (based on pressure difference).

Table 2
Periods of the research

| Period no. and description | Duration |
|---|---|
| (1) Natural ventilation in both crawl spaces | 22.4–19.6.1997 |
| (2) Extract ventilation with three extract fans (a leaky wall between crawl spaces and high air change also in naturally ventilated crawl space) | 19.6–2.9.1997 |
| (3) Air tightening the wall between the crawl spaces | 2.9–9.9.1997 |
| (4) Extract ventilation with three extract fans | 9.9–24.10.1997 |
| (5) Ventilation with one supply and two extract fans | 24.10–9.12.1997 |
| (6) Balanced ventilation, two supply and two extract fans. The number of ventilation pipes was reduced by half in naturally ventilated crawl space on 22.12.1997 (three pipes out of six were closed). Moisture evaporation was reduced by laying plastic sheet on ground, in naturally ventilated crawl space 20.3–6.8.1998 and in mechanically ventilated crawl space 25.5–6.8.1998. | 9.12.1997–13.5.1998 |
| (7) Supply ventilation with three supply and one extract fan | 13.5–3.9.1998 |
| (8) Extract ventilation with four extract fans | 3.9–1.10.1998 |
| (9) Natural ventilation in both crawl spaces | 1.10–14.10.1998 |

flow is only a few litres per second during this period. In other cases, the fans pressurised the crawl space and, thus, air change can be estimated from flows through the fans.

The measured supply and extract airflows in naturally ventilated crawl space are shown in Fig. 6. As later demonstrated, the supply flow indicates air change in naturally ventilated crawl space because only a proportion of the extract air exits through ventilation pipes as designed. It can be seen that supply and extract flows are not in balance even during the first, natural ventilation period. Starting the extract fans in mechanically ventilated crawl space (period 2) affects directly the naturally ventilated crawl space; the extract flow then vanishes completely and supply becomes more than twice as high. Here, the leakage through the wall between the crawl spaces was obvious and it was carefully sealed. After sealing the wall, some extract flows occurred in naturally ventilated crawl space (period 4), but supply and extract flows were still not in balance. The main reason was not leakage occurring between crawl spaces because the pressure difference between the crawl spaces was increased from 0.5 to 4 Pa (Fig. 9).

The reason for the unbalance in the supply and extract flows was found in January 1998, when the measurements of pressure difference between the crawl space and the selected apartment were started. Since there was a normal mechanical exhaust ventilation functioning in the building, it caused approximately 7 Pa pressure difference between the first floor and the crawl space. This under-pressure in the apartments caused a leakage through the base floor and a portion of the intake air was simply sucked from the crawl space. This pressure difference between apartments and the crawl space that acts as the driving force for natural ventilation is shown in Fig. 7 over one typical week. It can be seen that a two-speed fan is being used in the ventilation system of the building. Every day there are three periods at full speed and the rest of the time the fans work at half-speed.

When taking into account the pressure difference between naturally ventilated crawl space and outdoors (measured over three walls), the pressure difference between crawl spaces, and the pressure difference between naturally ventilated crawl space and the apartments, the resulting pressure conditions shown in Fig. 8 are obtained. Interpreting the results measured over three walls is somewhat tricky, as usually different readings are recorded from each wall. For determining the pressure level in the crawl space, the values of pressure are used when all three measured curves give a uniform result (corresponds to weather without any wind). Thus, values shown in Fig. 8 are free of wind effects.

The effect of supply ventilation and extract ventilation (mechanically ventilated crawl space) on air change in naturally ventilated crawl space can be seen from Fig. 6. Extract ventilation with a four-fan (period 8) causes a sharp raise in supply flow as the pressure difference between crawl spaces is 6–7 Pa (Fig. 9). Supply ventilation reduces the supply flow and also increases slightly the extract flow in naturally ventilated crawl space. To avoid significant leakage between crawl spaces, the pressure difference between crawl spaces was reduced by replacing one extract fan to a supply fan already in period 5. In period 6, the ventilation on the mechanical side was com-

Table 3
Air change rate in mechanically ventilated crawl space based on the flow through the fans

| Period no. | Air change rate | | |
|---|---|---|---|
| | l/s | l/s $m^2$ | ach |
| 1–4 (3 extract fans) | 130 | 1.0 | 3.3 |
| 5 (2 extract and 1 supply fan) | 90 | 0.7 | 2.3 |
| 6 (2 extract and 2 supply fans) | 110 | 0.9 | 2.8 |
| 7 (1 extract and 3 supply fans) | 130 | 1.0 | 3.3 |
| 8 (4 extract fans) | 170 | 1.3 | 4.4 |

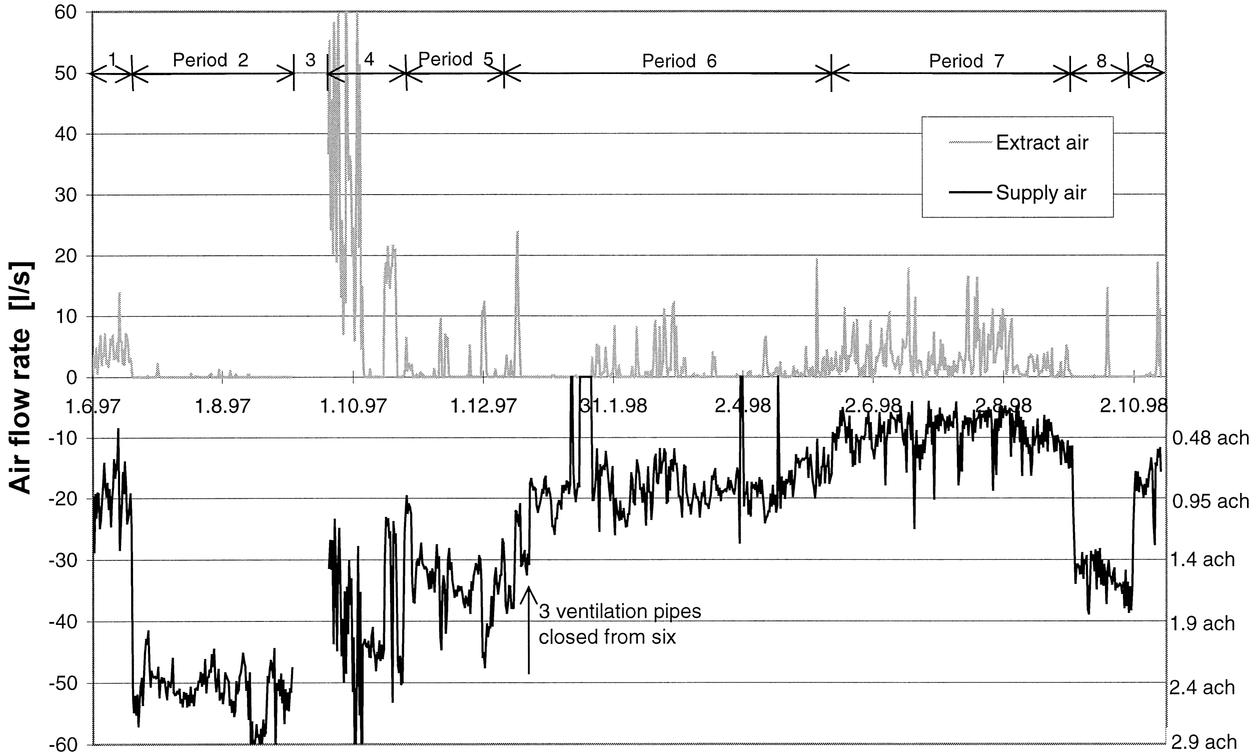



Fig. 6. Measured supply and extract flows in naturally ventilated crawl space. (Values are moving averages with 12-h period).

pletely balanced, but no change occurred in the airflows of naturally ventilated crawl space. The only change can be seen on 22.12.1997, after the reduction of the number of ventilation pipes.

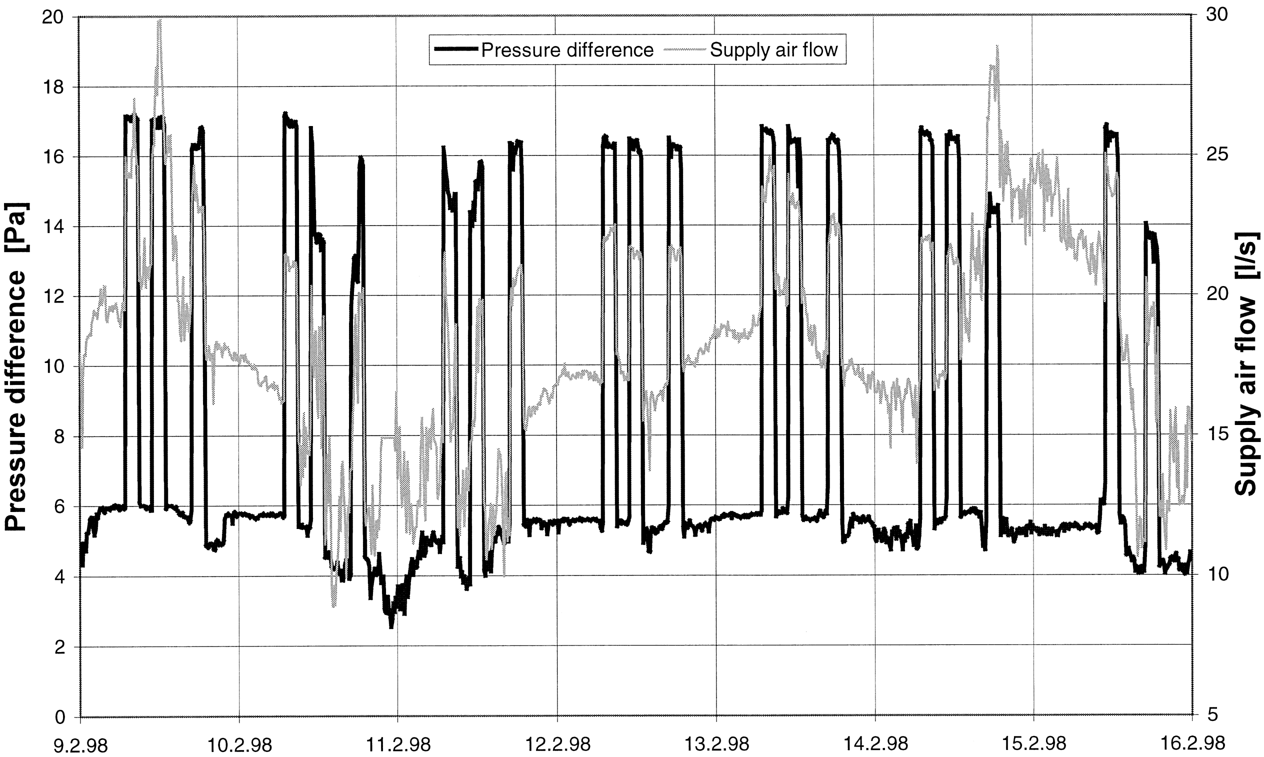



Fig. 7. Pressure variation between naturally ventilated crawl space and the selected apartment during a typical week. (Secondary axis: supply air flow in the crawl space, 20 l/s corresponds 0.95 ach.) Note under-pressure in the apartment and overpressure in the crawl space (10-min averages).

