Results in Engineering 7 (2020) 100158

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.editorialmanager.com/rineng/Default.aspx

Experimental investigation of a crawl space located in a sub-arctic climate

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ARTICLE INFO

Keywords:
Crawl space
Mass transfer
Moisture
Mould

ABSTRACT

A common type of foundation for family houses in Northern countries is crawl spaces, where mould and moisture are a common problem for a large share of these. In this study, measurement in a crawl space located in a subarctic climate has been performed for over a year. Calculation and prediction of the climate inside the crawl space are performed both for the experimental case with a dehumidifier and a theoretical case without a dehumidifier. The results show that it is not necessary to measure at several points in the crawl space since the difference between the measurement points is small. The relative humidity is below the critical in the investigated crawl space during the whole year when a dehumidifier is used and therefore is no risk for mould growth. Prediction for a naturally ventilated crawl space with ACR of 1.5 shows that mould index will reach almost four and very close not to reach zero between different years, which indicates that mould index could start to increase between the years and cause problems.

1. Introduction

A common type of foundation for family houses in Northern countries is crawl spaces, where mould and moisture are a common problem for a large share of these. In Sweden, it's estimated that over 130 thousand family houses that have crawl space foundation have issues with mould, the smell from mould or high moisture content in the construction [1].

Actions against these damages often give high costs, and it is of most concern to establish the causes to prevent the problems in the future. Proposals using natural measures, for instance, it is recommended to always covering the soil in the crawl space with plastic sheeting to stop moisture from the soil. Ground covers like plastic sheets have shown to reduce moisture transfer from the ground very effectively [2]. A further recommendation is to ventilate the space through several perforations and thereby increase the air change rate. It has been shown that to low and to high air change rate in the crawl will increase the relative humidity [3]. Although these recommendations have been in practice for an extended period, the problem remains.

The temperature in the crawl space is lower than the outdoor temperature during the summer, warm air has a higher humidity ratio, and thereby when cooling down under the house, the relative humidity increases and mould can start to grow during the right conditions. To be able to create solutions to mould and moisture problems, it's essential to be able to measure the conditions inside the crawl space correctly.

Measurements of the climate in the crawl space have been carried out but only in a few buildings on some locations and only in some limited points inside the crawl space. In Finland, measurement in both naturally and mechanical ventilated crawl space has been performed by Kurnitski [4]. The measurement was performed at three different heights in the middle point of the crawl space. Also, investigation of the effect of different thermal insulation on the ground in the foundation for the mould growth index has been performed on the same crawl space [5]. The main result was that the safest way to control the moisture conditions is to insulate ground in the crawl space and have a low air exchange in the foundation.

Furthermore, experimental studies and modeling have been performed by Kesikuru et al. [6] where they investigated a crawl space located at Tampere, a town in the south of Finland. The crawl space was using a pressurization system with exhaust air from inside the house to prevent the flow of radon to the house. In the study, the temperature was measured only at one point in the crawl space.

In this study, measurement in a crawl space located in a subarctic climate has been performed for several years. The difference from previous studies is that measurement is done at eight different locations evenly distributed in the crawl space together with a mechanical dehumidifier which is used part of the year. Earlier, measurement data from this crawl space have been used to validate a numerical model that predicts the heat losses from different types of foundations and the impact of snow and soil freezing [7,8]. These previous studies only used the average values of the measurement and focus on heat losses. Heat

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https://doi.org/10.1016/j.rineng.2020.100158
Received 15 June 2020; Received in revised form 28 July 2020; Accepted 29 July 2020

Table 1
Classification of mould index [10].

Mould growth index	Discription
0	no growth
1	some growth detected only with microscopy
2	moderate growth detected with microscopy (coverage of more than 10%)
3	some growth detected visually
4	visually detected coverage of more than 10%
5	visually detected coverage of more than 50%
6	visually detected coverage 100%

losses are of importance to study [9], but previous work didn't investigate each measurement point in detail and had no focus on moisture and mould growth. Also the current work predicts the conditions inside the crawl space if it instead was naturally ventilated by using a modified numerical model based on earlier work of Risberg et al. [7,8].

