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PROCEDURE FOR DETERMINING THE DESIGN VALUE OF THE THERMAL CONDUCTIVITY OF THERMAL INSULATION MATERIALS

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Procedure for determining the design value of the thermal conductivity of thermal insulation materials

PREFACE

The present report is the end-result of the project "Fugtteknisk grundlag for fastsættelse af designværdier for varmeledningsevnen ud fra deklarerede værdier for varmeledningsmateriale i typiske bygningskonstruktioner" (Moisture based basis for determination of design values for the thermal conductivity based on declared values for thermal insulation material in typical building constructions) financed by the Danish Energy Agency (j. nr. 75664/00-0022).

The project has been carried out at the Department of Civil Engineering, Technical University of Denmark and at Danish Standard. Project leader has been Jørgen Dufour from Danish Standard. Project members from Department of Civil Engineering are Claus Rudbeck, Carsten Rode and Svend Svendsen.

During the course of the project a number of persons have been attached to the project. They are: Helge Høyer (Rockwool International), Torben Henriksen (LECA), Mogens Byberg (Varmeisoleringskontrollen) and Kurt Stokbæk. Sincere thanks are expressed to all participants. Furthermore, two international experts have offered their opinions regarding the developed methodology. Our sincere thanks go to Brian Anderson (British Research Establishment, Glasgow, Scotland) and Per Ingvar Sandberg (Sveriges Provnings- och Forskningsinstitut, Borås, Sweden).

Lyngby, June 2001
Claus Rudbeck and Carsten Rode

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1. INTRODUCTION

This report concerns determination of the moisture conversion factor for insulation materials.
The determination of the moisture conversion factor is performed of a number of insulation materials, which is necessary as the insulation materials have different moisture properties and different uses in the building constructions. In this report, the moisture conversion factors are reported for mineral wool, expanded polystyrene, light weight aggregate concrete, cellular concrete, cellulose fibre and flax. Other types of insulation materials exist, e.g. sheep's wool and straw, are also being used in some building envelopes. However, material properties for these insulation materials are lacking and it is therefore impossible to perform the calculations which are needed to determine the moisture conversion factor of the thermal conductivity.
Determination of the moisture conversion factor for insulation materials is based on calculation of the moisture content of the insulation under in-use conditions. This requires that calculation models of different building envelope constructions, including the insulation, are created and that indoor and outdoor climatic boundary conditions are determined. Once these steps are completed, the moisture content of the insulation may be determined.
Information regarding the moisture content combined with moisture conversion coefficients from the international standard EN ISO 10456 makes it possible to determine the thermal conductivity of the examined insulation materials under in-use conditions.
The end result is a table showing the moisture conversion factor, i.e. the design value divided by the declared value, for each of the examined insulation materials.

2. THERMAL PERFORMANCE OF MOIST INSULATION MATERIALS

When mentioning the thermal conductivity of a material, or an insulation material in particular, one should recognize the fact that several values are used to represent the thermal conductivity. According to international standardisation, two thermal conductivities may be referred to: one being the declared value of the thermal conductivity and the other being the design value of the thermal conductivity. The two values are defined in EN ISO 10456 (1999) as:

Declared value: Expected value of a thermal property of a building material or product assessed from measured data at reference conditions of temperature and humidity; given for a stated fraction of confidence level; corresponding to a reasonable expected service lifetime under normal conditions.

Design value: Value of thermal property of a building material or product under specific external and internal conditions which can be considered as typical of the performance of that material or product when incorporated in a building component.

The declared value is only supplied by the manufacturer and it may be certified.
As mentioned in the definition of the design values of thermal properties, climate and building constructions should be taken into account. As both climate and building construction differ from country to country, or even within regions of countries, determination of the moisture conversion factor for materials should be performed in each country.
Under some climatic conditions and for some building constructions the difference between the declared and the design value may be large. However, it makes no sense to determine the moisture conversion factor without assessing the moisture content of the insulation layer in the specific construction under specific climatic conditions.

