Mapping of moisture by U-value metering combined with ISO 10456 founded calculations

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Abstract:

Energy performance in buildings are needed more than they have ever been before. To achieve energy savings in buildings we have to gain a better understanding of the thermal properties in a building.

U-value meter is a device used to measure the heat passing through material, a good insulation will have a low lambda value as possible to reduce heat loss. U-value is mainly estimated by calculating the thermal properties of the layers inside a wall. The Building Research Establishment, an organization to investigate building materials and methods of construction for new housing has announced that U-value calculations are frequently incorrect and that there is further research required to reach a more accurate estimation.

The aim of this work is to is to analyze if there’s any correlation between moisture readings and U-values. The survey was conducted was by analyzing a terraced house in Matinkylä (Espoo) with moisture problems. Arcada rapid U-value meters were used to reach a more accurate U-value and moisture reading of the walls. The findings showed that the theoretical U-value didn’t match with the measured U-values. The moisture readings showed unsystematic correlation with U-values. The findings in this study suggest that moisture meters are not reliable tool for diagnosing moisture problems.. Instead moisture meter should be used to map a profile of moisture, meaning just to distinguish areas which are moist and dry. However, measuring U-value, with the Arcada U-value meters, to determine moisture problems represents an innovative alternative and non-destructive method to get a more accurate and reliable information. It can be foreseen that U-value metering will revolutionize mapping for moisture in the near future.

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Contents

1 INTRODUCTION

1.1 Background

Energy performance of buildings have become more and more essential. “It has been frequently confirmed by many researchers that in recent decades the thermal properties of building materials are significantly affected by the moisture content and not so much by temperature”. [1] Few researchers have addressed that detecting moisture and increased heat flow in building elements is a crucial problem. Traditional moisture mapping with moisture meters and thermal camera are unreliable and not giving any specific details about the insulation performance. Detection of heat fluxes throughout the building envelopes are important when analyzing extend and location of moisture in constructions for, e.g., quality control of both new and old buildings regarding heating/cooling demand, accurate information for Energy Performance Certificate (EPC) and information for improving thermal comfort. Measured Heat fluxes are a procedure not just describing heating but also highlights moisture in construction materials and lack insulation. [2]

1.2 Purpose of the research

The purpose of this study is to see if moisture measurement values correlate with U-values This survey was done using Arcada U-value meters . Measured U-values were converted to moisture contents according to ISO 10456. Due to the high precision of U-value meters and calculations founded on existing standard we take U-value meter-based values for moisture contents as the correct ones.

2 THEORY

It might be hot, and it might be cold but in science we want to quantify everything we can. Stating something is hot or cold isn’t enough, we want to be able say with numbers. Different types of energy can be converted into heat, for example light, electrical and thermal energy can cause a substance to heat up by increasing the speed of its molecule. To sum it up higher temperatures simply means faster moving particles. This kinetic energy of motion is distributed amongst translational or side-to-side, rotational, spinning and vibrational motions where the covalent bonds bend and stretch. Heat will flow from a hot object to cool objects because as the particles move, they will contribute some of their kinetic energy onto other particles through collisions. Until the whole system is that the same temperature, which is called thermal equilibrium. [3]

2.1 Heat transfer

Heat transfer is known as the exchange of internal energy that occurs due to temperature differences between two mediums. Heat transfer occurs through conduction, convection and radiation. Conduction is direct transfer of heat from one object to another. The amount of heat that passes through an object is based on the object's thermal transmittance. Substances that conduct heat well are called conductors for example metal. Substances that don't conduct heat well and gradually slows down the heat transfer, are called insulators. All insulators have low density (wood, wool, expanded polystyrene etc.). Convection occurs when heat is transferred by a flow of fluids or gases. Radiation takes place when heat is transferred by electromagnetic waves. [3]

The heat flow is represented with the letter $\dot{Q}$ and the SI-unit is J (Joule). "Heat transfer (or heat) is thermal energy in transit due to spatial temperature difference" [3]

Whenever there is a temperature differences between two mediums, heat will always transfer to a cooler area. In a case where two mediums have the same temperature they are in thermal equilibrium. The SI unit of heat flow rate is joules per second [J/s] or more commonly Watts [W].

$$Q = \int_{t_2}^{t_1} \dot{Q}\, dt \tag{1}$$

Eq. 1defines the energy that transfers through a wall with the three previously mentioned forms of heat transfer. Thermal energy starts with passing through the wall with conduction Q_1. Afterwards when it passes through the wall as convection Q_2 and radiationQ_3. [3]

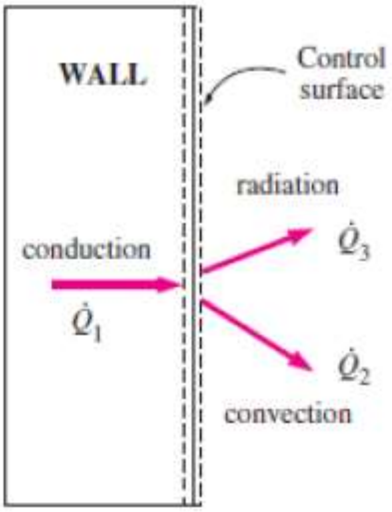


Figure 1. Balance of heat rate [3]

2.1.1 Conduction

Conduction is the transfer of heat that goes between two objects that are in direct contact with each other. However, there should be a free electron translation or lattice vibration for a condition to occur. Fourier's law of heat conduction states, that "The rate of heat transfer is directly proportional to the area normal to the direction of heat flow and temperature gradient. [3]

$$Q_{cond} = k \cdot A \cdot \frac{T_1 - T_2}{L} \tag{2}$$

A=Wall area [m^2]
k=Thermal conductivity [W/m^2°C]
T_1=Temperature of the inner surface of the wall [°C]
T_2=Temperature of the outer surface of the wall [°C]
L=Wall thickness [m]

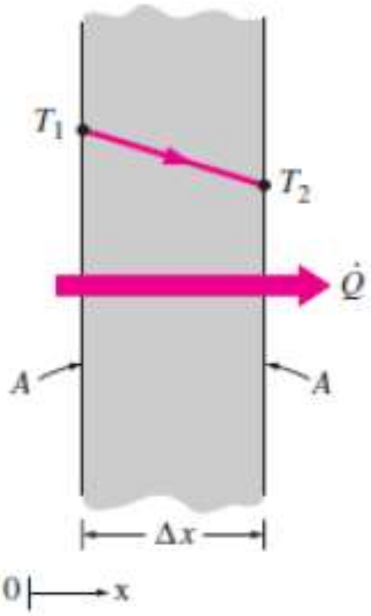


Figure 2. Conduction through a wall [3]

2.1.2 Convection

Convection is heat transfer between two media which requires at least one medium to be in motion. Fig 3 presents a hot block in which the block gives off heat to the air. Newton's cooling law describes convection. [3]

$$Q_{conv} = h \cdot A \cdot (T_s - T_\infty) \tag{3}$$

A= Surface area [m^2]
h= Heat transfer coefficient [W/m^2°C]
T_s= Surface temperature [°C]
T_∞=Ambient temperature [°C]

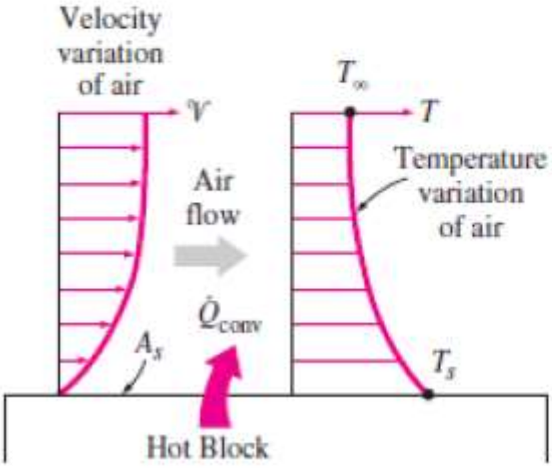


Figure 3. Convection from a warm surface

2.1.3 Heat radiation

Convection and conduction both require the presence of molecules to take place. Radiation is the only heat transfer that does not requires a medium (i.e. molecules) to transfer energy from a hotter area to a cooler area. Radiation consists of electromagnetic waves. The rate of radiation which heat leaves an object, this is explained with the help Stefan Boltzmann's law. Given by the following formula. [3]

$$Q = \varepsilon\sigma A(T_1^4 - T_2^4) \tag{4}$$

A= Surface area [m^2]
σ= Boltzmann constant ($5.67x10^{-8}$) [W/m]
T_1= Temperature of the first body [°C]
T_2= Temperature of the second body [°C]
ε= emissivity of the surface ($0 \leq \varepsilon \leq 1$)

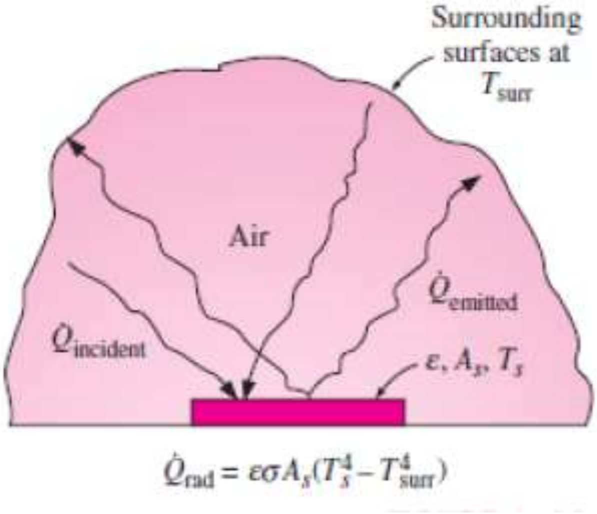


Figure 4. Heat radiation from an object

2.2 U-Value

Thermal transmittance, also known as U-value, is used to describe how effective elements of a construction’s layers are as insulators. The lower U-value of an element, the slower heat can transmit through it. This is beneficial because the less energy is required to maintain comfortable conditions. The unit for U-value is $W/m^{2*}K$, is the sum of the thermal resistance of the layers that make up the element plus the thermal resistance of the outside and inside surfaces. [4]

2.3 Moisture and thermal conductivity

Moisture is the key factor that affects building’s thermal conductivity. ISO 10456 (International Organization for Standardization) [5] gives outlines for the correlation between thermal transmittance and moisture content for various construction materials.
This information is most useful for the building sector as materials that are affected by moisture have reduced insulation performance and subsequently will lead to excessive heat loss or unbearable indoor conditions.
Thermal conductivity is affected by the moisture e.g., in a wall, which signifies that the heat flow passes at a much faster pace compared to a dry wall. Fig 5. shows