2. Theory

The air in the crawl space consists of moisture and a mixture of other gas components. All the other gas components except water have low boiling points and, therefore, can be seen as inserts. Water will start to condense if the partial pressure of water vapor is above saturation pressure for the specific temperature. Therefore, the amount of moisture in the air will variate. The following are the main equations used for calculation of moist air:

$$x = \frac{m_v}{m_a} \tag{1}$$

where x is the absolute humidity, m_v is the mass of water vapor and m_a is the mass of dry air.

$$\varphi = \frac{P_v}{P_s} \tag{2}$$

where φ is the relative humidity, P_v is the partial pressure of water vapor and P_s is the saturation pressure of water vapor at current temperature. Using the ideal gas, Eq. (1) can be expressed as

$$x = 0.622\frac{P_v}{P_{tot} - P_v} \tag{3}$$

where P_{tot} is the total pressure of air and water vapor.

Mould growth index M was developed to be able to predict the growth rate for mould on different surfaces by Hukka and Viitanen [10] where the classification can be seen in Table 1 and the model equation is described below. To calculate the change of mould growth index the following equation was used when the index is below one:

$$\frac{dM}{dt} = \frac{1}{7*\exp(-0.68\ln(T) - 13.9\ln(RH) + 0.14W - 0.33SQ + 66.02)}, \quad M < 1 \tag{4}$$

where the SQ surface quality is equal to 1 (original kiln-dried wood) and W wood species is equal to 1 (spruce). If the Mould index is larger then 1 the following equation is used:

$$\frac{dM}{dt} = \frac{1}{7*\exp(-0.68\ln(T) - 13.9\ln(RH) + 0.14W - 0.33SQ + 66.02)}*k_1*k_2, \ M > 1 \tag{5}$$

The correction coefficient k_1 and k_2 is calculated as:

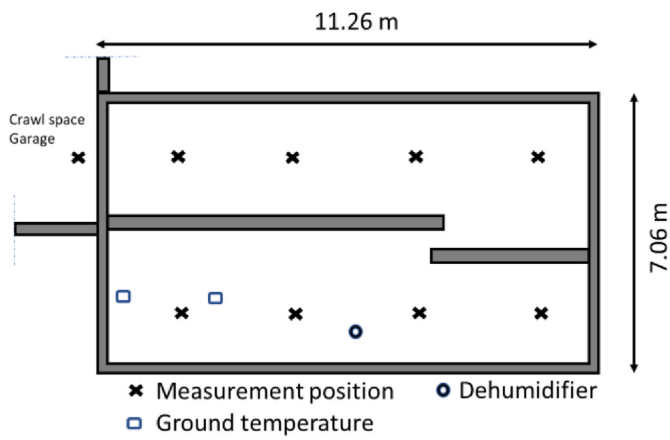

Fig. 1. Schematics of the crawl space (left).

$$k_1 = \frac{2}{\frac{t_v}{t_m} - 1} \tag{6}$$

$$k_2 = 1 - \exp[2.3(M - M_{max})] \tag{7}$$

where t_m and t_v is calculated as:

$$t_m = \exp(-0.68\ln(T) - 13.9\ln(RH) + 0.14W - 0.33SQ + 66.02) \tag{8}$$

$$t_v = \exp(-0.74\ln(T) - 12.72\ln(RH) + 0.06W + 61.50) \tag{9}$$

The largest possible mould growth is calculated as:

$$M_{max} = 1 + 7\frac{RH_{crit} - RH}{RH_{crit} - 100} - 2\left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2 \tag{10}$$

The critical relative humidity where it is favourable conditions for mould growth is calculated as:

$$RH_{crit} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100.0 & if \ \ T \le 20 \\ 80\% & if \ \ T > 20 \end{cases} \tag{11}$$

For non-favourable conditions for mould grow during dry periods the mould index decrease as:

$$\frac{dM}{dt} = \begin{cases} -0.032 \ \ if \ \ t - t_1 \le 6h \\ 0 \ \ if \ \ 6h \le t - t_1 \le 24h - 0.016 \ \ if \ \ t - t_1 > 24h \end{cases} \tag{12}$$