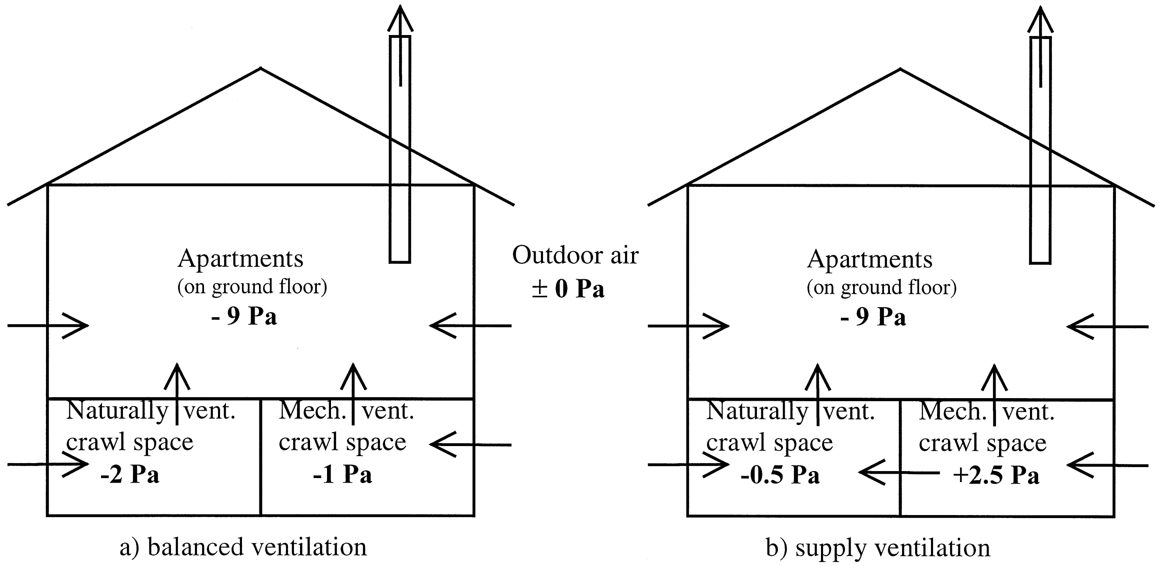



Fig. 8. The pressure conditions compared to outdoor and air flow directions in case of balanced ventilation (a) and supply ventilation (b) in mechanically ventilated crawl space.

Air change in naturally ventilated crawl space was reduced in December 1997 in order to achieve a greater difference between ventilation rates, as air change in naturally ventilated crawl space was remarkably high due to leakage through the base floor. On December 9, when the number of ventilation pipes was reduced to half, air change

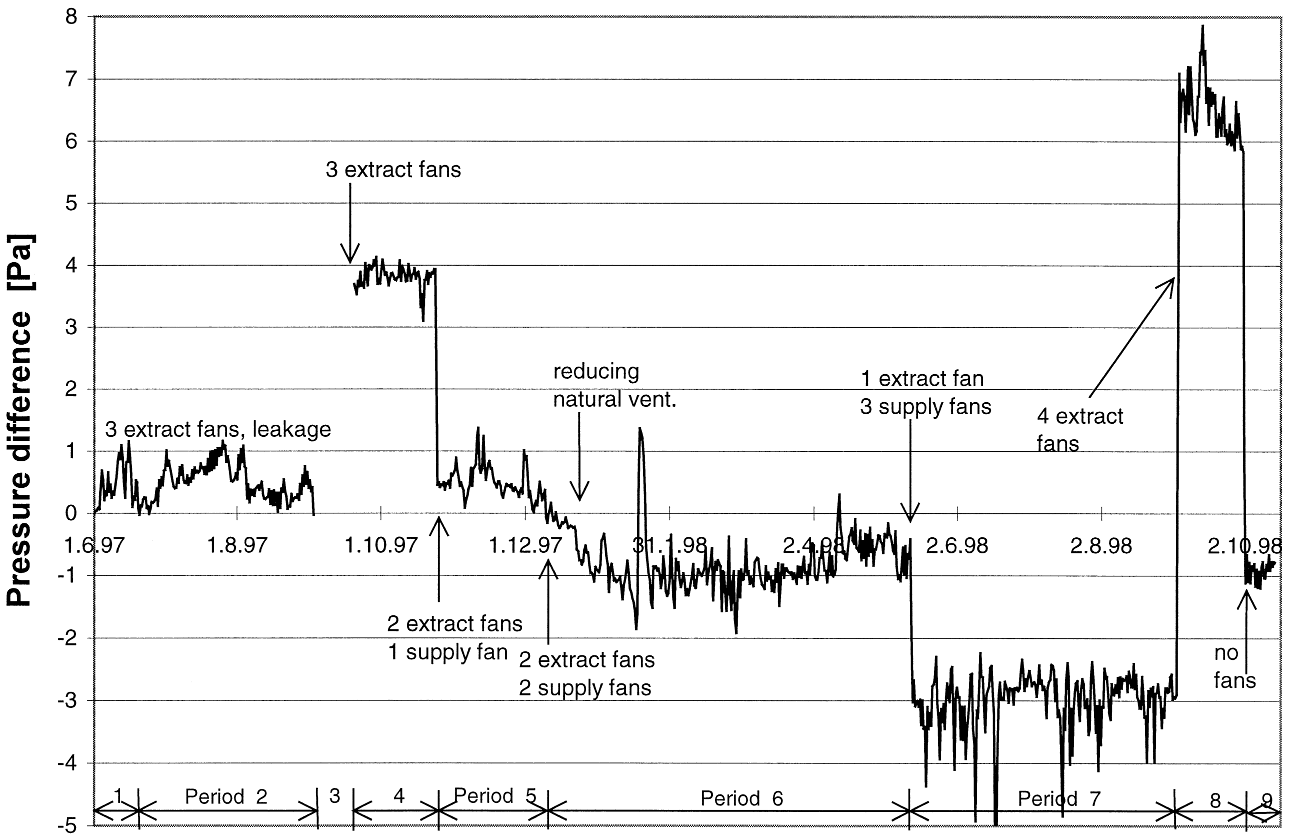



Fig. 9. Pressure difference between naturally and mechanically ventilated crawl space; positive values represent under-pressure in mechanically ventilated crawl space (12-h moving averages).

correspondingly reduced from 30 l/s to 17 l/s as shown in Fig. 10. The effect of decreased air change can be also seen as the rise in temperature (Fig. 13).

In addition, air distribution in crawl space was measured with six, three and two ventilation pipes opened by using tracer gas equipment. Certain measurement results, the local mean age-of-air at 12 measurement points, are shown in Fig. 11.

### *3.2.1. Conclusions*

(1) Under-pressure caused by the ventilation system of the building was the main driving force for naturally ventilated crawl space air change: in calm weather all extract flow from the crawl space flowed through the base floor to the apartments and other rooms. Only fluctuations in supply airflow are caused by wind and extract airflow peaks represent high wind velocities. Hence, the natural ventilation of crawl space was not working as it was designed — its function was not based on the pressure differences caused by wind flow.

(2) The supply ventilation period was the only period during which measured supply air flow through ventilation pipes did not indicate the complete air change in naturally ventilated crawl space. Based on an instantaneous change in supply airflow, the leakage airflow from mechanically ventilated crawl space to naturally ventilated crawl space was about 8 l/s. During balanced ventilation period there was no significant leakage because the pressure difference was absent. During extract ventilation periods, the leakage airflow from naturally ventilated crawl space to mechanically ventilated one is merged with supply flows, measured through the ventilation pipes.

(3) There is notable under-pressure in the apartments as compared to crawl space in the case of balanced or supply ventilation in the crawl space. Even extract ventilation with three extract fans remained at about 3 Pa under-pressure in the apartments, but the extract ventilation with four fans removed the pressure difference between apartments and the crawl space, causing a slight 0–1 Pa under-pressure in the crawl space. Thus, for removing the pressure difference between the apartments and crawl space by the extract ventilation of crawl space, an air change rate at least 4 ach was needed, and this is about four times more than the values applied in practice.

(4) The number of ventilation pipes did not affect air distribution in the crawl space. In all the cases, measured mixing was almost complete.