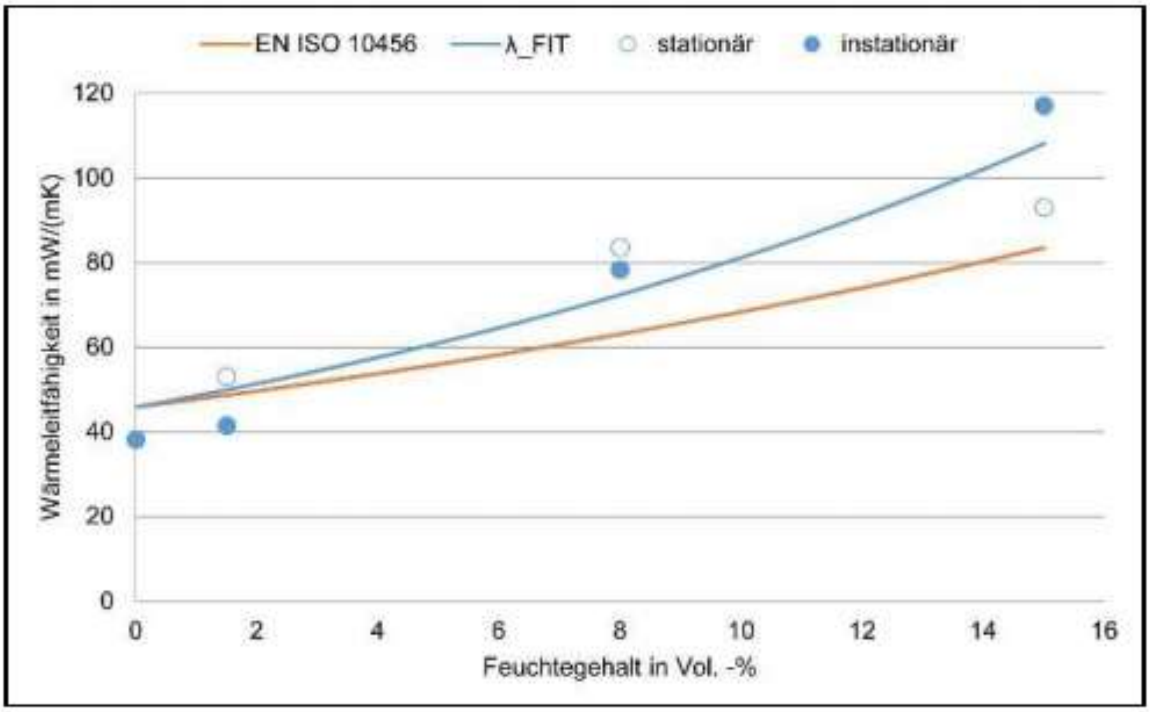


Figure 5. "Thermal conductivity as a function of the moisture content for thermal insulation material insulation material made from mineral wool" [6].

that thermal conductivity as a function of the moisture content for thermal insulation material made from mineral (x-axes moisture content by volume and y-axes is the thermal conductivity). Also indicates that the increase of moisture content leads to a higher thermal conductivity value. Both calculated and measured thermal conductivity are affected by moisture. [6]

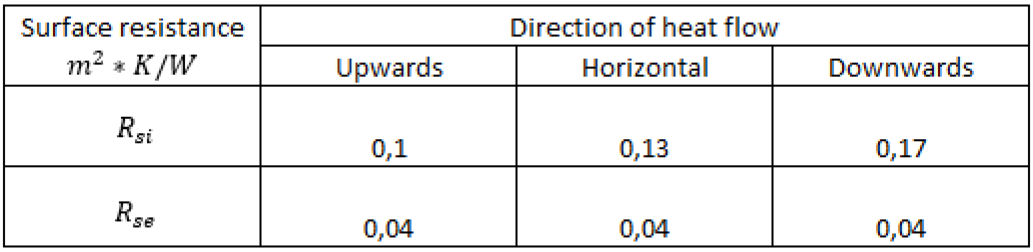
2.4 Calculating U-value

U-value is a good way to standardize evaluation of building components. The definition for U-value is presented in Equation 5.

$$U = \frac{1}{R_T} \tag{5}$$

U=is thermal transmittance and has the unit of [W/ (m^{2}K)]

Table 1. Conventional surface



Surface resistance $m^2 * K/W$	Direction of heat flow		
	Upwards	Horizontal	Downwards
R_{si}	0,1	0,13	0,17
R_{se}	0,04	0,04	0,04

U-value determines amount of heat (watts) that goes through the building material of a certain surface area and with a certain temperature difference from the inside building material to the outside building material. Total thermal resistance R_T is obtained by summing the existing thermal resistances. The values of the surface resistance are obtained through ISO 6946 as seen in Table 1. (R_{si} and R_{se}). [7]

The following equation can be used to calculate the total resistance:

$$R_T = R_{si} + \sum R_i + R_{se} \tag{6}$$

R_T= Total resistance
R_{si}= Internal resistance
R_{se}= External resistance
$\sum R_i$= Thermal resistance layers

Surface resistance is a quantification of the added resistance from radiation and convection at building surfaces in contact with air. Surface resistance is abbreviated to R_{si} (internal resistance) and R_{se} (external resistance).

To be able to determine thermal resistance layers we will be using this formula

$$R = R_1 + R_2 + \cdots R_n \tag{7}$$

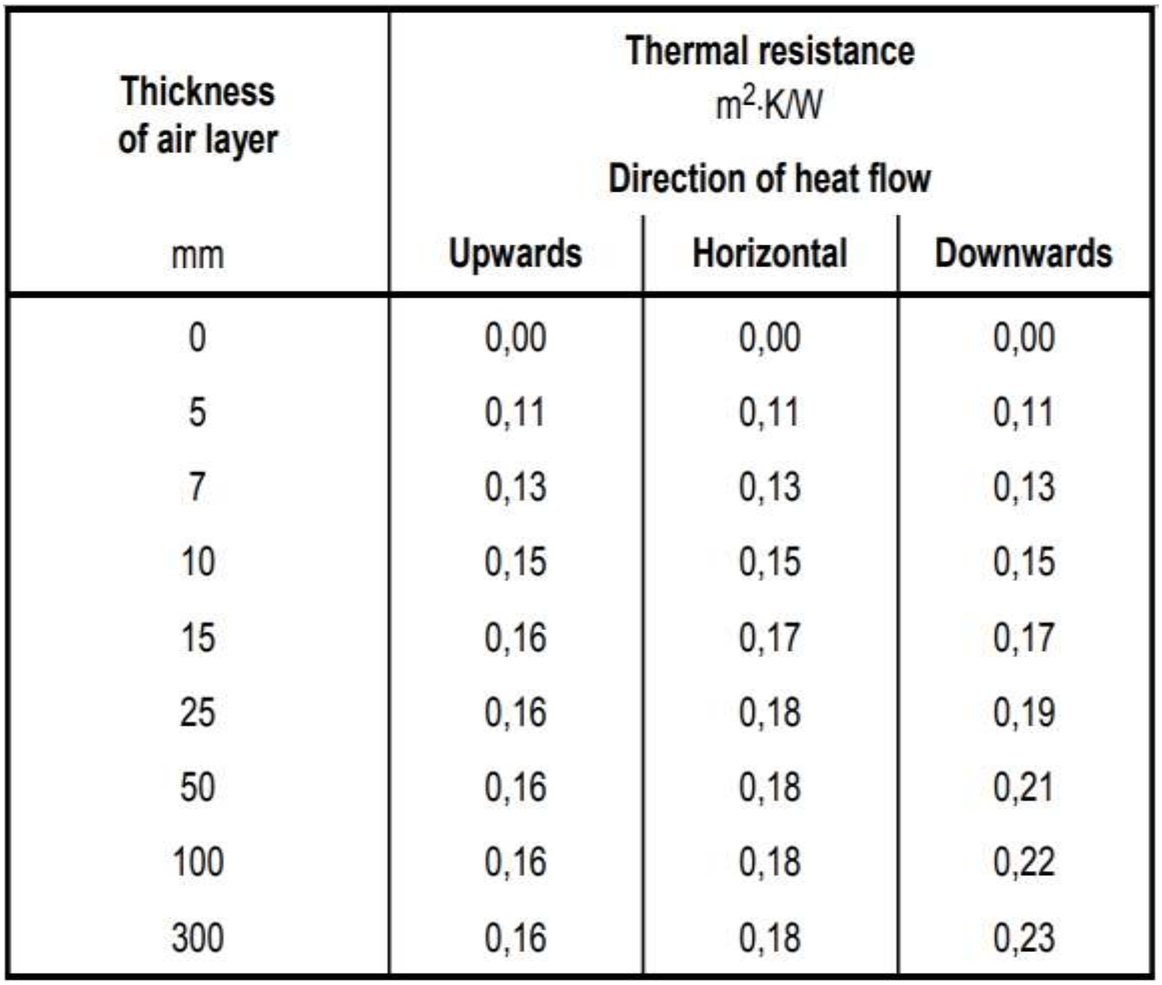
R = Thermal resistance

Thermal resistance for a homogenous wall can be derived as followed [3]:

$$R = \frac{d}{\lambda} \tag{8}$$

d = Thickness of the material [m]
λ = Designed thermal conductivity. [W/mk]

Table 2. unventilated air gap thermal resistance (ISO 6946)



Thickness of air layer	Thermal resistance m²·K/W Direction of heat flow		
mm	Upwards	Horizontal	Downwards
0	0,00	0,00	0,00
5	0,11	0,11	0,11
7	0,13	0,13	0,13
10	0,15	0,15	0,15
15	0,16	0,17	0,17
25	0,16	0,18	0,19
50	0,16	0,18	0,21
100	0,16	0,18	0,22
300	0,16	0,18	0,23

The thermal conductivity values can be found in ISO standard 10456, which describes the thermal properties of materials. For instance, an air gap in a wall also creates a resistance and is listed in ISO 6946. Details on the influence of air layer thickness is given in Table 2. [7]. The overall heat flow is proportional to thermal conductivity, wall area, and temperature difference, but inversely proportional to wall thickness.” [8]

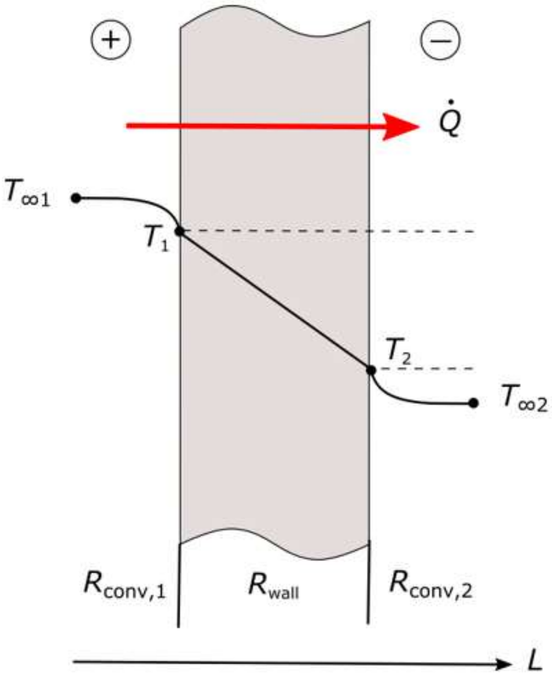


Figure 6. Temperature drops across the wall

Convection and radiation occur the same time depending on the boundary condition. The sum of heat at the surface is obtained by adding (or subtracting) the radiation and convection components.