3. ASSESSMENT OF HEAT AND MOISTURE TRANSFER

A method is proposed to assess the moisture conditions for typical Danish building constructions and their insulation layers and transforming this information into values of moisture conversion factors. The proposed method uses calculation with a computational model to assess the moisture conditions.

3.1 Construction of model

To determine the moisture conversion factor for insulation material, a calculation model of the chosen construction is used. This calculation model is built up in a heat and moisture transfer calculation tool. As heat and moisture transfer calculation tool, MATCH (Pedersen 1990) is used. To illustrate the procedure when the design value is to be determined, a walk-through of a calculation is provided by means of an example. The calculation is made for a Danish exterior wall construction with an inner and an outer layer of brick with insulation material in between the brick layers. The insulation material is not in direct contact with the outer brick leaf as there is an air gap in between. The dimensions of the different layers defined from outside and in are:

108 mm brick work
10 mm air cavity
125 mm cellulose insulation
108 mm brick work

Output from the calculations are the amount and location of moisture in the insulation layer. The tool provides an average moisture content for each layer in the model, so to determine a moisture

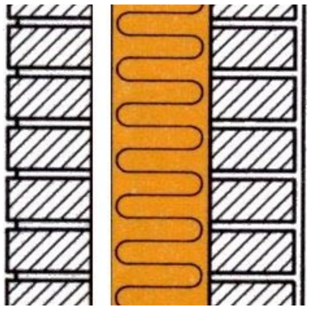


Figure 3.1 Section of external wall with insulation between two brick layers

profile, subdivision of the layers are needed. Although an increase in material layers will generally increase the level of precision, it will also increase the time spent on the calculations. The subdivision of the model which is created to represent the specified construction is shown in Figure 3.2 and in Figure 3.3.

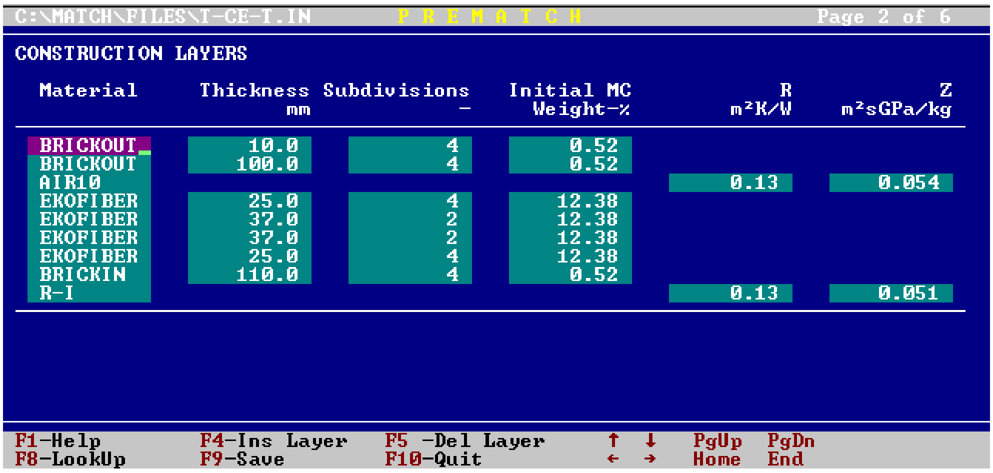


Figure 3.2 Subdivision of model representing an exterior wall with hammer milled cellulose insulation

The layers of the exterior wall construction as defined in MATCH is shown in Figure 3.2 with the subdivision being shown in Figure 3.3.