3. Method

3.1. Crawl space

The crawl space has the size (L*W) 11.26 × 7.06 m and a height of 0.80 m. The positions of temperature and relative humidity sensors are presented in Fig. 1. The crawl space investigated is the foundation for a single-family house located in Luleå, in the north of Sweden. In the middle of the crawl space, it's a beam that goes from the floor above to around 20 cm from the ground. Air is entering the crawl space through a leakage in the connection to the crawl space foundation of a garage next to the house (called supply air), therefore the air is preheated compared to outdoor conditions and had to be measured. The air in crawl space is transported up to the house since it uses an exhaust fan to ventilate the building. The crawl space has no additional openings to the surrounding and the ground in the crawl space is covered with plastic sheets.

The sampling time for the sensors was set to 15 min. The sensors are from Oregon Scientific and have an accuracy of 0.1 °C for temperature and 1% for relative humidity. The studied measurement period is between 2016 and 01-01 and 2016-12-31. During this time, a dehumidifier was running during 2016–05-15 to 2016-12-01. The dehumidifier used is

Fig. 2. Images from the studied crawl space.

placed according to Fig. 1. For the analysis, the measurement values were recalculated to hourly average values. In total 8 different measurement points were installed 0.14 m from the top in the crawl space and one located under garage part (supply air) together with a measurement of outdoor conditions together with two measurements of the ground temperature inside the crawl space. In Fig. 2 images of the studies crawl space are presented.

3.2. Prediction calculation

To calculate the moisture transfer from the ground the heat and mass transfer analogy was used according to:

$$\overline{h_m} = \frac{\overline{h}}{\rho c_p Le^{0.7}} \tag{13}$$

where $\overline{h_m}$ is the average convection mass transfer coefficient, $\overline{h}$ heat transfer coefficient, ρ the air density, c_p specific heat capacity of moist air and Le is the Lewis number. The Lewis number are calculated as thermal diffusivity divided by the mass diffusivity.

The heat transfer coefficient was calculated as:

$$\overline{h_m} = \frac{\overline{Nu_L} k}{L} \tag{14}$$

where $\overline{Nu_L}$ was calculated according to the following correlation if the ground surface temperature is above the air temperature in the crawl space:

$$\overline{Nu_L} = 0.54(GrPr)^{1/4} \ \ for \ \ 10^4 < GrPr < 10^7 \tag{15}$$

$$\overline{Nu_L} = 0.54(GrPr)^{1/4} \ \ for \ \ 10^7 < GrPr < 10^{11} \tag{16}$$

If the ground surface is below the air temperature in the crawl space the following expression was used:

$$\overline{Nu_L} = 0.52(GrPr)^{1/4} \tag{17}$$

Grashof Prantl number is calculated as:

$$GrPr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2} * Pr \tag{18}$$

where g is the gravitational acceleration, β it the thermal expansion coefficient, T_s is the ground surface temperature, L is the characteristic length, ν is the kinematic viscosity and Pr it the Prantln number.

The characterstic length are calculated as:

$$L = \frac{A}{P} = \frac{A}{4*L} \tag{19}$$

The moisture transfer is then calculated as:

$$\dot{m}_{H2O} = \overline{h_m} A * (x_s - x_\infty) * \rho_{air} \tag{20}$$

where $\dot{m}_{H2O}$ is the moisture mass rate, A is surface area, x_s and x_∞ is the absolute humidity at the ground surface and in the crawl space, respectively and ρ_{air} is the air density inside the crawl space. The absolute humidity at the ground was assumed to be saturated. The change in the absolute humidity in the crawl space is calculated as:

$$x(t) = x(t-1) + \frac{3600 * \dot{V}_{air} * \rho_{supplyair} * \left(x_{supply}(t) - x(t-1)\right) + 3600 * \dot{m}_{H2O}}{V * \rho_{air}} \tag{21}$$

where ρ is the density, x is the absolute humidity, t is the time step in hours, V is the volume of the crawl space and $\dot{V}_{air}$ is the volume flow of supply air. The volume flow of supply air $\dot{V}_{air}$ was calculated from a mass balance over the crawl space for the period without dehumidifier as:

$$\dot{V}_{air} = \frac{\overline{\dot{m}_{H2O}}}{\rho_{air}\left(\overline{x} - \overline{x_{supply}}\right)} \tag{22}$$

where all the values are average values for the period when the dehumidifier is not running (3378 h). In these calculations, the area is unknown therefore the area needs to be calculated. This was performed by variate the area between 0 and 1 m^2 and calculate the summation of the difference between calculated values and measurement data for the period when the dehumidifier was not running. The value for the area with the smallest error is then used to calculate the mass rate of moisture for the whole year. The calculated airflow to the crawl space was also set constant since the flow rate only depends on pressure differences between indoor and outdoor conditions, which are constant and depend on the exhaust fan running with constant speed. All the calculation above was performed with a combination of Igor Pro and Matlab. The schematic of the calculation procedure is presented in Fig. 3.

3.3. Prediction calculation naturally ventilated crawl space

To calculate the conditions inside a naturally ventilated crawl space a modified version of a previously developed numerical by Risberg et al. [7,8] was used. It was modified by adding an inlet and outlet to the model and then the model was run for the year 2016 with inlet conditions set according to measurement values for the outdoor temperature and relative humidity. The output for the model was the temperature inside the crawl space, which then were used together with the method described under 3.2. From this the mould index could be predicted. The ACR in this work was specified to 1.5 air exchange per hour according to previous research [4] on naturally ventilated crawl spaces.