## *3.3. Thermal conditions*

The measured air temperature in the crawl space at a middle height and outdoors during 1997 are shown in Fig. 12. The temperature at the ground surface was almost the same as the air temperature, the difference never exceeded 1–2°C. At the beginning (period 1, natural ventilation in both crawl spaces), the temperature was almost the same in both crawl spaces. During period 2, when the extract air of naturally ventilated crawl space was removed through

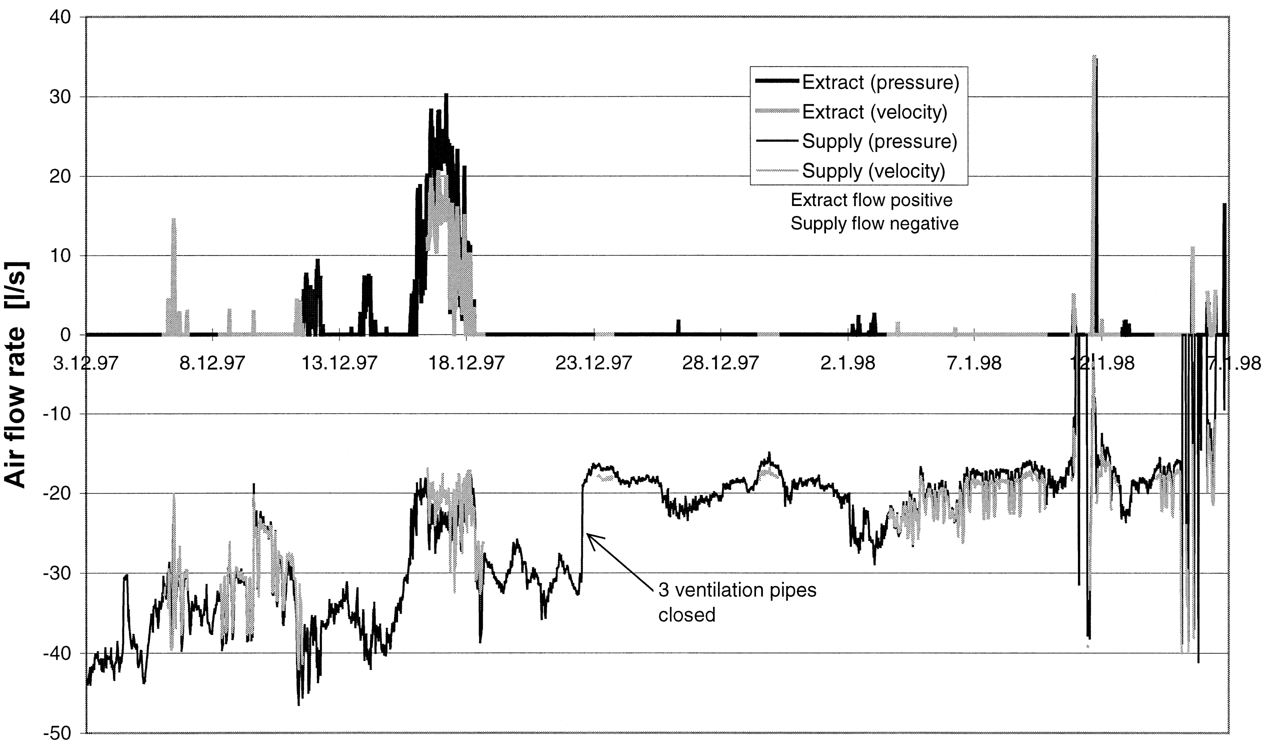



Fig. 10. The effect of reducing the number of ventilation pipes from six to three in naturally ventilated crawl space. 1/2-h average values measured by methods based on pressure difference and velocity.

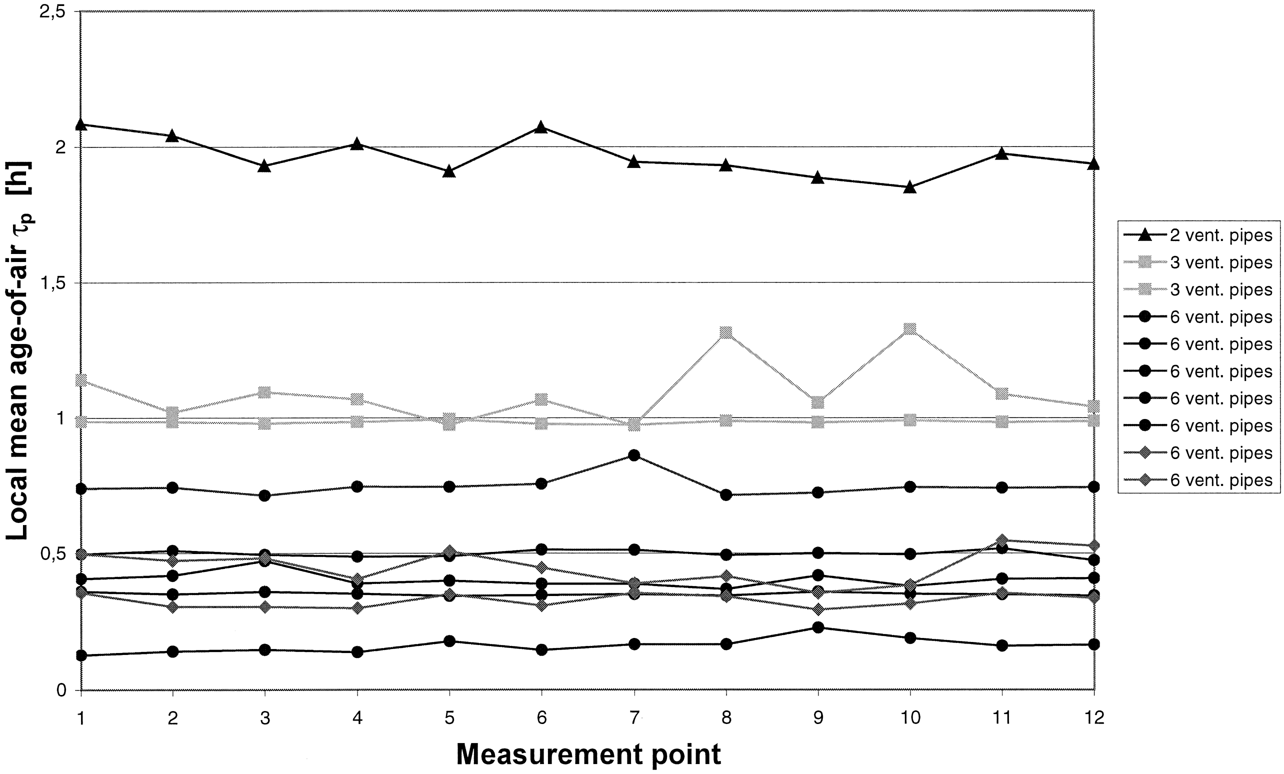



Fig. 11. An example of air distribution in naturally ventilated crawl space. Local mean age-of-air at 12 measurement points.

mechanically ventilated crawl space, the temperature of the latter was about 1°C lower. After sealing the wall between crawl spaces, the temperature was again almost the same in both crawl spaces.

Replacing one extract fan to a supply fan on 24.10.97 caused a slight temperature rise (0.5–1°C) in naturally ventilated crawl space that was result of reduced ventilation. Installing a second supply fan cooled the mechani-

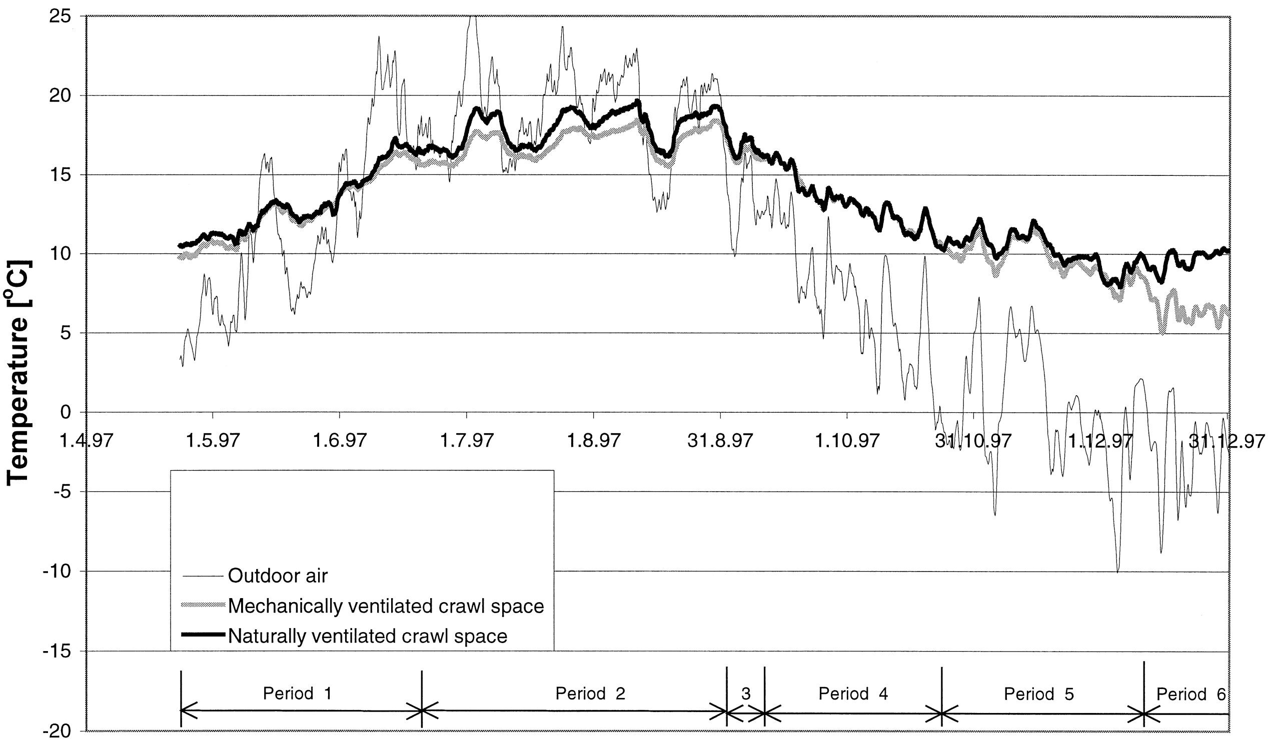



Fig. 12. Air temperature in the crawl space and outdoors during 1997 (24-h moving averages).