Applying an energy balance over an element (where disregarding radiation heat transfer) is express as following;

$$\dot{Q} = \dot{Q}_{into\ wall} = \dot{Q}_{through\ wall} = \dot{Q}_{from\ wall} \tag{9}$$

The general function for Q is shown as following

$$\dot{Q} = \frac{1}{R}\Delta TA = \frac{\Delta TA}{R} \tag{10}$$

Applying an energy balance over the wall in the Fig. 6, disregarding radiation, gives following

$$\begin{pmatrix} Rate\ of heat\ convection \\ into\ wall \end{pmatrix} = \begin{pmatrix} Rate\ of\ heat\ conduction \\ through\ the\ wall \end{pmatrix} = \begin{pmatrix} Rate\ of\ heat\ convection \\ from\ the\ wall \end{pmatrix}$$

Using heat transfer formula this can be expressed as

$$\dot{Q} = \frac{A(T_{\infty 1} - T_1)}{R_{conv,1}} = \frac{A(T_1 - T_2)}{R_{wall}} = \frac{A(T_2 - T_{\infty 2})}{R_{conv,2}} \tag{11}$$

This means that heat flow through a wall can be calculated by calculating only heat flow through parts. The room temperature, the interior wall temperature and the internal transfer are known. And the Q can be obtained with the help equation 10 which is written;

$$\dot{Q} = \frac{A\Delta T_{1-\infty 2}}{R_{wall} + R_{conv,2}} \tag{12}$$

Equation 11 uses a temperature differences between the inner and the outer temperature. Therefore, there is total thermal resistance for the wall in the denominator. The equation doesn't include the area but will be added later in the calculation.

The equation used to determine the heat flow using the U-value is shown below

$$\dot{Q} = UA\Delta T \tag{13}$$

$\dot{Q}$= The rate of heat transfer[W]
U= U-value [W/ m^2°C]
A= The specific area of the wall [W]
ΔT= Temperature difference [°C]

In the equation 4 U was equal to the inverse of the total thermal resistance. The Arcada U-value meters uses the inner wall surface temperature as a reference point during the measurement, which implies neglecting $R_{conv,1}$ and $T_{\infty 1}$in the derivation.
Equation 13 to 16 explains how derive the U-value with the Arcada U-value measurement device. In addition to obtain the result the outer temperature needs to be measured as well, as previously stated the Arcada U-value meter measures the wall surface temperature.

The thermal resistance can thus be derived with the help of equation 4

$$U = \frac{1}{R_{tot}} = \frac{1}{R_{conv,1} + R_{wall} + R_{conv,2}} \tag{14}$$

With the formula shown in the equation 11 we can determine R_{wall} as following

$$R_{wall} = \frac{A\Delta T_{1-\infty}}{\dot{Q}} - R_{conv,2} \tag{15}$$

The temperature difference is represented in figure 6 where $T_{\infty 1}$ is outside air temperature and $T_{\infty 2}$ inside air temperature in the building.

When combining equation 13 and 14, replacing the R_{wall} ,we get the following;

$$U = \frac{1}{R_{conv,1} + \left(\frac{A_{device}\Delta T_{1-\infty 2}}{\dot{Q}} - R_{conv,2}\right) + R_{conv,2}} \tag{16}$$

Before calculating the U-value the formula needs to be refined. As seen in the equation 14 $R_{conv,2}$take each other out. The area of the device which is measures an area of 100 cm^2 (0,01m^2) [8]. Lastly adding wind correction which is shown below

$$U = \frac{1}{R_{conv,1} + \left(\frac{A_{device}\Delta T_{1-\infty 2}}{\dot{Q}}\right) + R_{wind\ corr}} \tag{17}$$

Source reference for equation 8 to 15 are based on U-value meter manual version [8]. The equation used for Arcada's meters is explained in the next chapter 2.4.1

2.4.1 Calculation U-values with measured values

Before calculation can be carried out, the wind correction between the wall and the outdoor needs to be determined. The wind correction shown in the Table 3 [8].

Table 3. "Wind speed correction factors associated to R_{se} at different wind speed [8]"

Wind speed/ m/s	wind corr wind
0	– 0.09
0.5	– 0.07
1	– 0.04
2	– 0.01
3	– 0.01
4	0
5	0
7	0.01
10	0.02

The general formula for calculating the Arcada rapid U-value for walls following

$$U - value = \frac{1}{R_{si} + R_{ADAsi} + R_{wind\ corr} + \left(\frac{\left(T_{in\ facade}\ - T_{out\ air}\right) \cdot A}{P\ (electronics + heating + Solar}\right)} \qquad (18)$$

R_{si} stands for indoor transfer resistance, R_{ADAsi} is a correction factor necessary when measuring with an adapter on the instrument allowing measurements on uneven and rough surfaces, $R_{wind\ corr}$ is the wind correction necessary for high precision measurements and in the case that the measured wind speed is significantly different than 4 m/s. Wind speed corrections are given in Table 3 T_1 is the inner wall surface temperature measured by the U-value meter, while T_2 is the outdoor air temperature, A is the area measurement area covered by the U-value meter, while P refers to the heat supply, Electronics is heat generated by the instrument and $Solar$ is referred as solar radiation. [8]

In this study the measured wall is underground meaning in this case the formula for calculating U-value needs to be modified. In Fig. 6 the same principles will be followed as in the previous chapter. However, if the outside of the wall is covered earth, the following can be assumed $T_2 \approx T_{\infty 2}$. Meaning the outside temperature $T_{\infty 2}$ is equal to the temperature of the outside surface wall T_2. Which is expressed as following

$$U - value = \frac{1}{R_{si} + R_{ADAsi} + \left(\frac{\left(T_{in\ facade}\ - T_{out,surface\ wall}\right) \cdot A}{P\ (electronics + heating)}\right)} \qquad (19)$$

3 INFLUENCE OF MOISTURE ON THERMAL CONDUCTIVITY

Recent findings have shown that U-values of walls have worsened due to moisture content [6]. With the help of ISO 10456 we can evaluate the insulation moisture content based on deriving thermal conductivity.

In the equation 19 thermal conductivity λ_1 is the thermal conductivity which is given in the materials data sheet. Temperature conversion factor F_T in this study was regarded as a constant because this study doesn’t take into consideration how thermal conductivity behave in certain temperature. The conversion factor for ageing F_a was neglected in this study since measurements weren’t subjected to accelerated ageing. The conversion of thermal conductivity values from one set of conditions λ_1 to another λ_2 are carried out according to equation 19. [5]

The following equations is used to determine moisture influence on thermal conductivity

$$\lambda_2 = \lambda_1 * F_T * F_m * F_a \tag{20}$$

λ=Thermal conductivity
F_T=Temperature conversion factor
F_m=moisture conversion factor
F_a=ageing conversion factor

$$\lambda_2 = \lambda_1 * 1 * F_m \tag{21}$$

“Conversion of thermal values from one set of conditions (λ_1, R_1) to another set of conditions (λ_2, R_2) are carried out according to the following expressions” [5]

$$R_2 = \frac{R_1}{(F_T * F_m * F_a)} \tag{22}$$

R=Thermal resistance

If the conversion for moisture content is volume by volume is obtain through equation:

$$F_m = e^{f\psi(\psi_2 - \psi_1)} \tag{23}$$

f_ψ =Moisture content conversion coefficient volume by volume
ψ_1=Moisture content volume by volume of the first set of conditions
ψ_2 =Moisture content volume by volume of the second set of conditions [5]

4 CALCULATION OF THERMAL CONDUCTIVITY AND U-VALUE FOR MOISTURE CONTENT

To fulfill this study a more accurate reading is required to be able to define the amount moisture in a wall construction. Calculations are made according to the previous chapter 3 MOISTURE INFLUENCE ON THERMAL CONDUCTIVITY.
To determine the moisture content for each measured U-value point the equation 20 is important for this calculation. The moisture conversion factor can be derived with the help of equation 22. The moisture conversion factor f_ψ for mineral wool is 4 [5]. The first sets of condition for moisture content volume by volume ψ_1 is disregarded, because we don't want to calculate the difference between moisture point. The second sets of condition for moisture content volume by volume ψ_2, we can determine the moisture conversion factor for each moisture content point (0-100). As shown in the following equation.

$$F_m = e^{f\,\psi(\psi_2-\psi_1)} = e^{f\,\psi(\psi_2)} = e^{4(0,1\ldots1)} \tag{24}$$

After calculating every conversion factor point, these results are shown in Appendix 3.

Knowing the moisture conversion factor, the equation 18 can be used to extract the thermal conductivity. For this study the mineral wool thermal conductivity λ_1 will be 0,04 W/mK [23]. Gives following equation

$$\lambda_2 = 0{,}04 * 1 * e^{f\,\psi(\psi_2)} \tag{25}$$

What we know is the designed thermal conductivity $\lambda_2$for mineral wool based on its moisture content. We can determine the U-value for every moisture content point, by knowing the λ_2 for moisture containing materials. The U-value were obtained by using a commercially available software IDA ICE. This software can calculate U-value when the mineral wool thermal conductivity is changing (Appendix 2).