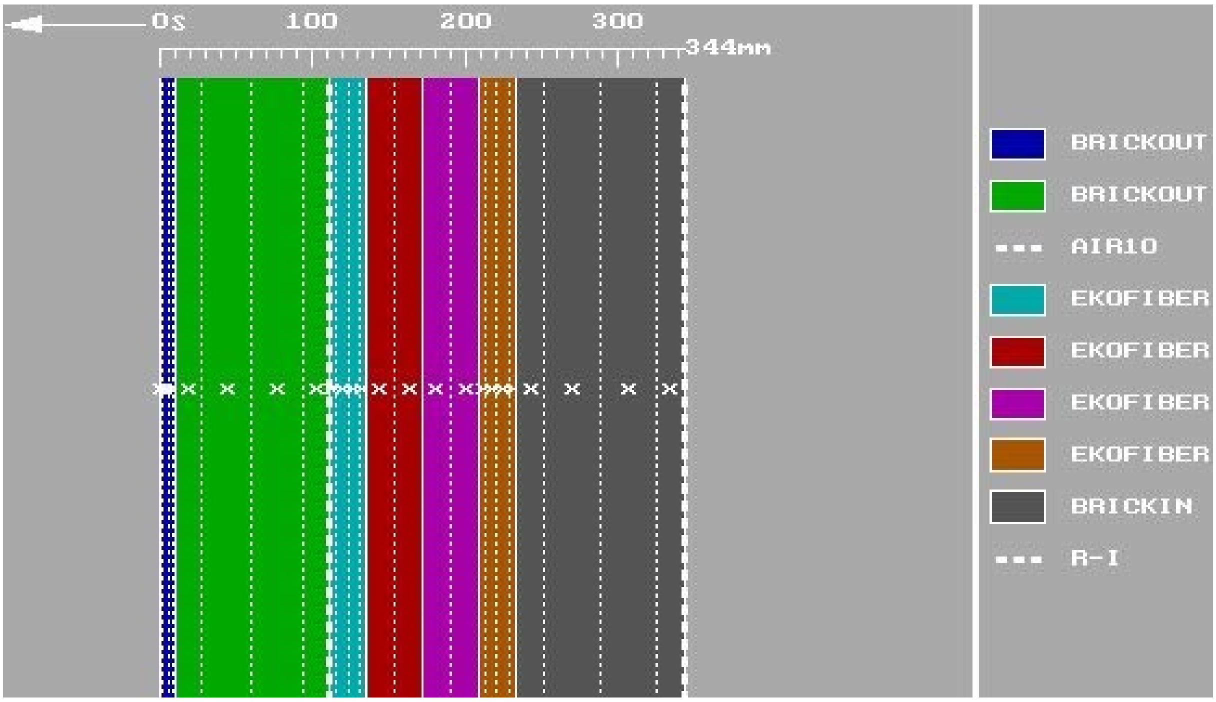


Figure 3.3 Subdivision of materials layers for exterior wall with cellulose insulation

Before the calculations may be initiated, definition of the interior and the exterior climatic boundary conditions are needed. The indoor climate varies between 21°C and 23°C combined with a moisture addition of +2 to +3 g/m^3 compared with the vapour concentration of the external climate.

Detailing of the moisture addition is not performed at this stage. Later in the report, the effect of different moisture addition rates are examined.
Further description of the variation of the indoor climate is performed in detail together with the results of the calculation.
As the exterior climate, the Danish Test Reference Year (Commission of the European Communities 1985) is used.

3.2 Determining moisture conditions in insulation material

The design vales are to be given as averages for a period of one year. To get the proper initial distribution of the moisture in the constructions, a period of two years is included in the beginning of the calculations. Only the results from the last year of the calculations are examined. In the examination of the results, the daily average values are used.
The moisture content for the layers of the cellulose insulation is shown in Table 3.1.

Table 3.1 Daily averages of the moisture content given in weight-% for the different parts of the cellulose-insulation

	Outer layer			Inner layer
Time [days]	Moisture content 25 mm	Moisture content 37 mm	Moisture content 37 mm	Moisture content 25 mm
0.5	17.15	10.47	7.43	5.57
1.5	16.67	10.44	7.51	5.81
2.5	16.41	10.42	7.56	5.89
3.5	16.09	10.46	7.64	6.02
⋮	⋮	⋮	⋮	⋮

Two international standards dealing with methods and values used in transformation of moisture content into thermal conductivity are referred to. These are EN ISO 10456 (1999) and EN 12524 (2000). In these two standards moisture content are linked to thermal conductivity by moisture conversion coefficients. For some materials, the moisture conversion coefficient is related to the moisture content in volume-% and for other materials it is related to the moisture content in weight-%.
If needed, the moisture content of the insulation given in volume-% may be calculated using Equation 1.