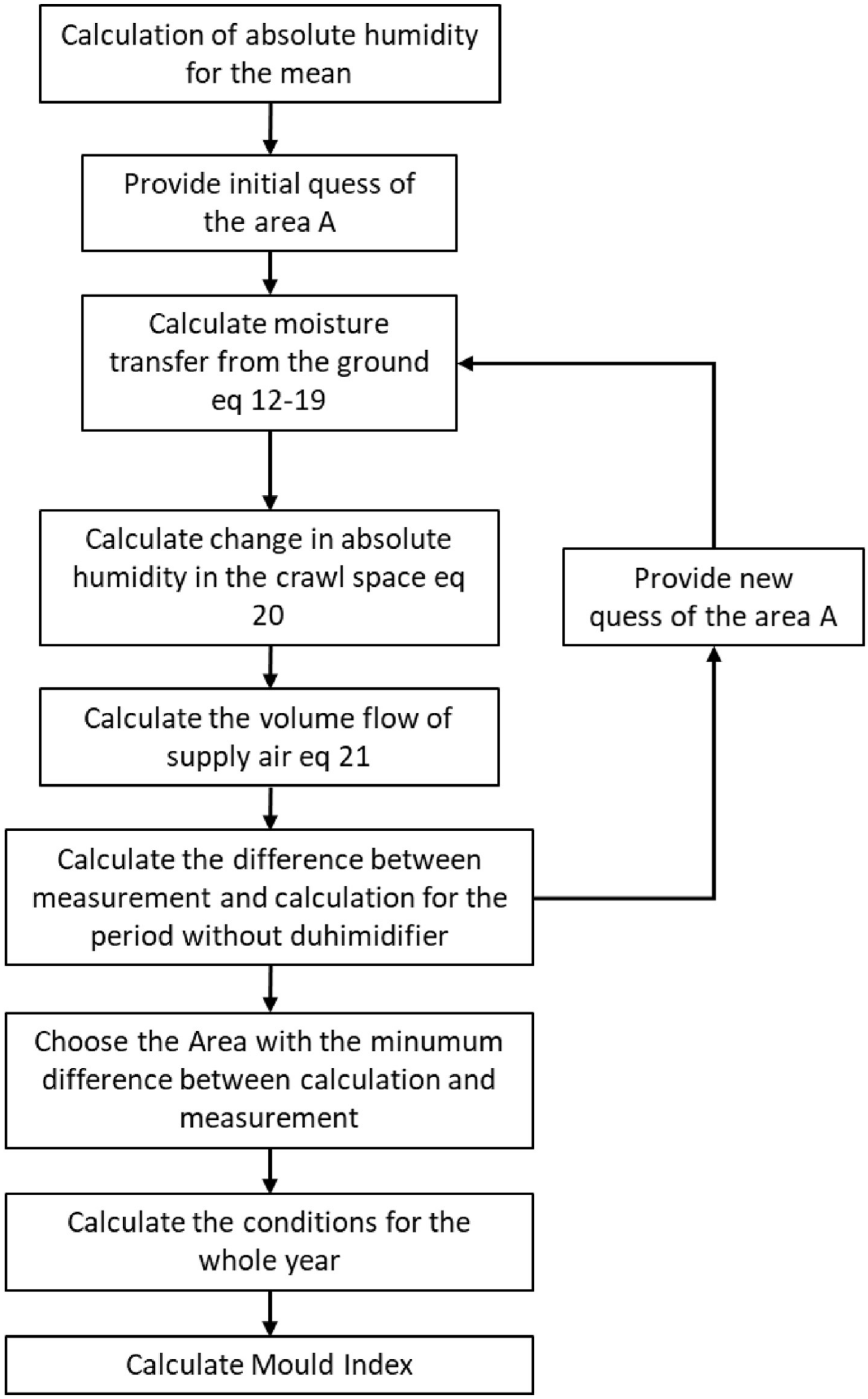

Fig. 3. Schematic of the calculation procedure for the prediction without dehumidifier.

4. Results and discussion

In Fig. 4, variations in absolute humidity for a period without dehumidifier are presented. It can be seen that the differences between different measurement points are under 5%. In the figure also an estimate of the measurement error calculated based on average values, all the measurement points in the crawl space are presented. It can be seen that almost all values are inside the range of the estimated measurement error calculated based on average values. This indicates that it is not necessary to measure temperature and humidity at several points in the crawl space when the dehumidifier is not running. For the measurement, the standard variations are 0.27 °C for temperature and 2.07 %RH for the relative Humidity.

Fig. 5 presents the variations in absolute humidity for a period when the dehumidifier is running. It can be seen that variations in absolute humidity are larger compares to the case without a dehumidifier. The measurement point with the lowest absolute humidity is the point closest to the dehumidifier, and the point with the highest values is closest to the supply air leakage. The rest of the measurement points values are inside the estimated measurement error range for the average value in the crawl

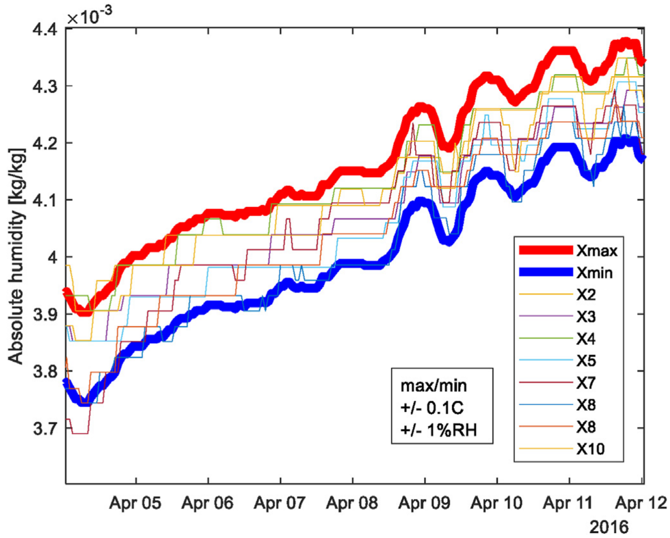

Fig. 4. Variations in absolute humidity for a period without dehumidifier.

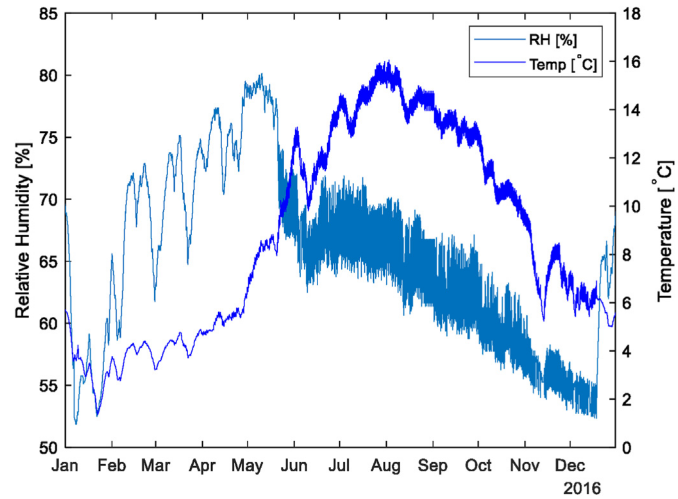

Fig. 7. Relative humidity and temperature inside the crawl space during 2016.