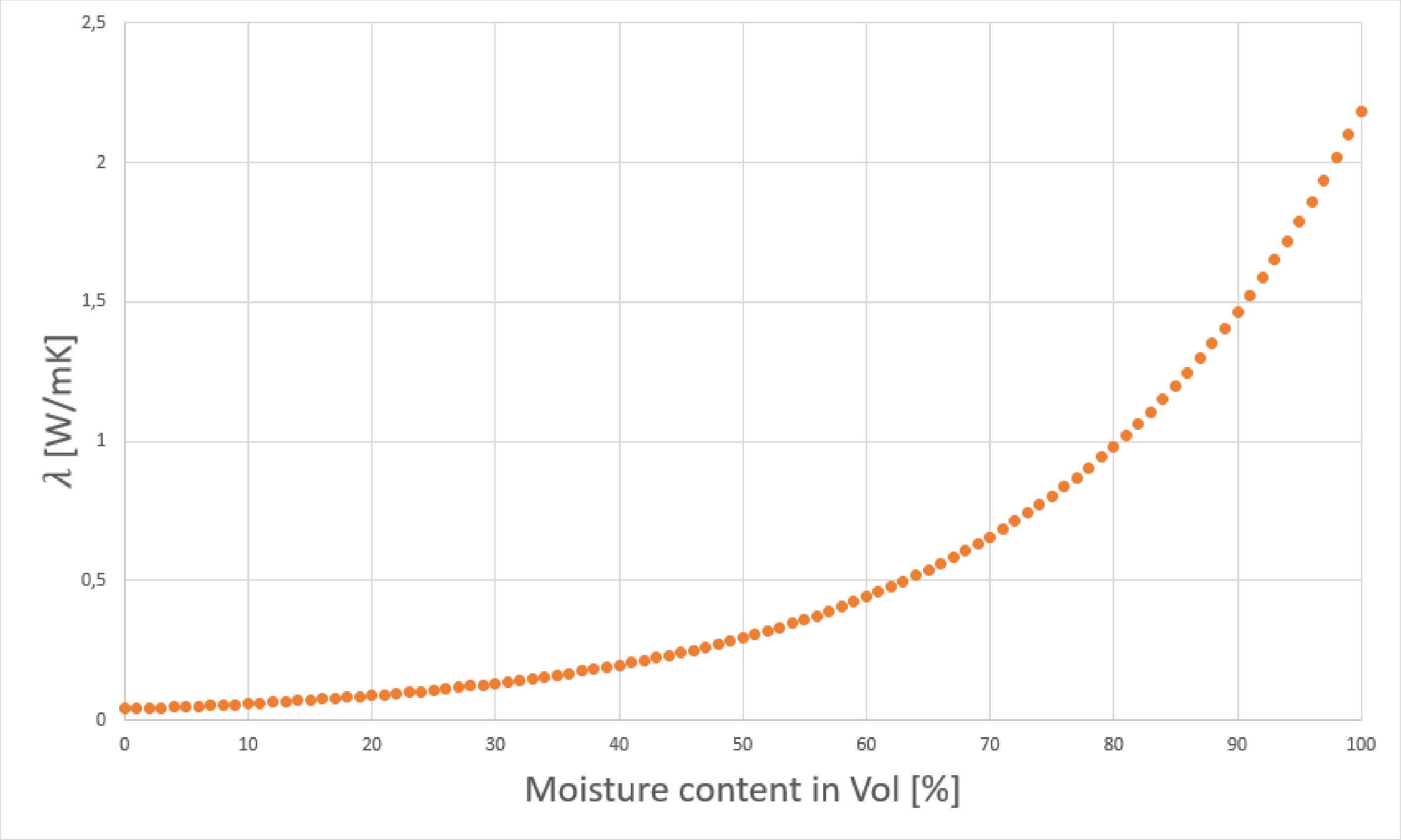


Figure 7. Thermal conductivity as a function of the moisture content for thermal insulation material made from mineral wool

Knowing the designed moisture affected λ_2 and its moisture content equations 5 and 8 allows us to determine U-value and its moisture content. By assuming moisture changes fundamentally on the thermal conductivity values for mineral wool (hundreds of %) but affects less for concrete and bricks. Resulting the following equation:

$$U = \frac{1}{R_{brick} + R_{concrete} + R_{light\ insulation} + R_{mineral\ wool}} \left(\frac{\mathrm{W}}{m^2\mathrm{K}}\right) \qquad (26)$$

λ_{brick}=0,6[W/mk]
$\lambda_{concrete}$=1,7[W/mk]
$\lambda_{light\ insulation}$=0,22[W/mk]
$\lambda_{mineral\ wool}$=Appendix 3 [W/mk]

U-value for each moisture content point from 0-100 Vol% Appendix 4.

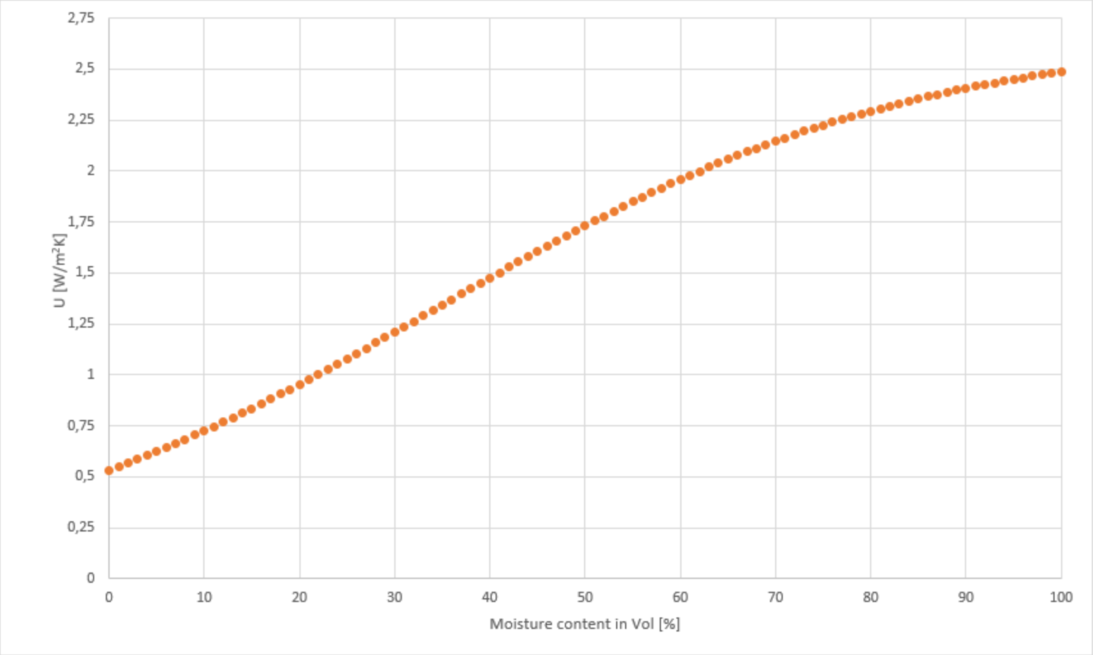


Figure 8. U-value as a function of the moisture content for thermal insulation material made from the measured object

5 PROCEDURE AND DATA

As previously mentioned in the chapter 1.1 this study will compare two different methods for moisture mapping in existing walls. The U-value measurement method will be performed as following; firstly, preliminary investigation of the measurement points, secondly measuring with the U-value measurement and lastly is data analysis. Before this can be started the theoretical background must be derived in order that the results of the meters can be used correctly. The reason behind this is because as stated in the chapter 2.4 Arcada U-value meters do not measure the indoor temperature but instead from the interior wall temperature to the outdoor temperature. The theoretical material consists of derived formulas as well as manuals and instruction for in situ measurements of the heat flow [9]. The technical equipment is described in more detail in chapter 4.1.1 to 4.1.4. With the help of these devices we can diagnose the object and define how extensive the moisture problem is and where the excessive moisture originated from.

The wall of this object was made of different material layers. Calculating U-value of an existing building with a non-intrusive method it can be difficult. Leading to skepticism or refusal on the part of the owner. To successfully define the real U-values three different values are needed: surface temperature of the inner wall, outdoor temperature and the heat flow value. The external wall is underground, between 10,20 m to 7,34 m below the ground surface, hence our reference point for outside temperature will be 6°C. Which is the annual average ground temperature in Finland [10]. This temperature reference point $T_{out,surface\ wall}$ is necessary for this study to be able to calculate the U-value of the object. The measurement with was conducted 4th January 2019 from 8am to 3pm.

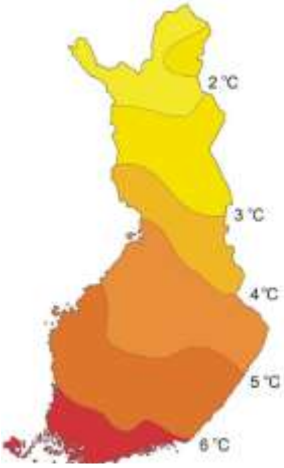


Figure 9. Average ground temperature in Finland [10]

5.1 Measured wall

The building is in Espoo and was built in 1973 was a terraced house with 2 floors. The ventilation system was natural ventilation, which worked with the pressure difference in the air, meaning there were no fans that drove the indoor air out of the building. Renovations were made in the year 2018. The measurement were used to detect what is causing the smell and moisture problems on the wall. Fig. 10 shows the wall which was measured.

Figure 10. Measured wall

5.1.1 Arcada U-value meters

The U-value describes how well a window, or some other part of a building, insulates against heat loss. The lower the U-value the better the isolation. [11] U-value meters deliver, according to its specifications, a result with a margin of error of +/- 7% or 0.07[W/m²K] and have an average measurement time of 60 minutes. [12]

Figure 11. Arcada U-value meter

5.1.2 Moisture meter

Moisture diagnoses are often carried out when testing the dampness of walls. Diagnoses are typically conducted using a pin or pinless moisture meter. These provide a "Wood Moisture Equivalent" (WME), expressed as a percentage [13]. WME is the theoretical moisture content if the material be made of wood. This can be applied to other materials as long with the help of Protimeter readings which is shown in Table 4. Protimeter readings range from 0 to 100 which measures only the free water in a material, although they do not measure relative humidity. However, these devices closely show the relative dampness of different material. [14]

These devices use an electromagnetic radio wave frequency that passes through the structure to detect presence of moisture. The radio wave bounces back to the moisture meter and checks the distortions in the wave to estimate the moisture. [15]

Figure 12. Moisture & humidity meter (Biltema)

Table 4. Protimeter readings for the moisture device [14]

BUILDING MATERIAL	VALUE	MOISTURE STATUS
Gypsym	<30	DRY
	30-60	RISK
	>60	WET
Cement	<25	DRY
	25-50	RISK
	>50	WET
Wood	<50	DRY
	50-80	RISK
	>80	WET

Pinless moisture meter, is a non-destructive device that measures the levels of moisture in walls, ceilings and floors. These measurement devices are convenient ways to get an efficient and cost-effective way to ensure materials are dry enough, which could prevent problems from arising [16]. The guidelines for this device are in the manual which comes with the device. [17]

5.1.3 Thermal camera

Thermal imaging is a method used to monitor and diagnose the condition of a building. With the help of this device you can identify problems such as air leakage and moisture problems. Thermal imaging camera allows recording of surface temperatures of building elements. Significant variation in heat can therefore be interpreted as variation of U-values. [18]

Figure 13. Thermal imaging camera Flir C2

5.1.4 Stud sensor

The stud sensor detects electric wires inside walls and studs up to 19mm below the surface material. It is also equipped with sequential LED light and audible beeps. The stud sensor is utilized to select a thermally homogenous area for U-value measurements. The guidelines for this detection device can be found in the manual [19].