$$MC[volume] = \frac{MC[weight - \%]}{100\%} * \frac{\rho_{insulation}}{\rho_{water}} \qquad \textbf{(1)}$$

where
MC moisture content
ρ density

3.3 Transformation of moisture conditions to thermal conductivity

To translate the calculated moisture conditions into an effect on the thermal conductivity, equations from EN ISO 10456 (1999) are used. The linkage between the thermal conductivity under two different conditions are given by equation 2 or equation 3.

$$\lambda_2 = \lambda_1 * e^{f_u(u_2 - u_1)} \quad \textbf{(2)}$$

$$\lambda_2 = \lambda_1 * e^{f_\psi(\psi_2 - \psi_1)} \quad \textbf{(3)}$$

In equation 2 and 3, λ_1 and λ_2 are the thermal conductivity in conditions 1 and 2, f_u (or f_Ψ) is the moisture content conversion coefficient and u_1 and u_2 (or Ψ_1 and Ψ_2) are the moisture content for the first and second set of conditions. f_u and f_Ψ can be found in EN 12524 (2000).

If condition 1 represent the state where the insulation is under standard conditions (23 °C, 50% relative humidity), u_1=0.11 kg/kg according to EN 12524 (2000) and λ_1 equals the value of the thermal conductivity under these conditions. In this instance the declared value is put at a value of 0.039 W/mK. If other information regarding the declared value is available, this may be used. Using the values from Table 3.1 as u_2, combined with f_u obtained from EN 12524 (2000), yields the content of Table 3.2.

Table 3.2 Thermal conductivity of moist cellulose insulation material using moisture conditions from Table 3.1.

	Outer layer			Inner layer
Time [days]	Thermal conductivity 25 mm	Thermal conductivity 37 mm	Thermal conductivity 37 mm	Thermal conductivity 25 mm
0.5	0.040218	0.038897	0.03831	0.037955
1.5	0.040121	0.038891	0.038325	0.038001
2.5	0.040069	0.038887	0.038335	0.038016
3.5	0.040005	0.038895	0.03835	0.038041
⋮	⋮	⋮	⋮	⋮

As can be seen from the results in Table 3.2, the thermal conductivity of the insulation material depends on the location of the insulation in the exterior wall. Having to use the entire content of Table 3.2 each time the thermal performance of a component is to be evaluated would be very cumbersome. Instead, the need is for a single number which adequately represents the data in Table 3.2 and which is easily included in calculations. To condense the content of Table 3.2 into one number, being the design value for the thermal conductivity for cellulose insulation in this specific construction under these climatic conditions, an appropriate average must be made.

3.4 Determination of design value of thermal conductivity

The results of Table 3.2 are weighed with the temperature difference between inside and outside to get the correct influence of the varying thermal conductivity especially during the winter

months.
Table 3.3 shows the indoor and outdoor temperatures. The outdoor temperature is obtained from (Commission of the European Communities 1985). The thermal conductivity of the moist insulation material is obtained from Table 3.2. Coupling the thermal conductivity of the moist insulation materials with knowledge regarding the dimensions of the different insulation layers the heat transfer through the entire insulation layer, and temperature across the entire construction, is calculated with the results being shown in Table 3.3.

Table 3.3 Calculation of the average thermal conductivity of the insulation material weighed by the temperature difference between inside and outside. Only some days have been selected. $\Sigma_{heating}$ is the total heat transfer during the heating season.

	Temperature [°C]			Thermal conductivity				
Time [days]	Indoor	Outdoor	Difference	Outer layer 25 mm	37 mm	37 mm	inner layer 25 mm	Heat transfer [W/m²]
0.5	20	2.1	17.9	0.040218	0.038897	0.03831	0.037955	5.59
30.5	20	-0.7	20.7	0.040107	0.038872	0.038312	0.037959	6.78
90.5	20	2.8	17.2	0.040025	0.038981	0.038499	0.038191	5.7
280.5	21	10.4	10.6	0.039296	0.039051	0.038811	0.038635	3.33
$\Sigma_{heating}$			3811	⋮	⋮	⋮	⋮	1227