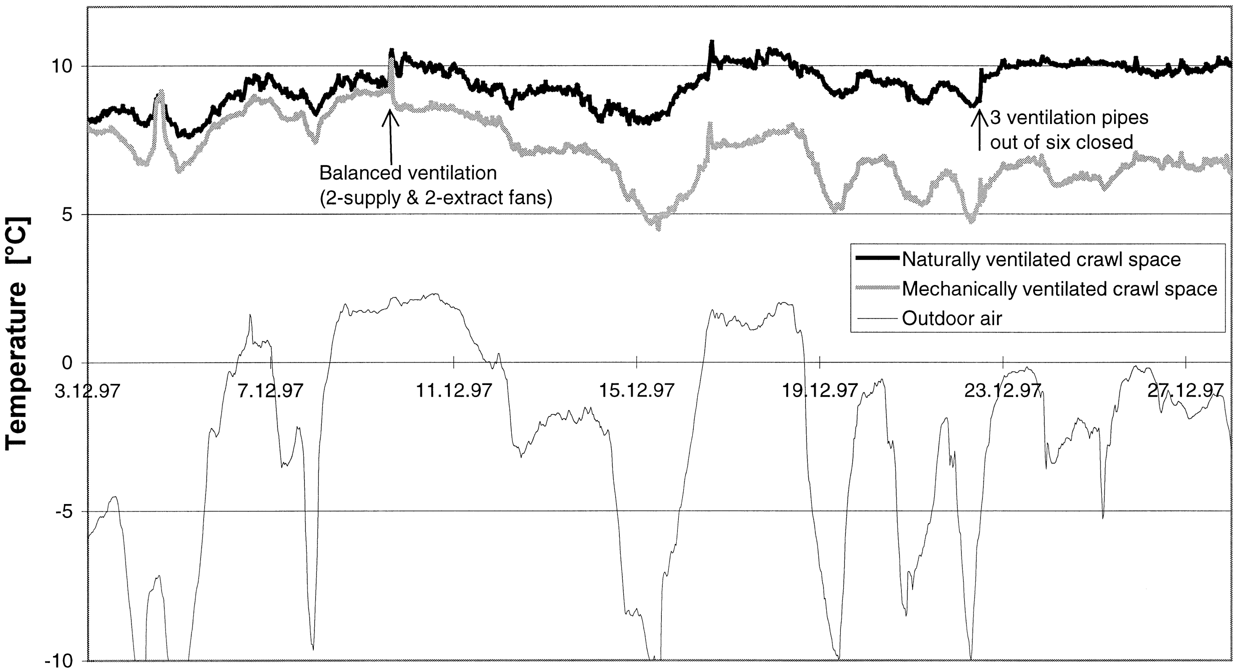



Fig. 13. The change in temperature after installing a second supply fan and after reducing the number of ventilation pipes in naturally ventilated crawl space (1/2-h averages).

cally ventilated crawl space down by about 2°C, and dropping the number of ventilation pipes by half in naturally ventilated crawl space raised the temperature in naturally ventilated side as shown in Fig. 13.

The temperatures during 1998 are shown in Fig. 14. It is noteworthy that during the period in September when four extract fans were used, the temperature in mechanically ventilated crawl space is almost the same as in

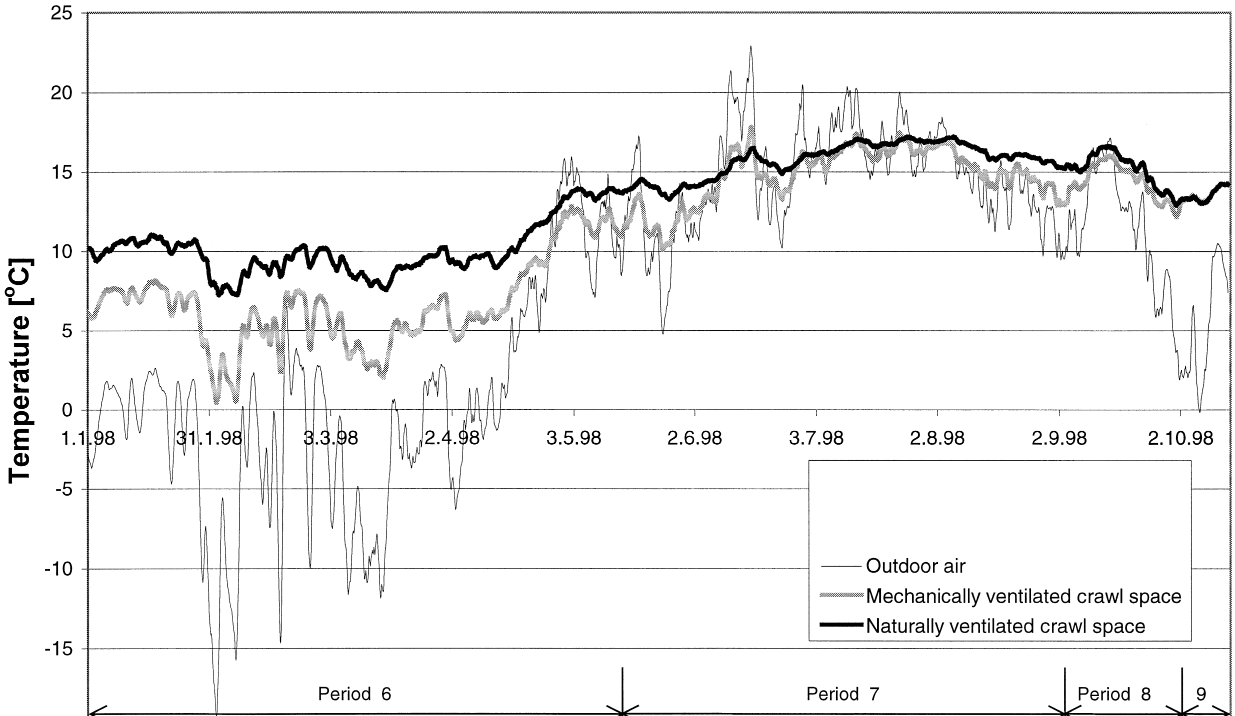



Fig. 14. Air temperature in the crawl space and outdoors during 1998 (24-h moving averages).

naturally ventilated crawl space. It demonstrates the effect of the leakage from the adjacent crawl spaces that keep the temperature high. At the end of the research, the temperature remains the same in both crawl spaces, as there is natural ventilation in both crawl spaces.

*3.3.1. Conclusions*

(1) In winter, the temperature in mechanically ventilated crawl space was 3–5°C lower than that in naturally ventilated crawl space. In the coldest weather, the temperature in mechanically ventilated crawl space was close to 0°C, but in daily average values, it remained over 0°C.

(2) In spring, mechanically ventilated crawl space warmed up and it can be seen from Fig. 14 how its temperature conformed with outdoor air. In June, the temperature in mechanically ventilated crawl space attained the temperature of naturally ventilated crawl space. During summer, mechanically ventilated crawl space was sometimes warmer and sometimes cooler than naturally ventilated crawl space, yet the differences were small.

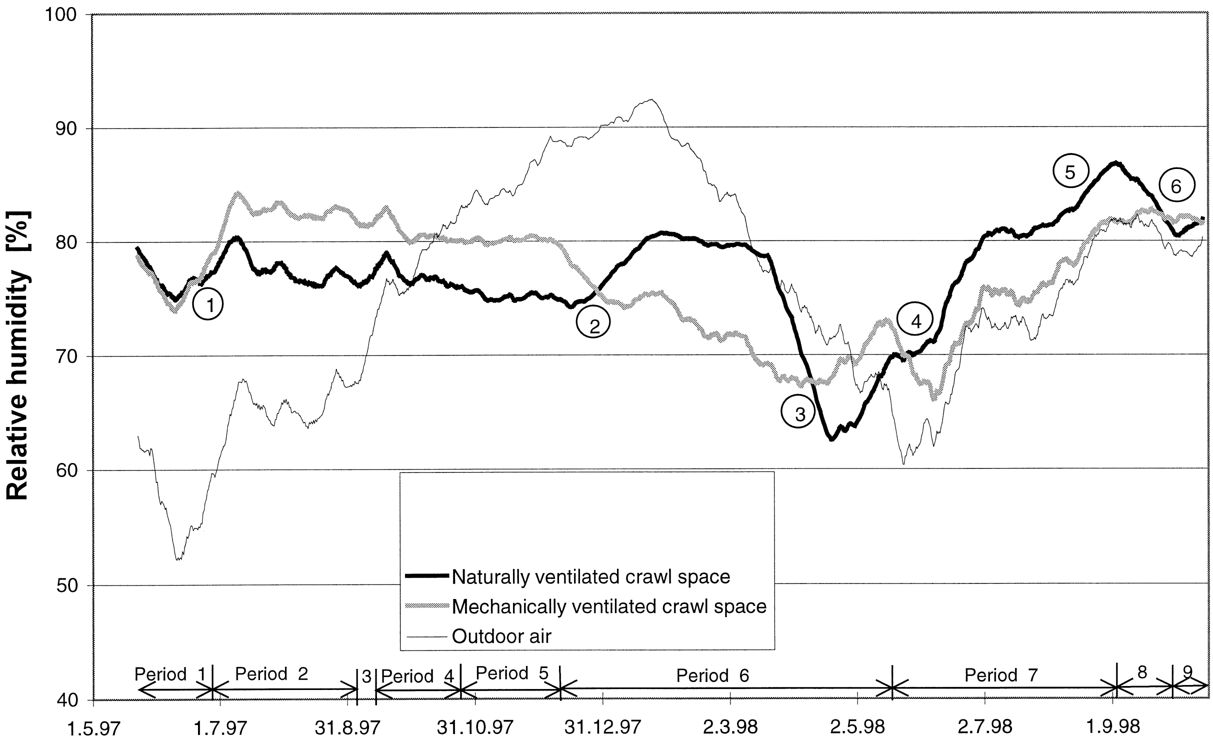
(3) Both crawl spaces were noticeably warm during the summers 1997 and 1998. In summer 1998, the temperature level in both crawl space and outdoors was about 17°C, and the outdoor air was remarkably warmer ($\Delta T$ about 5°C) than the crawl space only for a few days. During the hot summer of 1997 the temperatures were higher, and periods up to one week can be found when outdoor air was remarkably warmer than crawl space.