Figure 14. Stud sensor (Stanley S100)

6 WORKING METHODS

The data collection and analysis process involved three steps. In the first step, theoretical U-value calculations were carried out with the following data: concrete 270 mm, mineral wool 60 mm, brick 75 mm, and 20 mm light insulation. In the second step, the moisture readings were organized and illustrated. Finally, in the third step, U-value measurements were gathered and the "calculation template.xlsx" was used in the study to calculate the measured U-value calculation template (Appendix 1) [20]. The calculated U-value of the object, based on the layer materials, gave a U-value of 0.3978 W/m^{2}K. Furthermore, these measurement is measured on the surface of the external wall which is shown in the Fig.15

#	Layers	thickness [mm]	Thermal conductivity λ (W/(mK))
1	Concrete	270	1.7
2	Mineral wool	60	0.04
3	Brick	75	0.6
4	Light insulation	20	0.22
Total thickness [mm]	0.425		
U-value [W/(m2)(K)]	0.3978		

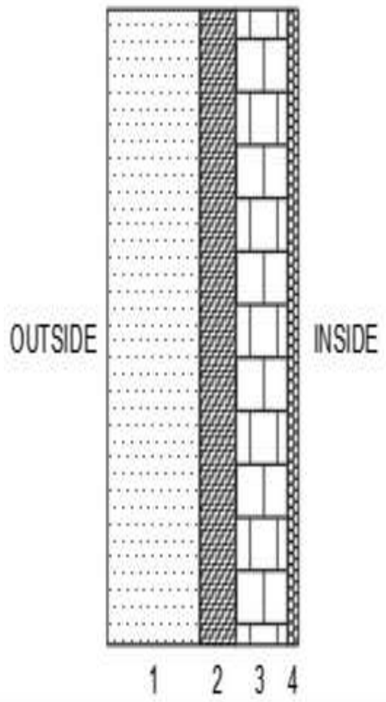


Figure 15. Technical characteristics and physical properties of the wall

7 RESULT

The Ministry of Environment legal standard 1970 U-value for concrete-framed terrace houses pre-1970's as 0.45 W/m^{2}K for the external wall (thickness of 300 mm). [21] The theoretical U-value calculation for the measured wall and the building code differ by 11.6 %. The measured points, the average U-values over the period at each sensor point varied between 0.09 to 1.32 W/m^{2}K, with an average of 0.34 W/m^{2}K for the external wall. The U-value measured positions were thermally homogeneous, meaning that there were no anomalies that could affect the measurement results. The placement of these measurement was marked and measured the same exact point when measuring moisture and U-value meters.

The moisture Protimeter values were compared to U-values measured in respective positions. The main aim was to find a correlation between these two readings, Protimeter and U-value, in order to determine if the moisture level directly influenced the U-value.

A Protimeter value below 30 is deemed dry, values between 25-60 are considered wet, depending on the material of the layer [14]. Table 5. compares the different approaches of correlating the theoretical, measured U-value with Protimeter readings. There is no direct relationship between the two measurements based on the data that has been collected. The unknown point, which can be seen in Fig 16, there were some error with the U-value device therefore no values were given at that point.

When looking at the thermal images (refer to Fig. 17), one can identify which locations of the wall are presumably being affected by moisture. By examining the moisture readings and thermal images, we can see connection. The source of the excess moisture comes from the supply vent in the upper right side of the wall. It is likely that the area containing the vent is not well insulated, which leads to condensation. [22] Another possible reason is cold air coming from the vent which cools down nearly located parts of the wall.

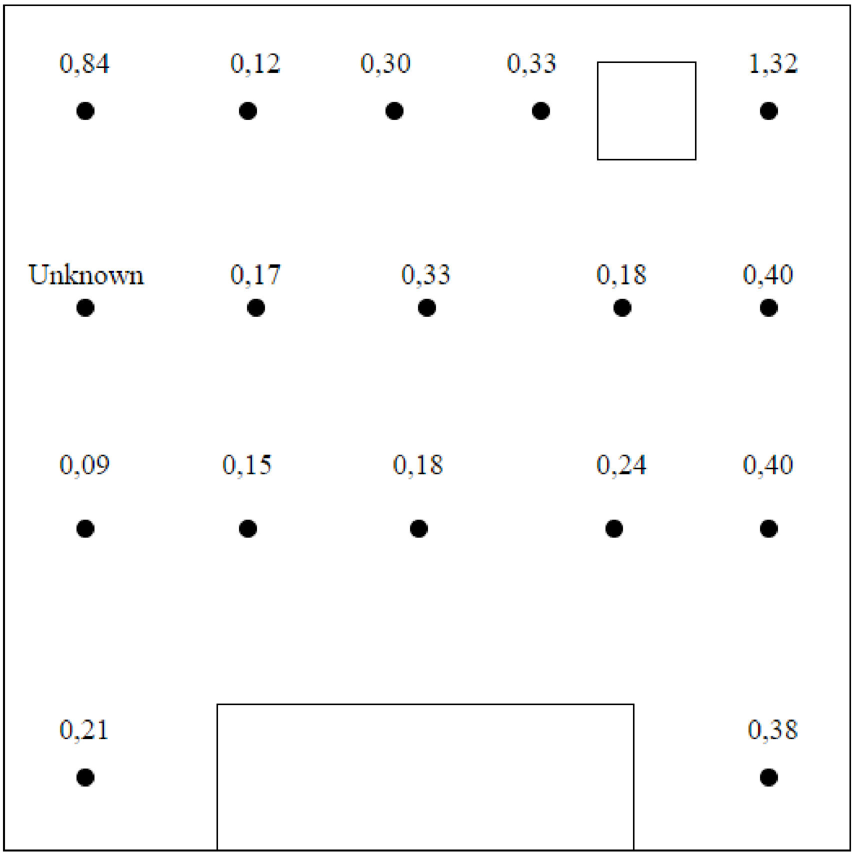


Figure 16. U-value readings of the measured wall

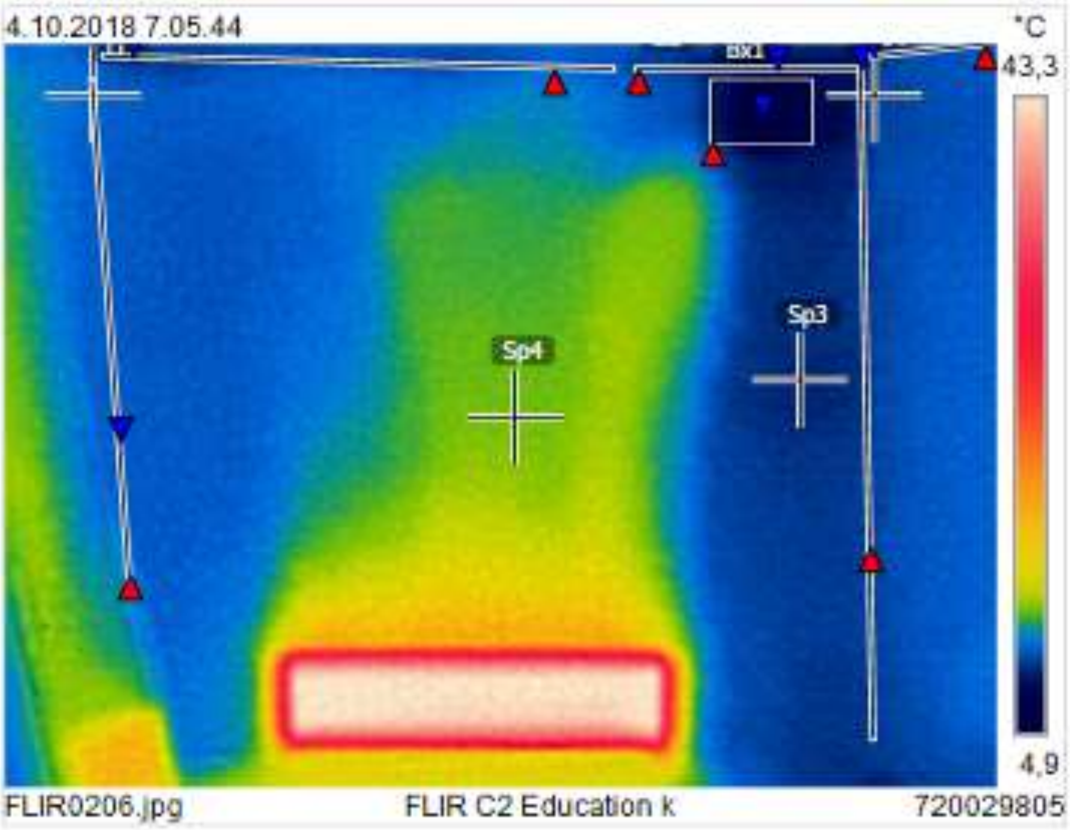


Figure 17. Thermal image of the wall

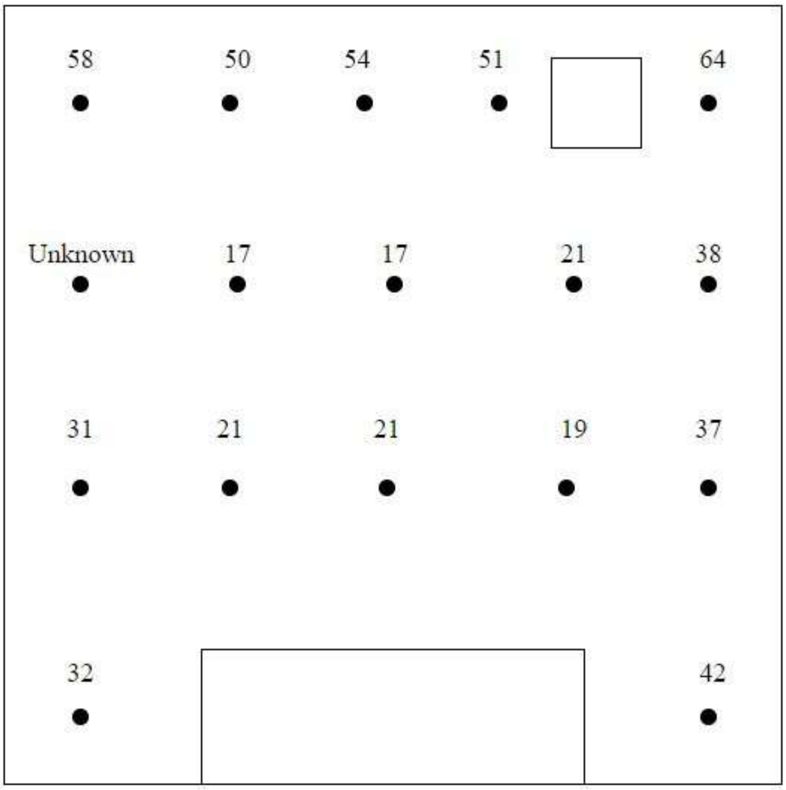


Figure 18. Protimeter reading of the measured wall

Moisture readings above 30% indicate that the wall is wet in the areas that were assessed. The thermal imaging showed sign of wetness areas that align with the measured U-value. The higher U-value corresponds to the thermal image clearly, which helps in evaluating the wetness of the wall. This traditional moisture mapping method doesn't measure moisture content; however, this gives required information where to focus in further studies of moisture content. Fig. 19 shows reveals that there isn't any clear pattern for correlation between Protimeter and U-values.