The heat transfer properties are only taken into account during the heating season. The heating season in Denmark is used to denote the period from day 1 to day 133 (January 1st to April 13th) and from day 267 to day 365 (September 13th to December 31th).
Having obtained both the accumulated temperature difference and the accumulated heat transfer it is relatively easy to calculate the average thermal conductivity. Using $\Sigma T=3811$ as the accumulated temperature difference, $\Sigma H= 1227$ W/m^2 as the accumulated heat transfer and d=0,124 m as the total insulation thickness the average thermal conductivity may be calculated as $\lambda_{design}=(d*\Sigma H/\Sigma T)$. Use of exact values yields λ_{design} = 0.03885 W/mK which concludes the example. Calculating F_m, being the design value divided by the declared value, a value of 0.996 is obtained.
The reason for the design value being lower than the declared value is that the moisture content, as a weighed average, is below the average moisture conditions found at 23°C, 50% relative humidity at which the declared value is given.

3.5 Layering of the calculation model

Table 3.1 shows that the moisture content in the different layers of the insulation is very stepwise. As the exact location of moisture may have an impact on the thermal performance of the insulation material, the layering of the insulation in the calculation model has been investigated. The investigation started by increasing the number of control-volumes (layers) in the model. Because of limitations in the calculation tool, a maximum number of material layers could be

assigned to the insulation material.
The thinnest layers are to be located at the boundaries with increases in layer thickness as they distanced themselves from the outer boundary. The thickness of the first control volume was set to 1 mm.
The variation of the moisture content in the insulation material in a construction identical to the construction shown in Figure 3.2 and Figure 3.3 (although the number and dimensions of the control volume is different), is shown in Figure 3.4.