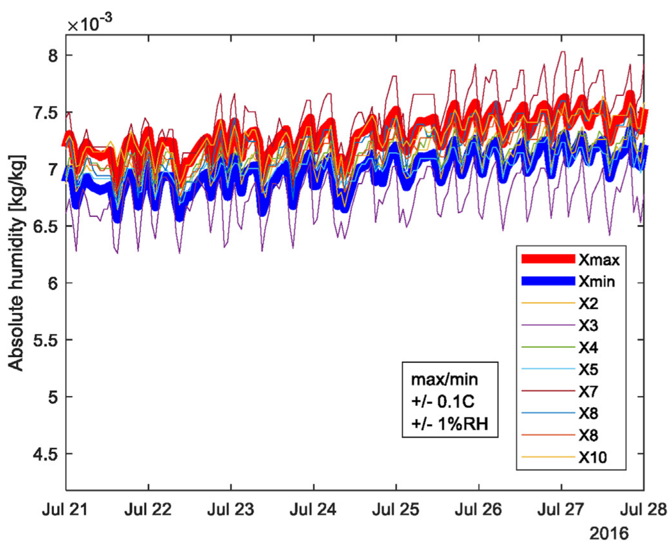

Fig. 5. Variations in absolute humidity for a period with a dehumidifier.

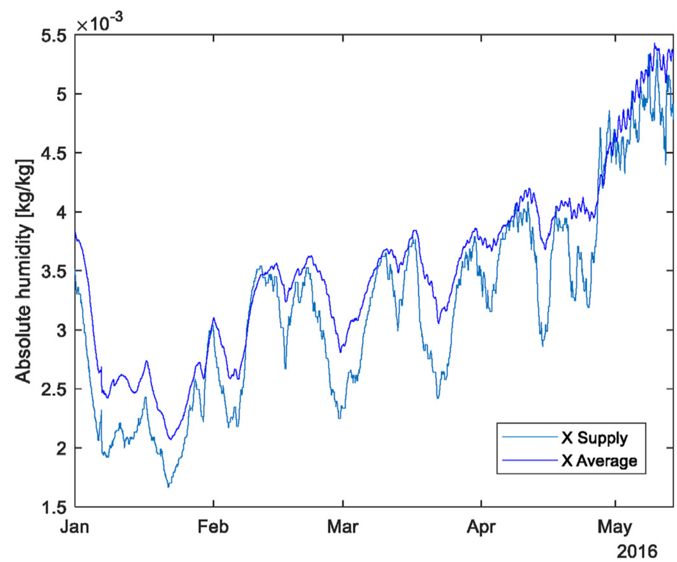

Fig. 8. Supply and average absolute humidity in crawl space.