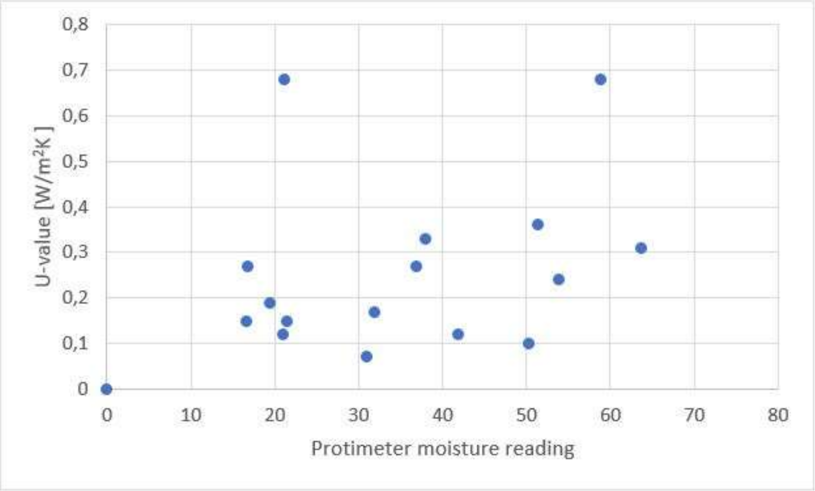


Figure 19. Comparison of U-value and Protimeter moisture readings

Table 5. Comparison of moisture, measured U-values and theoretical readings

Theoretical U-value W/m2K	Wood Dry <30% Risk <30-60% Wet >60%	Measured U-value W/m2K
0,3978	~58%	0,84
0,3978	unknown	unknown
0,3978	~31%	0,09
0,3978	~32%	0,21
0,3978	~50%	0,12
0,3978	~17%	0,17
0,3978	~21%	0,15
0,3978	~54%	0,3
0,3978	~17%	0,33
0,3978	~21%	0,18
0,3978	~51%	0,33
0,3978	~21%	0,18
0,3978	~19%	0,24
0,3978	~64%	1,32
0,3978	~38%	0,4
0,3978	~37%	0,4
0,3978	~42%	0,38

Moisture changes fundamentally on the thermal conductivity values for mineral wool (hundreds of %) but affects less for concrete and bricks [6]. It is well-founded to make some calculations both for a dry wall construction as a model and specific calculations for similar structures with having various degrees of moisture in mineral wool. Therefore, the known wall construction (consisting of concrete, mineral wool, bricks and EPS) were modelled in terms of changes in U-values with varying moisture content in mineral wool. "Or put it another way: A heavy material has much lower moisture content than light material which has the same amount of water in it" [14].

Table 6. summarizes the measured U-values and moisture content defined according to the main outlines of ISO 10456. The highest measured U-value of 1.32 corresponds to moisture content of 34 vol-% for mineral wool. This sort of information could not conclude based on the moisture meter readings. In other words, U-value metering founded measurements revealed extreme extend of wetting which should be refurbished due to the risk for mould. The true U-value can likewise be utilized to calculate dew points for various positions of the wall allowing adjustment of RH. This can limit temporarily risks associated to exposure to mould.

Table 6. Measured U-value and moisture content of the mineral wool

Measured U-value	Vol%
0,84	15
Unknown	Unknown
0,09	0
0,21	0
0,12	0
0,17	0
0,15	0
0,30	0
0,33	0
0,18	0
0,33	0
0,18	0
0,24	0
1,32	34
0,40	0
0,40	0
0,38	0

To show how the Table 6. was derived with formulas from ISO 10456. A single analysis will be shown as following; First the moisture conversion F_m will be determined with equation 23. The conversion factor ψ_2 will be 12%, which is our moisture content point. As previously stated, moisture conversion factor f_ψ for mineral wool is 4 [5].

$$F_m = e^{f\psi(\psi_2-\psi_1)} = e^{f\psi(\psi_2)} = e^{4(0,34)} = 3,896193302\ m^3/m^3 \tag{27}$$

Equation 24 will decide the designed thermal conductivity λ_2 as shown below.

$$\lambda_2 = 0,04 * 1 * e^{f4(0,34)} = 0,1558\ W/mK \tag{28}$$

After calculated the designed thermal conductivity λ_2 equation 26 and will be used to determine the U-value of that specific designed thermal conductivity. Which is shown as following

$$U = \frac{1}{R_{brick} + R_{concrete} + R_{light\ insulation} + R_{mineral\ wool(moisture\ 34\%)}}$$

$$= \frac{1}{\frac{0,075}{0,6} + \frac{0,27}{1,7} + \frac{0,02}{0,22} + \frac{0,06}{0,1558}} \tag{29}$$

$$=1,3163\left(\frac{\mathrm{W}}{m^2\mathrm{K}}\right)$$

These calculations are correlation to ISO 10456 so therefore hence, we can evaluate measured object content moisture based on the measured U-value. In this case moisture content for our measured U-value 1,32 $\left(\frac{\mathrm{W}}{m^2\mathrm{K}}\right)$ is 34 Vol%.

This gives a valid understanding how moist the wall is inside the wall which is represented in Table 6. Regarding the point with measured U-value unknown point should be disregarded. Because measuring there were some technical errors with the one specific measurement device.

8 CONCLUSIONS

Clearly wetted wall was studied in this work by analyzing it with a typical construction moisture meter, thermal imaging and by measuring U-values. The main goal of this work was to see if any correlation can be found between moisture meter and U-value meter-based values indicating moisture.

The traditional moisture mapping gave us good understanding which part of the wall is wet. Both moisture and thermal imaging couldn’t provide valid data how moist the wall was. Also, the moisture meter could only measure a depth of 20-40 mm. However, the thermal camera provided a more insight which parts of the wall had more moisture, with its thermal imaging. This method covers moisture problems before it gets out of hand and distinguish which part of the wall is wet and dry. This method in the end isn’t reliable tools or diagnosing for moisture problems. The traditional method should not base on the readings taken from the measured object. Instead they should be used to map a profile of moisture. When comparing these two methods the Protimeter only measure 20-40 mm deep inside the wall [17]. On the other hand, the Arcada U-value measures throughout the wall, which gives a more believable result. Fig. 20 illustrates how these two-measurement measure inside the measured object. The pinless moisture meter should just be used in cases of measuring moisture damages in lavatories areas. And not for detecting moisture problems in wider walls.

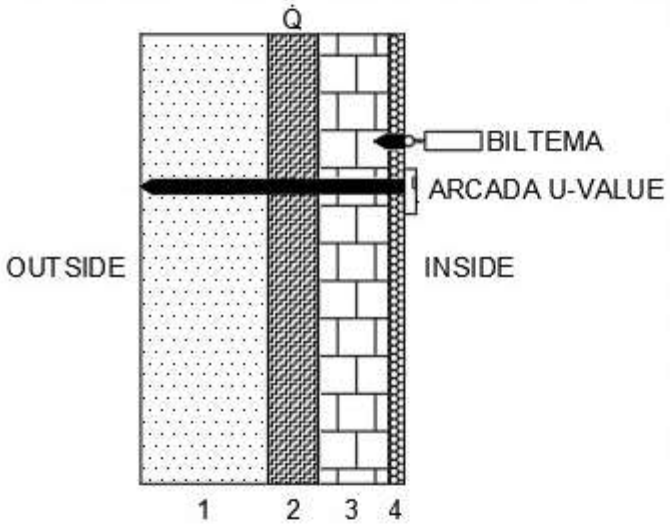


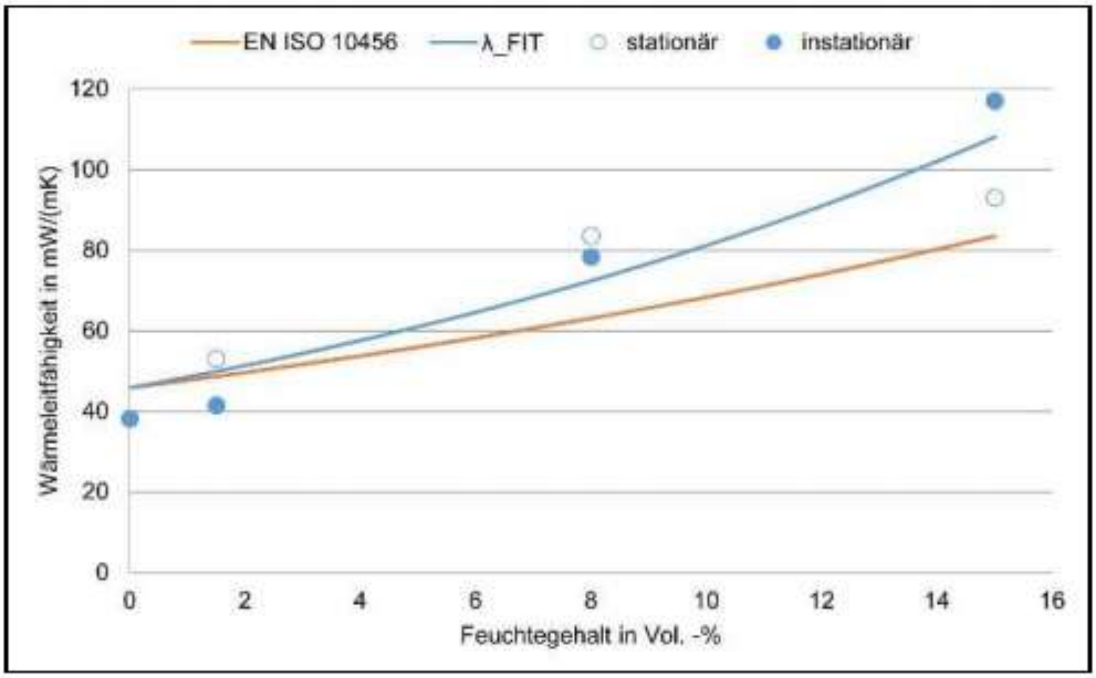
Figure 20. Measuring devices measurement depths illustrated

Due to the measurement principle of U-value metering true thermal performance of the outer could be investigated. Moisture uptake of insulation can be orders of magnitude higher than of the existing high-density mineral construction materials. However, the other method of mapping moisture gave us more valid result. Therefore, our conclusion is that moisture inside the wall can be detected by measuring thermal transmittance and correlating results to moisture content. Another benefit is the principle of measurement: U-value metering leaves no traces' and thus very favorable for initial mapping of moisture. When using this method in combination with thermal imaging this could change our perspective regarding moisture mapping. In terms of future work, it would be interesting to follow up this work with moisture transportation.