*3.4. Moisture conditions*

The effects of mechanical extract and supply ventilation and plastic sheet (PVC) cover are shown below. Relative humidity in the crawl space (monthly moving average values measured at middle height) is shown in Fig. 15.

The average values of relative humidity during the summers of 1997 and 1998 are shown in Table 4. It should be noted that these two summers cannot be directly compared because the summer 1998 was remarkably moist, and also in the summer of 1997 the air change rate in naturally ventilated crawl space was about five times higher because its extract air was removed through mechanically ventilated crawl space.

Daily average values of relative humidity during 1997 are shown in Fig. 16. Humidity was the same in both crawl spaces during the first natural ventilation period. During extract ventilation (3.3 ach) relative humidity was continuously higher in mechanically ventilated crawl space. No difference between periods 2, 3 and 4 can be seen. Even replacing one extract fan to a supply fan in period 5, that dropped under-pressure down in mechanically ventilated crawl space, did not cause any noticeable change in relative humidity. Changing to balanced ventilation (period 6)




1) Extract ventilation
2) Balanced vent. (in detail Fig. 16, 17)
3) PVC in nat. vent. crawl space
4) PVC in mech. vent. crawl space
5) PVC removed
6) Extract ventilation (in detail Fig. 18)

Fig. 15. Monthly moving average values of relative humidity during the entire research period.

Table 4
Average values of relative humidity during the summers of 1997 and 1998

| Period | Mechanically ventilated crawl space (%) | Naturally ventilated crawl space (%) | Outdoor air (%) |
|---|---|---|---|
| Summer 1998, 1.6–31.8 | 77.8 | 82.6 | 76.3 |
| Summer 1997[a], 1.6–31.8 | 82.0 | 78.3 | 64.7 |
| Summer 1998, only period with plastic sheet 1.6–6.8 | 76.0 | 80.8 | 73.8 |

[a] In 1997, air change in naturally ventilated crawl space was about five times higher than in 1998.

decreased relative humidity in mechanically ventilated crawl space.

The effect of balanced ventilation and the reducing ventilation in naturally ventilated crawl space are shown in detail in Fig. 17. After increasing the difference between the air change rates, i.e., after reducing air change in naturally ventilated crawl space, the lower relative humidity in mechanically ventilated crawl space can be seen more clearly. Air change was dropped at this moment from 1.4 ach to 0.8 ach and afterwards relative humidity in naturally ventilated crawl space was 5 to 10% higher than in mechanically ventilated crawl space. The effect of extract ventilation was tested again in September 1998. Then there was a higher air change rate of 4.4 ach and a higher under-pressure (6 to 7 Pa) in mechanically ventilated crawl space. The high under-pressure affected naturally ventilated crawl space by doubling its air change rate up to 1.5 ach. As before, a few percent higher relative humidity in mechanically ventilated crawl space was measured during the extract ventilation period (Fig. 18).

The effect of the plastic sheet cover can be seen from Fig. 18. At first, the plastic sheet was laid on the ground in naturally ventilated crawl space. The plastic sheet cuts out ground moisture evaporation almost completely, but some moisture evaporation remained because only about 90% of the ground surface area was covered with plastic. (The edges of the crawl space remained uncovered.) Before the plastic sheet was laid also to mechanically ventilated crawl space, supply ventilation period was started (Fig. 19).

The plastic sheets were removed at the same time from both crawl spaces (Fig. 18). After removal, the ground surface looked much darker and saturated (RH 100%) than

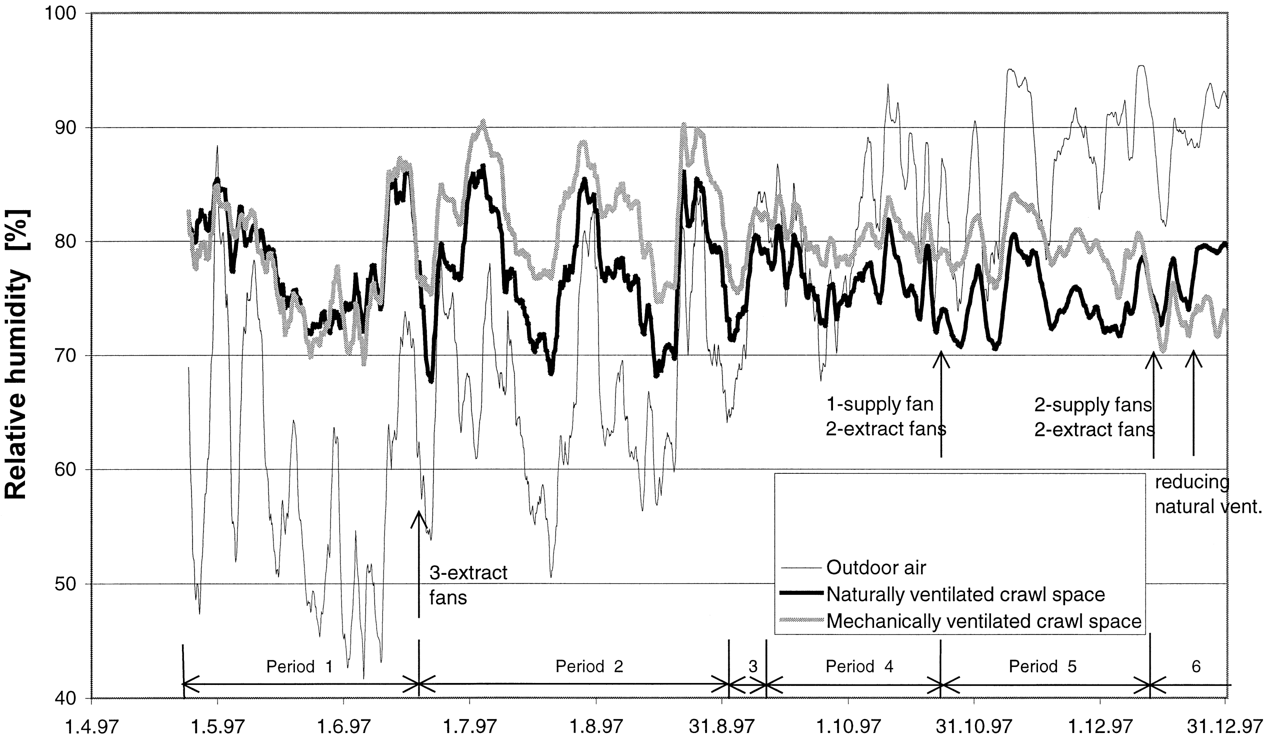



Fig. 16. Relative humidity in crawl space during 1997 (48-h moving averages).

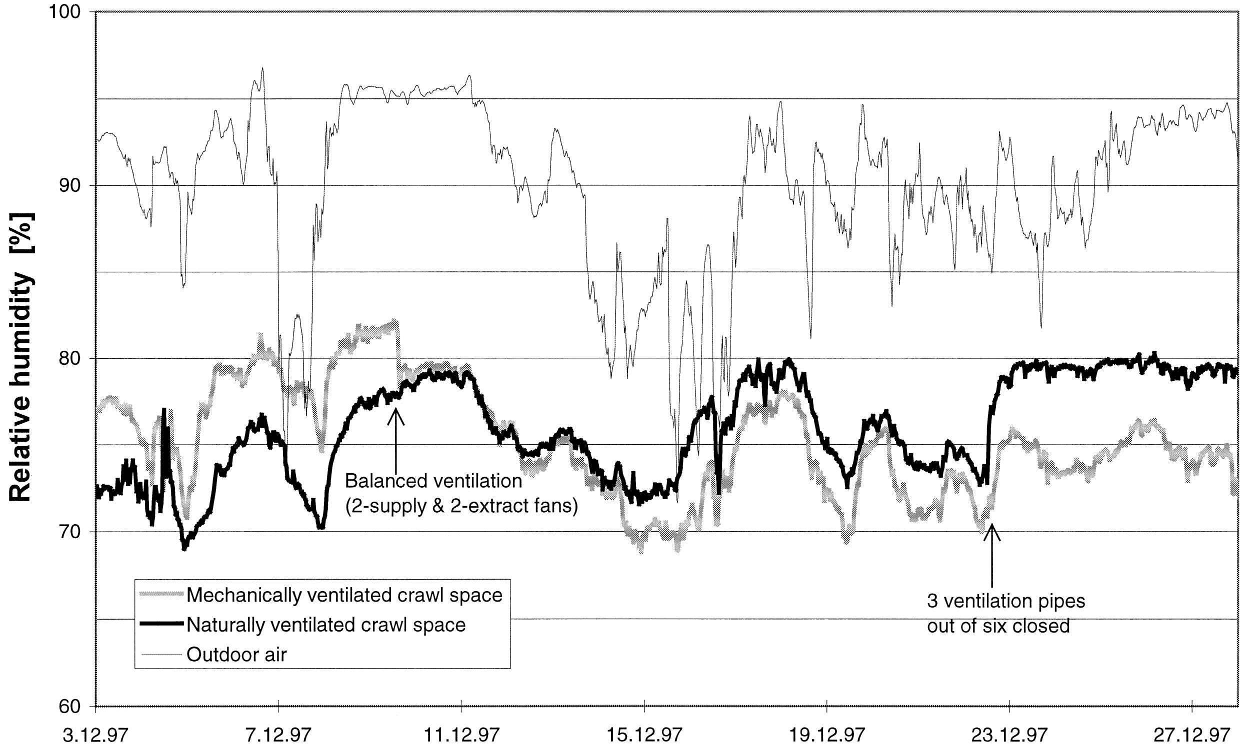



Fig. 17. The effect of balanced ventilation and reducing the number of ventilation pipes on relative humidity (1/2-h averages).

before. During the entire measurement period, the relative humidity on the ground surface was close to 100%, but a variation between 85 and 100% was measured.