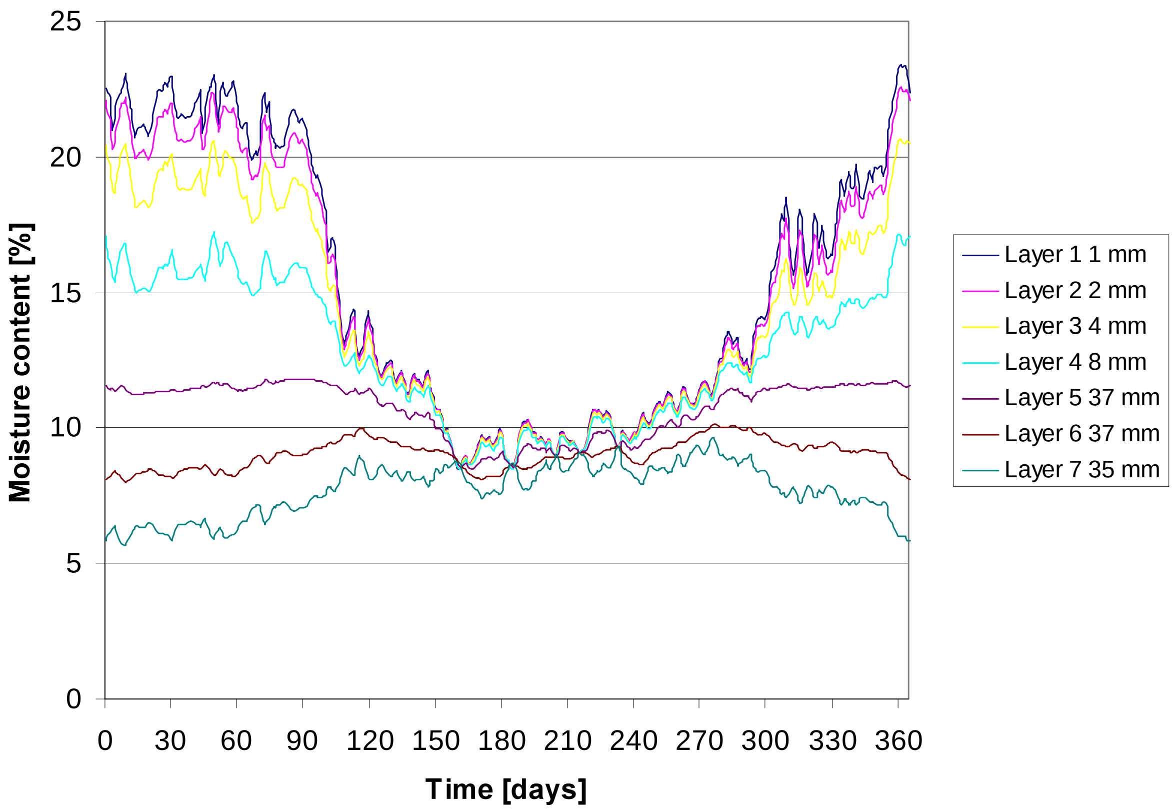


Figure 3.4 Variation of the moisture content (in weight-%) in the insulation layer using the maximum allowable number of layers.

Figure 3.4 shows that the moisture content varies across the insulation, with the highest values found at the external boundary and the lowest values at the inner boundary. Most of the variation in moisture content is found in the outermost 15 mm of the insulation. Therefore the control volumes is concentrated in these outer 15 mm of the insulation layer. For the construction illustrated in Figure 3.2, 3.3 and 3.4, the following thicknesses of the control volumes are (from outside and in): 5 mm, 5 mm, 5 mm, 10 mm, 25 mm, 35 mm and 40 mm. For larger insulation thicknesses, the thickness of the control volumes are scaled accordingly.

Table 3.4 Thickness of control volumes as percentage of the total insulation thickness

Control volume number	1	2	3	4	5	6	7
Thickness [% of total thickness]	4	4	4	8	20	28	32

The values in Table 3.4 are used as a guideline for the setup of control volumes for all the constructions where design values for the thermal conductivity is determinated.
Using this sub-division of the insulation layer in comparison with the original values, shown in Figure 3.2 and 3.3 and utilized in Table 3.2 and Table 3.3, a more precise calculation can be made. The improvement in the result of the calculation is noteworthy, however not very large.

3.6 Climate in crawl space

For most of the constructions, the external boundary conditions can be described by a collection of reference weather data. Crawl spaces do not belong to this group of constructions. To determine the heat and moisture conditions in a crawl space, a numerical calculation tool may be used. One such calculation tool is CICS, Calculation in Crawl Space, by (Åberg 1997).
Based on information on the physical built-up of the crawl space, the exterior climate and the micro-climate surrounding the building containing the crawl space, the tool makes it possible to predict the temperature and moisture conditions in the crawl space.
The data describing the external climate originates from the city of Lund located in Southern Sweden; a fair assumption is that the climate of Lund and the climate of Danish cities may be treated as equal.
As typical for Danish constructions, the crawl space is naturally ventilated with outside air.
The crawl space is treated as being uninsulated downwards, facing the soil, and the outer walls of the crawl space, facing the exterior climate, is also treated as uninsulated.
To get a proper examination of the moisture conditions in the crawl space it is important to include the effect of evaporation of moisture from the soil. Exact figures for the evaporation from the soil to the crawl space depends on the climate, the construction etc. and may therefore be hard to come by. Figures by (Kurnitski 2001) estimate the evaporation from soil ground with a polyethylene-membrane to be around 1.4 $g/h{\cdot}m^2$. Assuming the height of the crawl space to be 0.5 m the moisture flux from the soil to the crawl space is 2.8 $g/h{\cdot}m^3$.
By applying the tool by (Åberg 1997) on the data which has been provided, the temperature and moisture conditions in the crawl space is calculated. The temperature and moisture conditions for the crawl space are shown in Figure 3.5.