This method could be revolutionary for moisture mapping in buildings. The traditional of measuring moisture requires to takes samples, meaning could lead to be somewhat destructive. Either by drilling and collecting spoil removed by the drill, or by removing large parts of the wall. This is a drastic process which takes much time to map out the moisture. However, this method shown in this study shows that there is non-destructive method and requires no laboratory equipment. To confirm that this is a valid reading of moisture content for mineral wool and further examinations need to be done.

SAMMANDRAG

Energinivån i byggnader har blivit mer och mer väsentlig. Det har ofta bekräftats av många forskare att de senaste årtiondena har de termiska egenskaperna hos byggnadsmaterial påverkats avsevärt av fuktinnehållet och inte så mycket av temperaturen. Undersökningar har tagit upp att detektering av fukt och ökat värmeflöde i byggnadselement är ett avgörande problem. Den traditionella fuktkartläggningen med fuktmätare och termisk kamera verkar vara opålitlig och ger inga specifika detaljer om isolerings prestanda. Detektering av värmeflöden i byggnadens höljen är viktiga vid analys av utsträckning och placering av fukt i konstruktioner för t.ex. kvalitetskontroll av både nya och gamla byggnader avseende värme/kylbehov, exakt information för Energicertifikat och information för förbättrar termisk komfort. Uppmätt värmeflöden är en procedur som inte bara beskriver uppvärmning utan också belyser fukt i byggmaterial och brist på isolering.



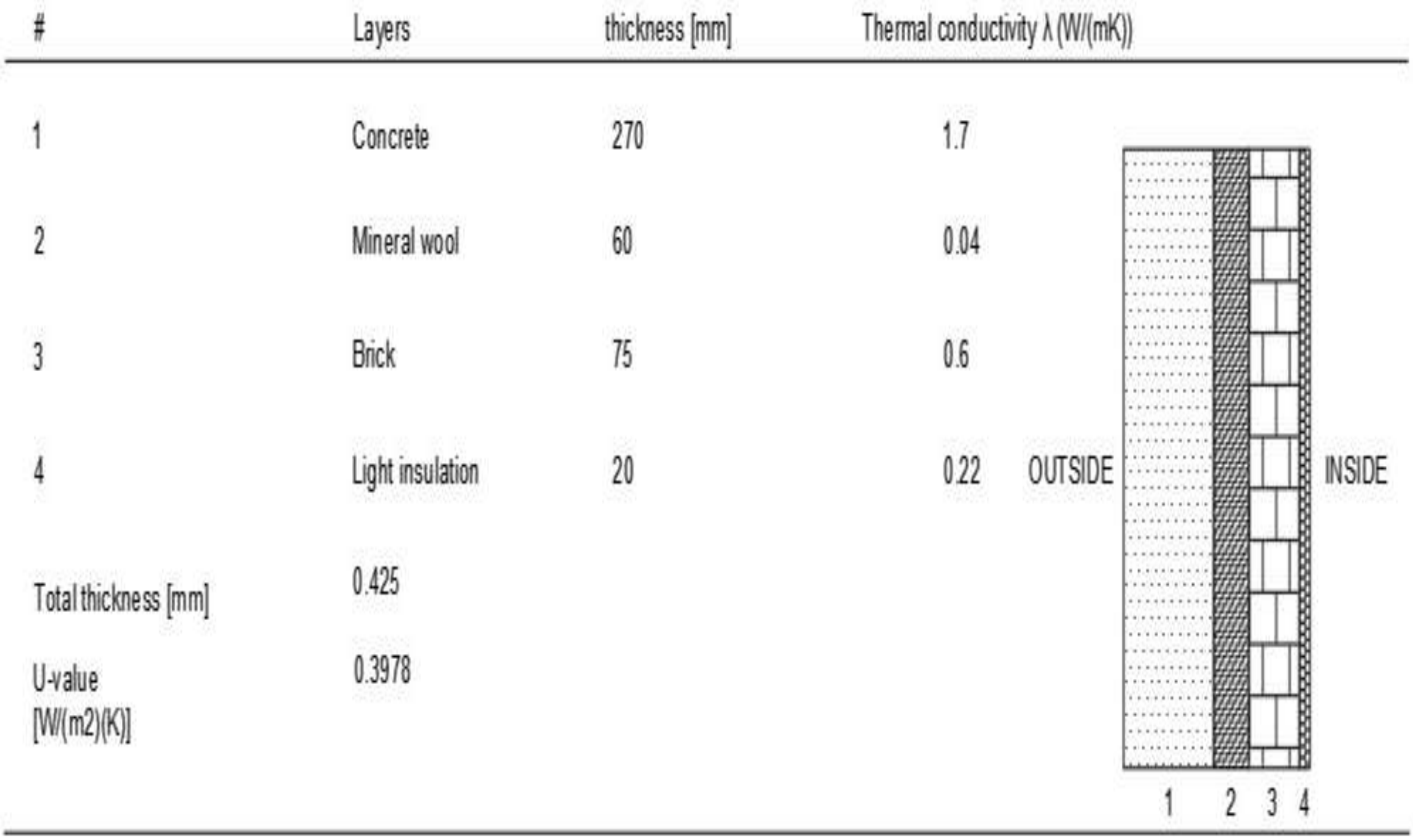
Figur 1. Värmeledningsförmåga som en funktion av fuktinnehållet för isoleringsmaterial för värmeisolerande material tillverkat av mineralull

Att bygga energiprestanda har blivit allt mer viktigare. Värmeöverföringen mellan byggnadens inside och utsida är beroende av byggnadens klimatskal som har en direkt relation till termiska prestationsförmåga. Därför är det viktigt att veta hur man mäter värden på byggmaterialets värmeegenskaper. Det har visats sig att många forskare under de senaste årtiondena, har kommit fram till att byggmaterialets termiska egenskaper påverkas avsevärt av fuktinnehållet och inte signifikant av temperaturen.

Syftet med denna arbetet är att jämföra den traditionella kartläggningen med värmeflödesmetoden. Och komma fram till vilkendera är en pålitlig diagnos för fuktkartläggning I detta examensarbete används Arcadas U-värde som utvecklas av Yrkeshögskolan Arcada. Detta arbete är auktoriserad av Mikael Paronen.

Figur 2. Upmätt vägg

Mätningen genomfördes i en lägenhet, som är byggd på 70-talet. Och alla deras mätningar är gjorda enligt deras riktlinjer. Väggkonstruktionen bestod av 270 mm betong, 60 mm mineralull, 70 mm tegel och 20 mm polystyren. Undersökningen genomfördes med hjälp av följande instrument; Arcadas U-värdemätare som ger oss väggkonstruktionens U-värde, IR-kamera visar värmebilder ("fruktspridning"), fuktmätare kan mäta fuktnivåer enligt byggnadsmaterialet (kolla jämförelsetabell i manualen) och konstruktionsdetektor för att säkerställa att väggen var från fri från anomalier. Mätningen genomfördes den 12.1.2019 i Esbo klockan från 8:00 till 15:00



#	Layers	thickness [mm]	Thermal conductivity λ (W/(mK))
1	Concrete	270	1.7
2	Mineral wool	60	0.04
3	Brick	75	0.6
4	Light insulation	20	0.22
Total thickness [mm]	0.425		
U-value [W/(m2)(K)]	0.3978		

Figur 3. Väggens tekniska och fysiska egenskaper

Med hjälp av dessa instrument kan vi åstadkomma en icke-destruktiv metod för att undersöka fuktskador i väggkonstruktionen vilket ger en möjlighet undvika rivning eller provtagning (borra ett hål). Med dessa mätningar kan vi uppnå en ny metod för att inspektera fuktproblem och inte bara förlita sig på noggrann visuell inspektion. Med denna metod kan vi komma fram till hur fuktig väggen är. För att förhindra fukten att expandera som leder till mögeltillväxt, vilket skapar luktproblem och allergier.

Resultaten upptäcktes det att den beräknande U-värde av byggmaterialet skilde sig från den ”realistiska” U-värde (som mättes på plats). Den beräknande U-värdeberäkning gav ett U-värde på 0,3978 W/m^{2}K. Och för det uppmätta punkterna varierade det mellan 0.09 och 1.32 W/m^{2}K med ett genomsnitt på 0.34 W/m^{2}K för ytterväggen. Vi kan komma fram till den uppfattningen att den beräknade U-värden som använder tabellvärden visar felaktiga resultat.

Fukt avläsning kunde sedan jämföras med U-värdemätningarna. Med hjälp av detta kan vi se en skillnad på hur mycket fukten påverkar på U-värden på väggen. Enligt våra data insamlad ökade U-värdet på basen av högre fuktavläsningar (som presenterades med figurer i examensarbete). Punkter där det skulle mycket möjligt vara fuktproblem hade U-värde omkring på 0.34 W/m^{2}K. Dock det här bevisar inte helt fullständigt att U-värden och fuktavläsningar har ett samband. Eftersom resultaten inte stödde uppfattningen att ju våtare väggen desto högre U-värde. Ytterligare forskning behövs göras inom fukttransport i olika byggmaterial.
I IR-bilderna kan vi klart se att fukten härstammar från friskluftsventilen. Det är tecken på att fukthalten blir hög pga. ventilen är inte väl isolerad vilket leder till kondens. Och väggen börjar att bli våtare vilket leder till att värmeledningsförmågan blir sämre. Med andra ord, U-värdet stiger desto högre fuktvärde som fås i fuktmätaren.