*3.4.1. Conclusions*

(1) Mechanical extract ventilation led to higher relative humidity than did natural ventilation. The advantage of the

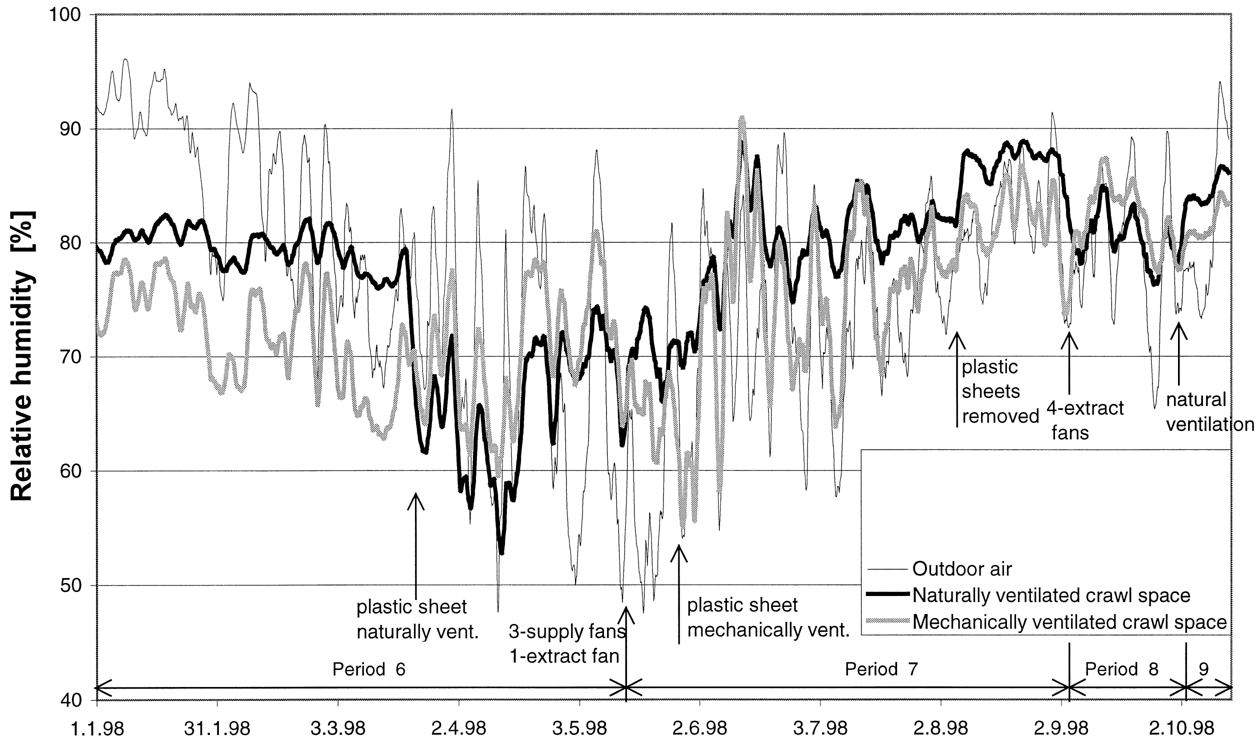



Fig. 18. Relative humidity in crawl space during 1998 (48-h moving averages).

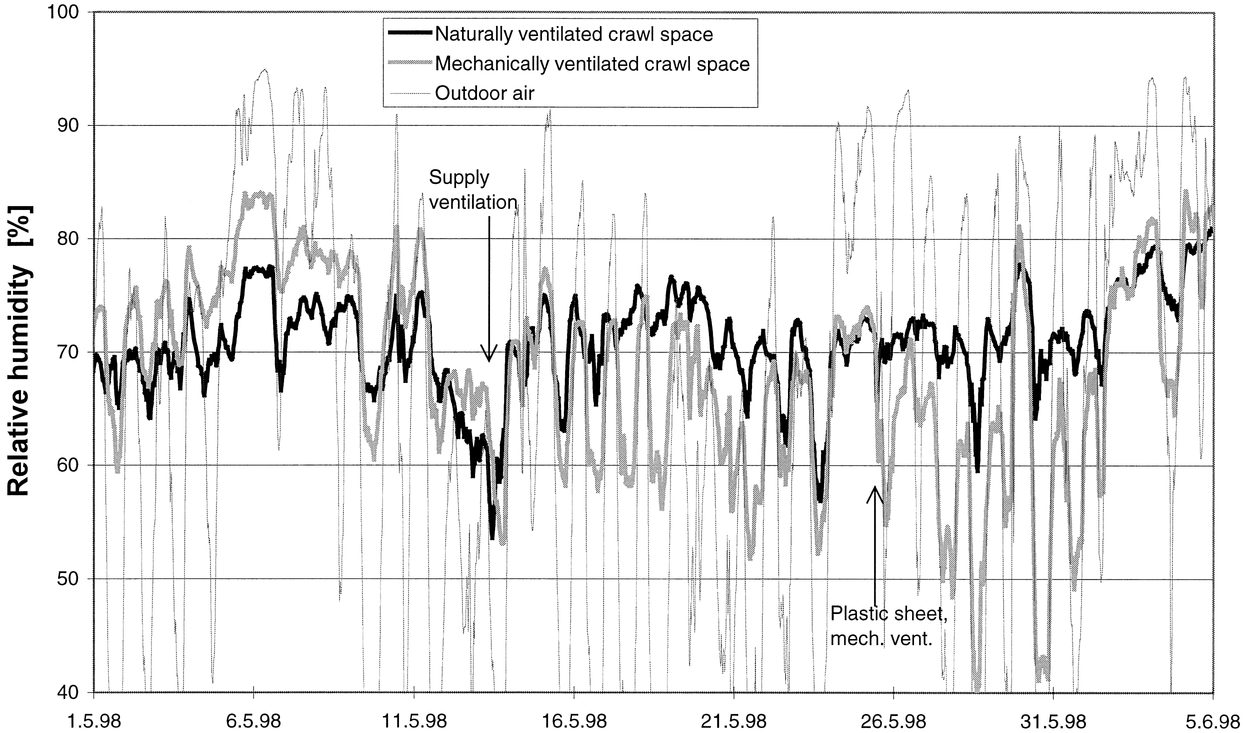



Fig. 19. The effect of supply ventilation and plastic sheet in mechanically ventilated crawl space to relative humidity. Plastic sheet in naturally ventilated crawl space since 20.3.1998 (1/2-h averages).

higher ventilation rate could be seen only when extract ventilation was changed to balanced ventilation. After the change to balanced ventilation, i.e., the removal of the under-pressure from mechanically ventilated crawl space, it was the first time when mechanically ventilated crawl space was drier, and this change remained permanent.

(2) Extract ventilation periods demonstrate that under-pressure causes flows through permeable soil, drainage gravel and possibly causes some direct leakage from adjacent blocks of crawl space. These transport the moisture and raise the humidity in the crawl space.

(3) It was notable that supply ventilation decreased instantly relative humidity in mechanically ventilated crawl space by 5% and later the difference rose up to 10% compared to naturally ventilated crawl space with the plastic sheet. A possible explanation is that in the earlier case of balanced ventilation there was still 1 Pa under-pressure in the crawl space caused by under-pressure in the apartments and leakage through base floor. Supply ventilation replaced this under-pressure to overpressure and also changed the direction of any possible flows in the ground soil and gravel, and moisture load was reduced.

(4) The plastic sheet cover caused almost 10% fast drop in relative humidity in naturally ventilated crawl space and about 5% fast drop in mechanically ventilated crawl space. After removing the plastic sheets, the rise in relative humidity was less than 10% in both crawl spaces. This was less than expected, as the ground surface was saturated, but it can be explained by effective air change, i.e., outdoor air was cooler than crawl space at that period and air change efficiently removed moisture from the crawl space.

(5) The lowest relative humidity in summer, 76% average value, was achieved with plastic sheet cover and supply ventilation of 3.3 ach. At the same time, the average value in naturally ventilated (about 0.4 ach) crawl space with ground cover was 81%. During summer 1997, when the air change rate in naturally ventilated crawl space was 2.5 ach (caused by leakage between crawl spaces), its relative humidity was remarkably low, 78% without ground cover.

(6) Relative humidity was not problematic during the heating season; it remained mostly between 70 and 80% when extract ventilation periods are not considered.

### 3.5. *Drying effect of ventilation and ground moisture evaporation*

Moisture behaviour, effects of ventilation, and plastic sheet cover can be studied by analysing the moisture content of the air. An important parameter is the difference in humidity between outdoor and crawl space air showing the amount of humidity that can be removed with ventilation. This humidity difference is shown in Fig. 20. It was almost the same in both crawl spaces during the extract ventilation periods at the beginning of the study. Both in summer 1997 and 1998 there are some negative peaks indicating a higher humidity in outdoor air than in crawl space. These peaks appear in hot weather, when outdoor temperature and humidity are above the corresponding