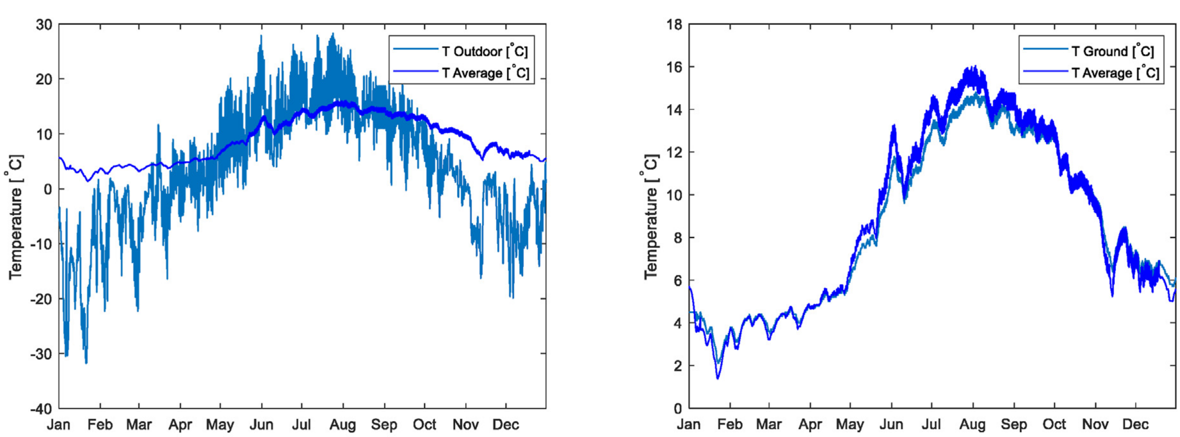

Fig. 6. Average temperature in the crawl space (left, right), outdoor temperature (left) and ground temperature (right).

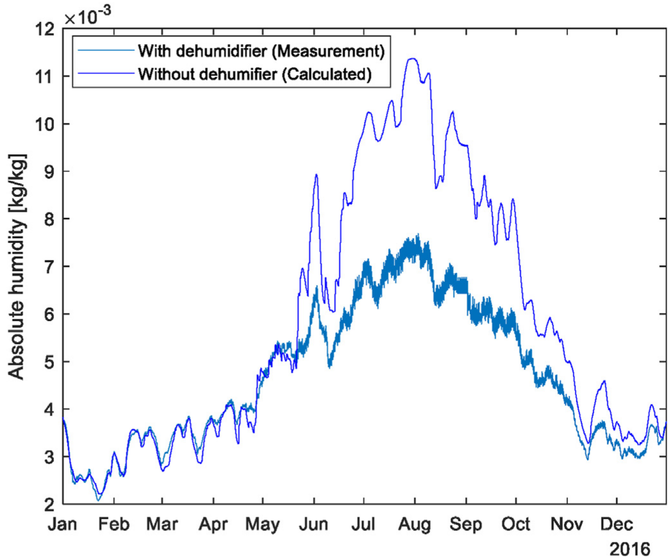

Fig. 9. Measurement (with dehumidifier) and prediction (without dehumidifier) of variations in absolute humidity over the year.

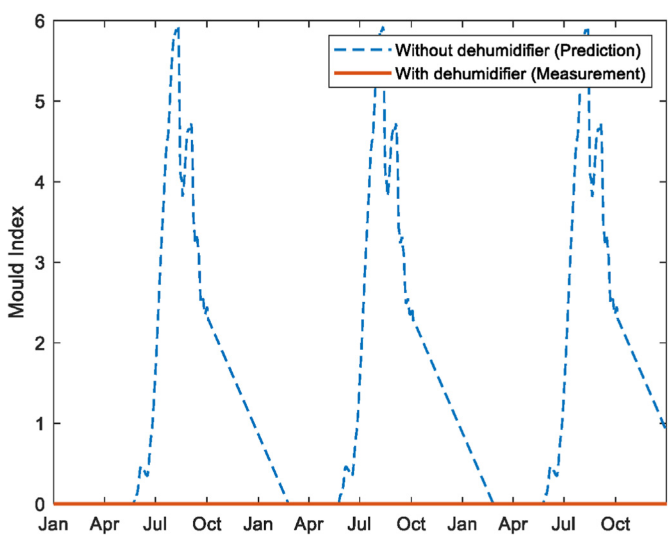

Fig. 10. Mould index calculation for both with and without dehumidifier.

space.

The outdoor temperature varies between −32.0 °C and +28.3 °C while the temperature in the crawlspace only change between +1.5 °C and 16.1 °C presented in Fig. 6. Variations in relative humidity are presented in Fig. 7. It can be seen that the absolute humidity is highest during the summer. The relative humidity is highest before the dehumidifier are started in the middle of May. The maximum relative humidity is below 80%RH, which is below the critical relative humidity of mould growth, and therefore the mould has no possibility to start to grow when a dehumidifier is used. If the dehumidifier is not used it is expected that relative humidity will reach above the critical relative humidity and mould could start to grow.