I detta arbete kunde vi härleda värmeledningsförmågan genom att räkna från de uppmätta U-värdemätningarna. Och med hjälp av tidigare forskning kan vi åstadkomma med grovt estimat fuktinnehållet av väggkonstruktionen. Och härledda en ny fuktkartläggning metod att få fuktinnehållet och klara riktlinjer hur våt det är inne i väggen. Att hur man skall beakta U-värdet när man planerar att fixa eller bygga nya byggnader.

Utmaningen med denna undersökning vad som orsakade fuktproblemet i lägenhet. Det kunde ha varit många faktorer som kunde förorsaka fuktproblem i väggen. Med hjälp av dessa instrument underlättade det mitt arbete.

Kostnaden för att reparera dessa skador är mycket dyrt. Alla yttre lager och isolering måste avlägsnas för att bestämma skadans omfattning. Kostnaden för att reparera kan sannolikt vara hälften av byggnadsvärdet. Med tanke på att detta, kan vi anta att undersökningen av U-värdet är avgörande och i följande renovering kan det leda till besparingar i energianvändningen.

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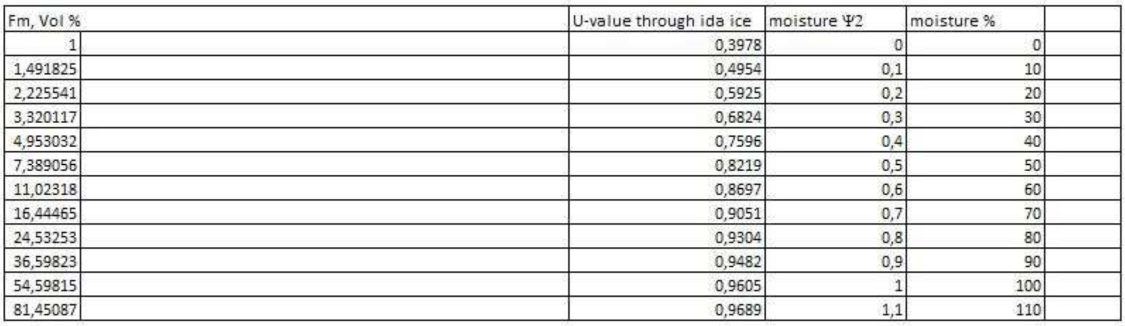
Appendix 1

U-value result with the Arcada measurement

Rse	wind on facade/ m/s	wind corr Rse-wind	Rsi	Adapter	facade T	outdoor T	instr. No	meas time	P/mW	T-in	steady: Y/N	solar	U-air
0,04	4	0	0,13	0	22	6	3	145	145	22	y	0	0,84
0,04	4	0	0,13	0	22	6	3	10	x	22	y	0	#VALUE!
0,04	4	0	0,13	0	22	6	3	30	10	22	y	0	0,09
0,04	4	0	0,13	0	22	6	3	15	30	22	y	0	0,21
0,04	4	0	0,13	0	22	6	3	22	15	22	y	0	0,12
0,04	4	0	0,13	0	22	6	3	20	22	22	y	0	0,17
0,04	4	0	0,13	0	22	6	3	45	20	22	y	0	0,15
0,04	4	0	0,13	0	22	6	3	50	45	22	y	0	0,30
0,04	4	0	0,13	0	22	6	3	25	50	22	y	0	0,33
0,04	4	0	0,13	0	22	6	3	51	25	22	y	0	0,18
0,04	4	0	0,13	0	22	6	3	25	51	22	y	0	0,33
0,04	4	0	0,13	0	22	6	3	35	25	22	y	0	0,18
0,04	4	0	0,13	0	22	6	3	8	35	22	y	0	0,24
0,04	4	0	0,13	0	22	6	3	60	250	22	y	0	1,32
0,04	4	0	0,13	0	22	6	3	65	62	22	y	0	0,40
0,04	4	0	0,13	0	22	6	3	65	82	22	y	0	0,40
0,04	4	0	0,13	0	22	6	3	50	59	22	y	0	0,38
0,04	4	0	0,13	0	22	6	3	20	8	22	y	0	0,08

Appendix 2

U-value affected by thermal conductivity and moisture content



Fm, Vol %		U-value through ida ice	moisture Ψ2	moisture %	
1		0,3978	0	0	
1,491825		0,4954	0,1	10	
2,225541		0,5925	0,2	20	
3,320117		0,6824	0,3	30	
4,953032		0,7596	0,4	40	
7,389056		0,8219	0,5	50	
11,02318		0,8697	0,6	60	
16,44465		0,9051	0,7	70	
24,53253		0,9304	0,8	80	
36,59823		0,9482	0,9	90	
54,59815		0,9605	1	100	
81,45087		0,9689	1,1	110	

Appendix 3

Moisture conversion factor and designed thermal conductivity

Fm	λ_2	ψ_2	Vol %
1	0,04	0	0
1,040810774	0,041632	0,01	1
1,083287068	0,043331	0,02	2
1,127496852	0,0451	0,03	3
1,173510871	0,04694	0,04	4
1,221402758	0,048856	0,05	5
1,27124915	0,05085	0,06	6
1,323129812	0,052925	0,07	7
1,377127764	0,055085	0,08	8
1,433329415	0,057333	0,09	9
1,491824698	0,059673	0,1	10
1,552707219	0,062108	0,11	11
1,616074402	0,064643	0,12	12
1,68202765	0,067281	0,13	13
1,7506725	0,070027	0,14	14
1,8221188	0,072885	0,15	15
1,896480879	0,075859	0,16	16
1,973877732	0,078955	0,17	17
2,054433211	0,082177	0,18	18
2,13827622	0,085531	0,19	19
2,225540928	0,089022	0,2	20
2,316366977	0,092655	0,21	21
2,410899706	0,096436	0,22	22
2,50929039	0,100372	0,23	23
2,611696473	0,104468	0,24	24
2,718281828	0,108731	0,25	25
2,829217014	0,113169	0,26	26
2,944679551	0,117787	0,27	27
3,064854203	0,122594	0,28	28
3,189933276	0,127597	0,29	29
3,320116923	0,132805	0,3	30
3,455613465	0,138225	0,31	31
3,596639726	0,143866	0,32	32
3,743421377	0,149737	0,33	33
3,896193302	0,155848	0,34	34
4,055199967	0,162208	0,35	35
4,220695817	0,168828	0,36	36
4,392945681	0,175718	0,37	37

4,572225195	0,182889	0,38	38
4,758821245	0,190353	0,39	39
4,953032424	0,198121	0,4	40
5,155169512	0,206207	0,41	41
5,365555971	0,214622	0,42	42
5,584528464	0,223381	0,43	43
5,812437394	0,232497	0,44	44
6,049647464	0,241986	0,45	45
6,296538261	0,251862	0,46	46
6,553504862	0,26214	0,47	47
6,820958469	0,272838	0,48	48
7,099327065	0,283973	0,49	49
7,389056099	0,295562	0,5	50
7,690609199	0,307624	0,51	51
8,004468914	0,320179	0,52	52
8,331137488	0,333245	0,53	53
8,671137658	0,346846	0,54	54
9,025013499	0,361001	0,55	55
9,393331287	0,375733	0,56	56
9,77668041	0,391067	0,57	57
10,17567431	0,407027	0,58	58
10,59095145	0,423638	0,59	59
11,02317638	0,440927	0,6	60
11,47304074	0,458922	0,61	61
11,94126442	0,477651	0,62	62
12,42859666	0,497144	0,63	63
12,93581732	0,517433	0,64	64
13,46373804	0,53855	0,65	65
14,01320361	0,560528	0,66	66
14,5850933	0,583404	0,67	67
15,18032224	0,607213	0,68	68
15,79984295	0,631994	0,69	69
16,44464677	0,657786	0,7	70
17,11576554	0,684631	0,71	71
17,81427318	0,712571	0,72	72
18,54128746	0,741651	0,73	73
19,29797176	0,771919	0,74	74
20,08553692	0,803421	0,75	75
20,90524324	0,83621	0,76	76
21,7584024	0,870336	0,77	77
22,64637964	0,905855	0,78	78
23,57059593	0,942824	0,79	79
24,5325302	0,981301	0,8	80
25,53372175	1,021349	0,81	81

26,5757727	1,063031	0,82	82
27,66035056	1,106414	0,83	83
28,78919088	1,151568	0,84	84
29,96410005	1,198564	0,85	85
31,18695817	1,247478	0,86	86
32,45972208	1,298389	0,87	87
33,78442846	1,351377	0,88	88
35,16319715	1,406528	0,89	89
36,59823444	1,463929	0,9	90
38,09183673	1,523673	0,91	91
39,64639407	1,585856	0,92	92
41,26439411	1,650576	0,93	93
42,94842598	1,717937	0,94	94
44,70118449	1,788047	0,95	95
46,52547444	1,861019	0,96	96
48,42421507	1,936969	0,97	97
50,40044478	2,016018	0,98	98
52,45732595	2,098293	0,99	99
54,59815003	2,183926	1	100

Appendix 4

U-value for each moisture content point of the measured object from 0-100 Vol%

U-value	Procent vol%
0,533409	0
0,550686	1
0,568373	2
0,586471	3
0,60498	4
0,623897	5
0,643221	6
0,662951	7
0,683081	8
0,703607	9
0,724526	10
0,74583	11
0,767514	12
0,789569	13
0,811987	14
0,834759	15
0,857875	16
0,881323	17

0,905091	18
0,929167	19
0,953538	20
0,978188	21
1,003103	22
1,028266	23
1,053661	24
1,07927	25
1,105077	26
1,131061	27
1,157203	28
1,183485	29
1,209886	30
1,236386	31
1,262963	32
1,289598	33
1,316268	34
1,342952	35
1,36963	36
1,396279	37
1,422879	38
1,449408	39
1,475846	40
1,502172	41
1,528366	42
1,554408	43
1,580278	44
1,605959	45
1,631431	46
1,656678	47
1,681681	48
1,706426	49
1,730896	50
1,755077	51
1,778954	52
1,802516	53
1,825749	54
1,848643	55
1,871186	56
1,893369	57
1,915184	58
1,936622	59
1,957677	60
1,978342	61
1,998611	62

2,018481	63
2,037948	64
2,057008	65
2,07566	66
2,093902	67
2,111733	68
2,129153	69
2,146164	70
2,162765	71
2,178959	72
2,194748	73
2,210135	74
2,225124	75
2,239717	76
2,25392	77
2,267736	78
2,281172	79
2,294231	80
2,30692	81
2,319244	82
2,33121	83
2,342823	84
2,35409	85
2,365019	86
2,375614	87
2,385884	88
2,395836	89
2,405476	90
2,414811	91
2,423848	92
2,432595	93
2,441059	94
2,449247	95
2,457165	96
2,464822	97
2,472223	98
2,479376	99
2,486288	100