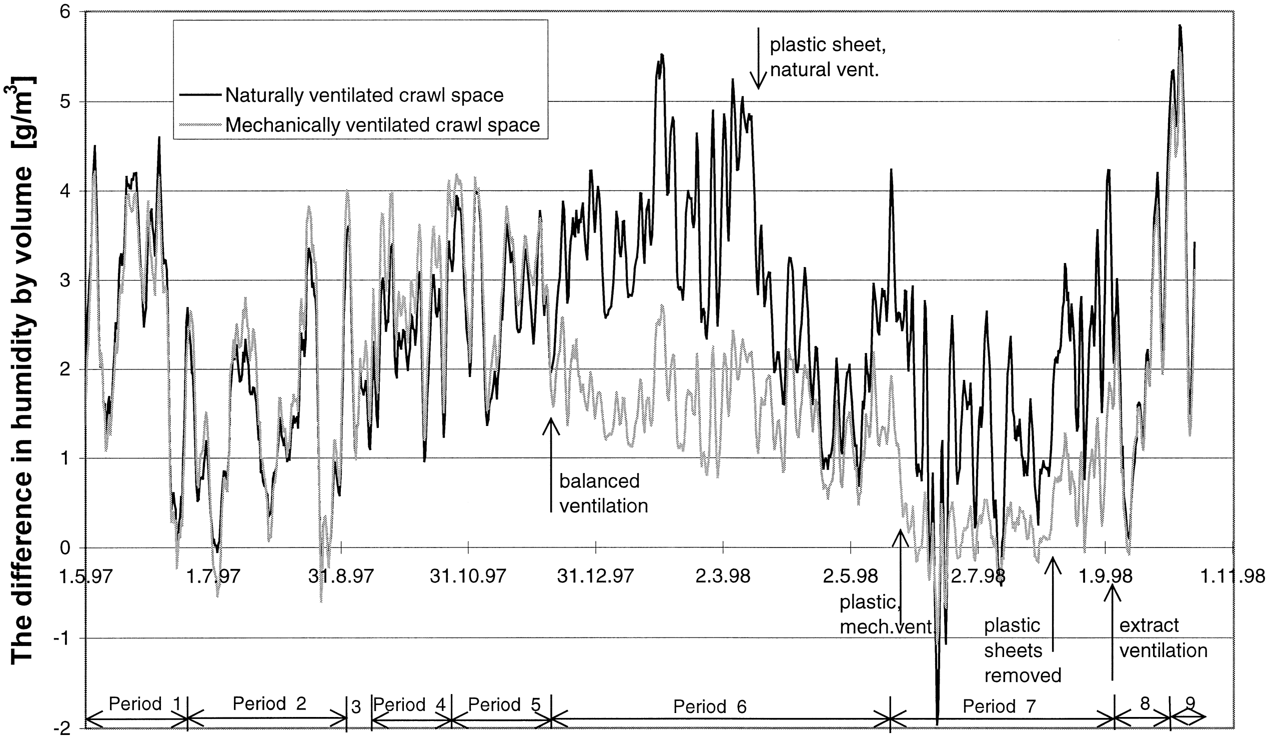



Fig. 20. The difference in humidity by volume between crawl space air and outdoors (48-h moving averages).

values in crawl space, and ventilation transports moisture into the crawl space, leading to a rise in humidity. A period of balanced ventilation is clearly exceptional from previous extract ventilation, as the humidity difference in mechanically ventilated crawl space is notably smaller than in naturally ventilated crawl space. Another period with low humidity difference is the plastic sheet period when especially in the mechanically ventilated crawl space

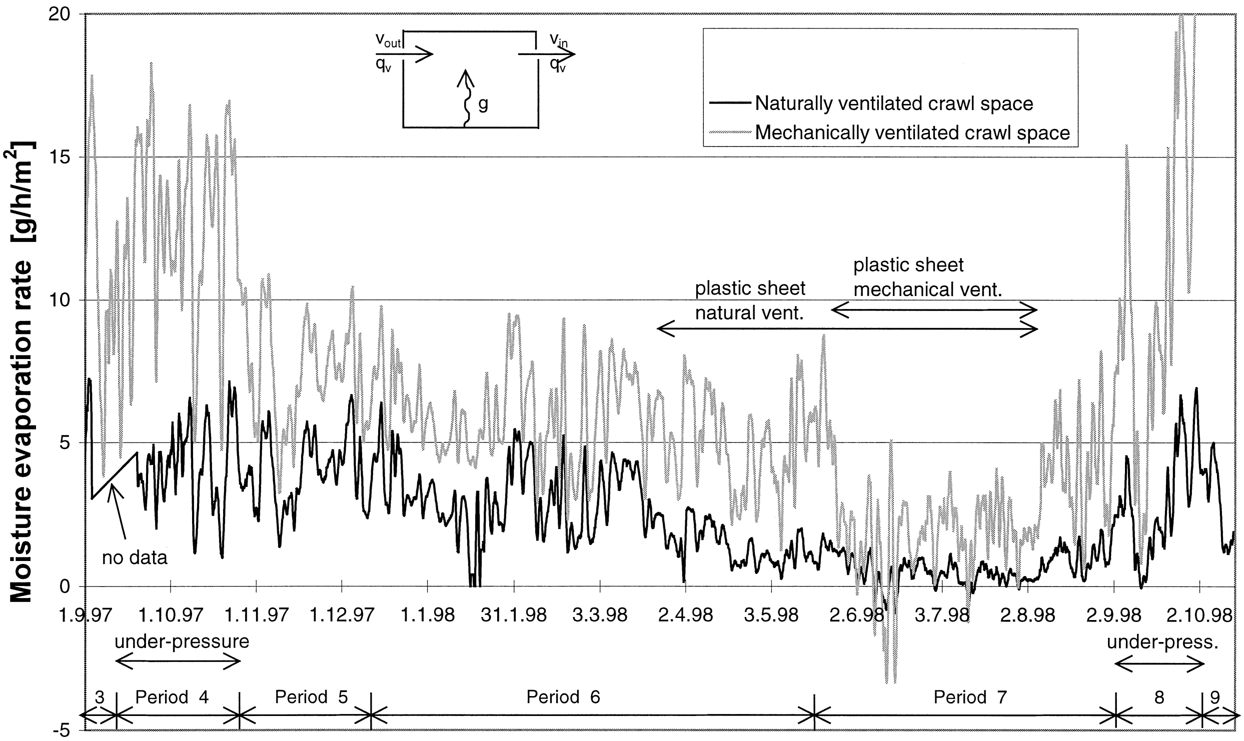



Fig. 21. Ground moisture evaporation rate. Calculation is based on the difference in moisture content of supply and extract air and the air change in crawl space (24-h moving averages).

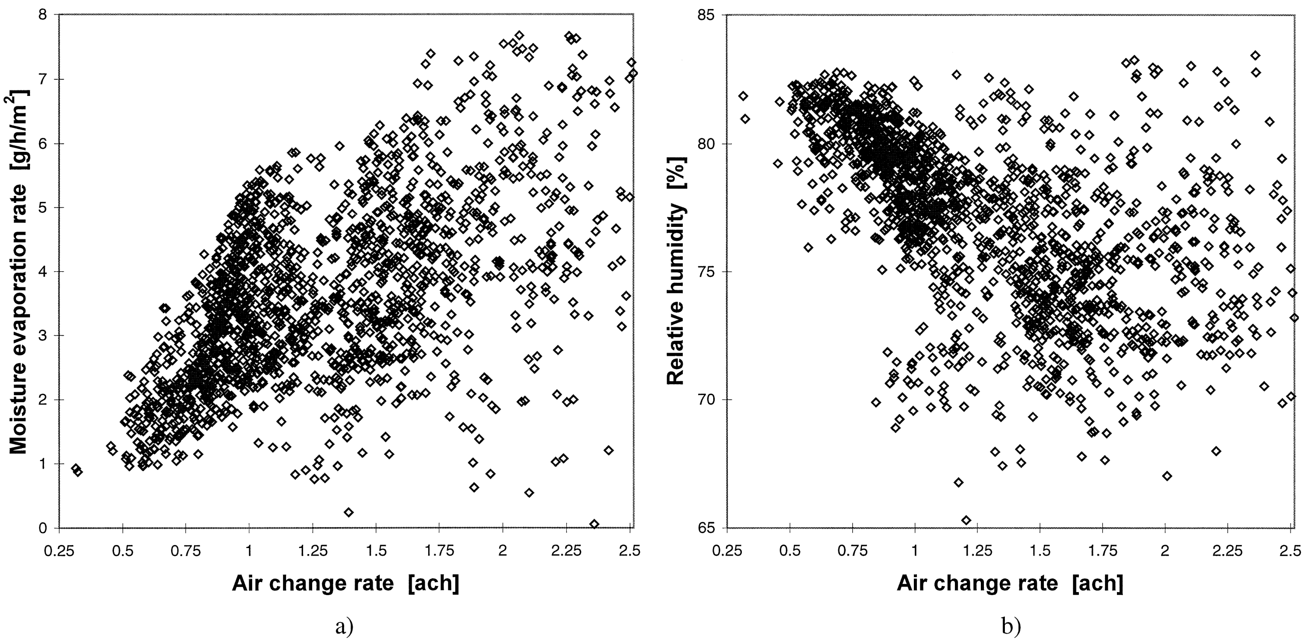



Fig. 22. The correlation between the moisture evaporation rate and air change (a) and between relative humidity and air change (b) in naturally ventilated crawl space during the period 19.9.1997–20.3.1998 (2.5-h averages).

the air was only very slightly more humid than the outdoor air.

The ground surface is the only moisture source in crawl space if moisture flows by air flows and through constructions are not considered and raining and surface waters are not present in crawl space, as should be provided by correct design. Thus, the moisture evaporation rate can be calculated from the balance of incoming and leaving moisture flow that are determined by air flow and moisture content of air. The calculated moisture evaporation from ground surface, based on measured humidity and air change (Eq. (3)), is shown in Fig. 21.

From the results of the measurement of air change rate, relative humidity and calculated moisture supply, it can be seen in principle that higher ventilation rates have led not only to a slightly lower relative humidity but also to higher moisture evaporation. This can be seen more clearly from the correlation shown in Fig. 22. The correlation between the moisture evaporation rate and air change, and between relative humidity and air change are drawn for period before the plastic sheet was laid in the naturally ventilated crawl space. $R$-squared value is about 0.4 in the whole range for both correlations.

In mechanically ventilated crawl space, a corresponding correlation cannot be drawn because the air change rate was constant. Moisture balance can be studied by using average values for each period, shown in Table 5 for mechanically ventilated crawl space and in Table 6 for naturally ventilated crawl space.