In Fig. 8 it can be seen that supply air has lower absolute moisture content compared to the average in the crawl space. This is resulting in that the moisture needs to come from another source. Since the ground is not completely moist safe, the main source of additional moisture will therefore be from the ground. Also, the water content in the crawl space follows the changes in supply air, which indicate that air is coming into the crawl space.

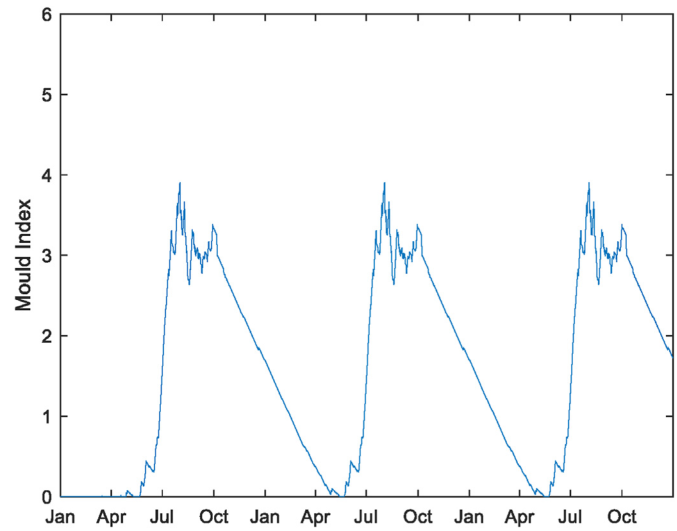

Fig. 11. Mould index for a naturally ventilated crawl space with ACR of 1.5.

By vary the area and calculate the minimum error for the absolute humidity for the period without dehumidifier the evaporation rate for the whole year was calculated and is presented in Fig. 9. The area found was 0.05 m^2 which gave a constant supply air mass flow rate of 0.52 l/s. In total 6.37 kg of water was evaporating from the ground inside the crawl for one year. Fig. 6 also presents measurements compared to the prediction without dehumidifier of the absolute humidity in the crawl space. The prediction calculation agrees with measurement for the period without a dehumidifier. The calculated values are little under measurement values, especially for periods when the absolute humidity is decreasing. One reason for this is that the calculation doesn't include the moisture uptake and release in the subfloor of the house. After the dehumidifier is started, it can clearly be seen that the absolute humidity is significantly higher for the prediction without dehumidifier compared to the measurement with the dehumidifier. From a mass balance over the year, the amount of water that the dehumidifier takes away is 20.6 kg. The amount of water that is supplied with the inlet air is 109.7 kg and the amount transported away with the exhaust air is 95.5 kg.

In Fig. 10 calculation of mould index with and without dehumidifier are presented. For the case with dehumidifier the mould index is always almost zero since the relative humidity is below the critical relative humidity during the whole year. For the case, without dehumidifier the mould index is increasing to almost six at the beginning of August. So it clearly that mould will be starting to grow and according to mould index the visually detected coverage will be between 50 and 100%. The mould index decreases to zero in March each year and therefore it will not increase between the years.

Fig. 11 shows the results for the naturally ventilated crawl space. The mould index reach almost four at a maximum which indicates it will be visually detected coverage more than 10% of mould in the crawl space. It can also be seen that the Mould index reach zero before its starting to increase again in may. Since it's very close not to reach zero between different years, it could be a problem for some years only if it's a few weeks longer before the mould index decrease in October. This indicates that it could be a problem with mould if the current crawl space is naturally ventilated compared to the case with the dehumidifier that will have no problem with mould.

5. Conclusions

In this study, an experimental investigation of a crawl space located in the sub-arctic climate is performed for one year. The results show that it is not necessary to measure at several points in the crawl space since the difference between the measurement points is small. The relative humidity is below the critical in the investigated crawl space during the whole year when a dehumidifier is used and therefore is no risk for mould growth. If the humidifier is not used the mould index is increased to almost six and therefore mould will start to grow. For a naturally crawl space with ACR of 1.5 the mould index almost reaches four and it's very close not to reach zero between the years and the mould index could start to increase between the years. Therefore a closed crawl space with a dehumidifier is preferable at the current location.

CRediT authorship contribution statement

Mikael Risberg: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Lars Westerlund:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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