### 3.5.1. Conclusions

(1) The moisture content in outdoor air was higher than in crawl space air during very short periods (a couple of days) in summer. Usually outdoor air was dryer and the

Table 5
Moisture evaporation and relative humidity during each period in mechanically ventilated crawl space

| Period (no.) extract/supply fans | Air change rate (l/h) | Evaporation rate (g/h m$^2$) | Relative humidity (%) |
|---|---|---|---|
| Extract ventilation (4) 3/– | 3.3 | 12.4 | 80.4 |
| Extract ventilation (5) 2/1 | 2.3 | 7.6 | 79.7 |
| Balanced ventilation (6) 2/2 | 2.8 | 5.7 | 71.6 |
| Supply ventilation, before PVC (7) 1/3 | 3.3 | 5.9 | 65.7 |
| Supply ventilation, PVC (7) 1/3 | 3.3 | 1.9 | 74.5 |
| Supply ventilation, after PVC (7) 1/3 | 3.3 | 4.4 | 81.9 |
| Extract ventilation (8) 4/– | 4.4 | 10.8 | 82.2 |
| Natural ventilation (9) –/– | | | 81.6 |

Table 6
Moisture evaporation and relative humidity during periods 4–7 in naturally ventilated crawl space

| Period | Air change rate (l/h) | Evaporation ($g/h\ m^2$) | Relative humidity (%) |
|---|---|---|---|
| Before reducing ventilation | 1.7 | 4.1 | 75.5 |
| After reducing ventilation | 0.9 | 3.1 | 79.5 |
| PVC (plastic sheet on ground) | 0.6 | 0.9 | 73.5 |

difference in humidity was beyond 1 $g/m^3$, which can guarantee effective performance of ventilation.

(2) Pressure conditions and plastic sheet affect clearly the moisture evaporation rate. The ground moisture evaporation was very high during mechanical extract ventilation periods in mechanically ventilated crawl space. It should be noted that these values include convection flow through drainage gravel and possible leakage. Certain negative values in the summer indicate moisture storage in crawl space. The average value of moisture evaporation was 3.6 g $h^{-1}$ $m^{-2}$ in naturally ventilated crawl space and 5.7 g $h^{-1}$ $m^{-2}$ in mechanically ventilated crawl space, if the periods with extract ventilation and plastic sheet cover were not considered. During the period with plastic sheet cover, the average value of moisture evaporation in naturally ventilated crawl space was 0.9 g $h^{-1}$ $m^{-2}$, and 1.9 g $h^{-1}$ $m^{-2}$ in mechanically ventilated crawl space. Thus, plastic sheet cover reduced the ground moisture evaporation by 70%.

(3) There was a clear positive correlation between moisture supply and air change, and a clear negative correlation between relative humidity and air change within a range of 0.5–1 ach in naturally ventilated crawl space. In mechanically ventilated crawl space the effects caused by pressure conditions overrun the effect of air change.

## 4. Discussion

As side result in this research it was noticed that a portion of the intake air of apartments was sucked through the leaky base floor from crawl space. Since the test building consist of a typical blocks of flats and was equipped with typical exhaust ventilation, it is a general question about ventilation hygiene. On the other hand, the driving force of natural ventilation in crawl space was not caused by wind pressure differences but by under-pressure in the building. This means that completely wrong design criteria has been used when ventilation pipes were sized for wind pressure difference. The question is: should the buildings with exhaust ventilation be designed in such a way that a part of intake air can be sucked from crawl space, or should this be avoided by air-tight base floor or even by using balanced ventilation in buildings? It was shown that mechanical extract ventilation in crawl space could not remove the pressure difference with any realistic air change rates (below 4 ach).

It was found that mechanical extract ventilation leads to higher humidity in crawl space due to under-pressure in the crawl space that causes flows through ground soil, gravel etc. To what extent the phenomenon was caused by ground flows and to what extent by direct leakage from the adjacent sections of crawl space did not become completely clear because only pressure difference and air tightness measurements were carried out, and tracer gas measurements for this purpose were not. Still, the effect of higher humidity was noticed also during the period with one supply and two extract fans when the under-pressure was only about 0.5 Pa. Only when the under-pressure in mechanically ventilated crawl space was removed by balanced ventilation, the mechanically ventilated crawl space was drier for the first time. This change was permanent and remained valid with the supply ventilation also. Thus, it seems that the rather commonly used mechanical extract ventilation cannot be recommended as it can brought about higher relative humidity compared to natural ventilation. A better solution would be a supply ventilation that can be arranged exactly in the same way as extract ventilation, except that the fan direction would be the opposite and air should be distributed on the upper surface of the crawl space to avoid high air velocities on the ground. If several fans are used, also a balanced ventilation can be easily arranged.

The role of ventilation can be analysed by observing the humidity and ground moisture evaporation. The difference in humidity between outdoor and crawl space air was remarkably small during supply ventilation and almost nonexisting during the period with plastic sheet cover. Here the humidity difference approaching to zero shows that the ventilation operates as effectively as possible because no more humidity can be removed by ventilation. It should be noted that from the aspect of resulting relative humidity, the warming or cooling effect of ventilation is also important. Results show that higher air change leads to higher moisture evaporation. However, the relation is not linear because higher air change leads to slightly lower relative humidity. A positive correlation between air change and moisture evaporation, and a negative correlation between air change and relative humidity were found. Such correlation cannot be very clear as it describes a moisture transfer process that is strongly temperature dependent. Still, these correlations can be interpreted as the final result of moisture and heat transfer and air change process within real boundary conditions, i.e., climatic data and the test building. Both of the aforementioned correlations were clear within an air change range from 0.5 to 1 ach. There is no remarkable correlation when the air change is over 1 ach. One can draw the conclusion that 1 ach is a lower limit of optimum ventilation. The upper limit depends on thermal behaviour; crawl space cannot be cooled down during the heating season and there is probably no upper limit in the warm season. Computer simulations that were also carried out, but not discussed in this paper, showed similar results — the optimum ventilation was 1–3 ach for the all-year-round simulation period. In the summer there was no upper limit for air change, the highest tested value was 20 ach. It can be concluded that in principle the role of ventilation is strongly connected to ground moisture evaporation. If there is no moisture source there is also no need for ventilation. In typical crawl space with moist ground surface the certain air change is needed for removing moisture.

In the test building, the average level of ground moisture evaporation was from 3 to 6 g $h^{-1}$ $m^{-2}$. This was close to clay mixed with gravel or moraine and sand in laboratory tests, made by Kettunen [15], with 0.03–0.1 m/s air velocity on the surface of sample. Laboratory tests showed that evaporation can vary strongly depending on the type of soil or other material. Clean clay was close to free water surface (20 g $h^{-1}$ $m^{-2}$), and for crushed stone with low capillary rise the evaporation was about 0.8 g $h^{-1}$ $m^{-2}$. The level of the evaporation can be compared to results given by Elmroth in Ref. [8] and Nieminen and Rantamäki [9]. Elmroth gives convective heat transfer coefficient 7 W $m^{-2}$ $K^{-1}$, but also reduction factor 0.1 that means for the resulting coefficient 0.7 W $m^{-2}$ $K^{-1}$. The moisture evaporation rate can be transformed into a mass transfer coefficient that is in naturally ventilated crawl space about 0.0012 m/s and in mechanically ventilated crawl space twice higher, 0.0018 m/s. These values correspond to the convective heat transfer coefficient 1.5 W $m^{-2}$ $K^{-1}$ and 2.2 W $m^{-2}$ $K^{-1}$. Thus, the results are higher when compared to the value recommended by Elmroth [8]. At the same time, the mass transfer coefficient given by Nieminen and Rantamäki [9], 0.0014 m/s, is very close to the value measured in crawl spaces.

High relative humidity values during the summertime are quite often reported in previous researches as in Ref. [1]. In the present research only brief, a few days condensation peaks were detected. Relative humidity level during the summer with natural ventilation and uncovered ground was less than 85%, and with ground cover or with balanced ventilation it did not exceed 80%. This is the result of relatively high temperature in crawl space. During the summer, the temperature in the crawl space was usually only a few degrees lower than outdoors. Temperature differences of over 5°C were quite unusual. A possible explanation can be the building type — the ground temperature under blocks of flats is higher than under detached houses. It is also possible that solar radiation plays a notable role. Massive foundation construction can store energy and heat up the crawl space. Direct conduction from the outside ground surface to the crawl space was also suspected as a factor causing temperature rise in crawl space, but this is not connected to building type. At least the differences in thermal behaviour caused by building type and other circumstances are worth of further study.

## 5. Conclusions

(1) In crawl space design it is worth taking into account that a proportion of flats' intake air may be sucked from the crawl space if there is normal mechanical exhaust ventilation in the building. In the naturally ventilated crawl space of the test building, the air change caused by wind was insignificant and almost the entire air change was caused by leakage through the base floor.

(2) The humidity in crawl space can be decreased by ventilation most efficiently by using supply or balanced ventilation. In this way, air flows through permeable soil and gravel to the crawl space can be avoided. In the test building, mechanical extract ventilation caused continuously higher relative humidity than natural ventilation. When extract ventilation was changed to balanced ventilation, the relative humidity in mechanically ventilated crawl space was decreased by about 10% and it was lower than in naturally ventilated crawl space.

(3) The optimum air change rate in crawl space is 1...3 ach for all the year round. In the warm season there is no upper limit to optimum air change, but in winter too high air change cools crawl space down and it is reasonable to apply a lower air change rate, such as 1 ach. If the moisture evaporation can be prevented completely, there is in principle no need for ventilation.

(4) Uncovered ground surface is not recommended in crawl space. In the case of a moist ground surface the higher air change rate leads to higher moisture evaporation and humidity can be reduced only within small limits. Ground moisture evaporation can be reduced by using gravel, crushed stone, granulated clay, plastic sheet, expanded polystyrene or other ground cover.

(5) A plastic sheet cover on the ground reduces relative humidity in crawl space. In the test building the ground moisture evaporation was reduced by 70% and the relative humidity by about 10%. However, the plastic sheet should be made penetrable by water because any water flowing into crawl space should have an exit route.

(6) The relative humidity level in the crawl spaces of blocks of flats does not exceed 80% in the summertime when supply or balanced ventilation 1–3 ach is used and ground moisture evaporation is reduced by suitable ground cover, and in the heating season the relative humidity will remain at a 70% level.

## Acknowledgements

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