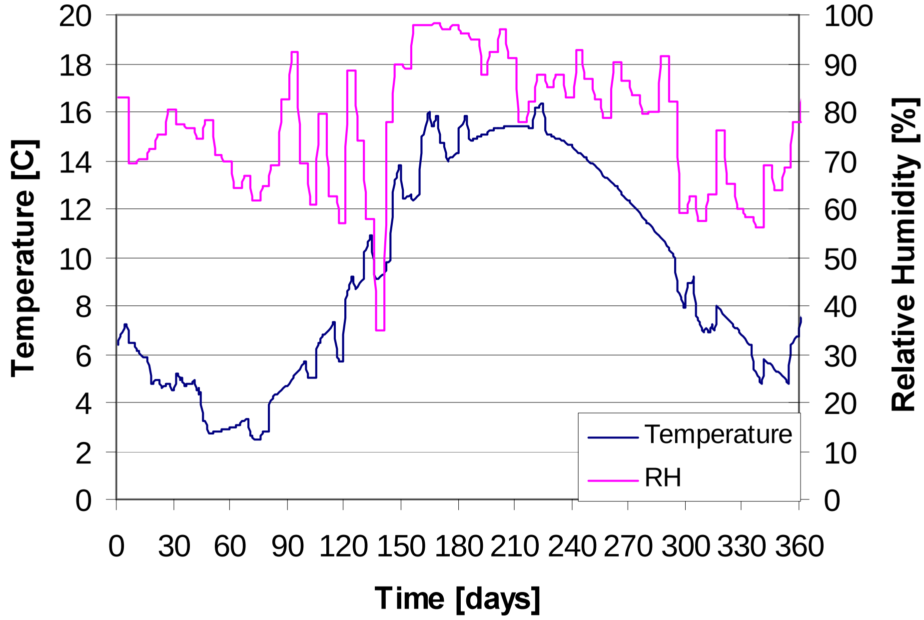


Figure 3.5 Temperature and moisture conditions in a crawl space under Danish/Southern Swedish climatic conditions

Figure 3.5 shows that the temperature in the considered crawl space varies between 2°C and 16°C in an sinusoidal-like variation. The relative humidity of the air in the crawl space varies between 60% relative humidity and 95% relative humidity, with a single exception, with the highest values found during summer. The single exception is found during spring where the relative humidity in the crawl space experience a rapid decline following by an increase. This variation in relative humidity exist because of a related decrease and increase in the outdoor temperature.

The values of Figure 3.5 is used as input values in the heat- and moisture calculation tool.

4. CONSTRUCTIONS

Once the general guidelines have been formulated regarding construction of the calculation models and the later processing of the results of these models, it is time to construct the calculation models themselves. The calculation models represent different building envelope constructions.

In the following, a list of typical Danish building envelope constructions are given. All types of constructions utilize some kind of insulation material where the thermal performance may be affected by moisture. Although some of the constructions may also be used in other countries it should be noted that the results cannot be used elsewhere but in Denmark as other climatic conditions may be found at these locations.

For each of the constructions, calculations will be made with a variation in the use of insulation material. The use of insulation material is limited to the types of materials that may be used under the given circumstances. Building envelope types that are included in the calculations are shown in Table 4.1.

Table 4.1 Building envelope construction types included in the calculations to determinate the design values of the thermal conductivity for insulation materials

No.	Building envelope construction type
1	Deck above crawl space
2	Slab on grade
3	Basement outer walls
4	Solid outer walls with exterior insulation
5	Solid outer wall with interior insulation
6	Cavity wall
7	Light-weight outer wall
8	Concrete sandwich elements
9	Unventilated roof
10	Ventilated roof

Although several designs exist for each of the building envelope constructions shown in Table 4.1, the designs often resemble each other from a moisture-related point of view. By modelling a few designs for each construction type it is possible to cover the most traditional envelope constructions.

In the following, each of the construction types are dealt with. For each of the construction types mentioned in Table 4.1, recommendations for designs which should be dealt with are given. The result of these recommendations is a limited number of potential calculations model. This should be obtained without neglecting parts of those constructions found in Denmark.

A number of different insulation materials are available on the market, but not all of them can be used in all construction types. Furthermore, physical properties are scarce for some of the materials making modelling and interpretation of results impossible.

Several materials which may be characterized as insulation materials exist, e.g. Mineral wool, Expanded polystyrene, Extruded polystyrene, Light weight concrete, Light weight aggregate concrete, Perlite (expanded stone material), Hammer milled cellulose fibres, Defibred cellulose fibres, Virgin cellulose fibres, Flax, Hemp, Sheep’s wool, Straw and In-situ cellular concrete.

Regarding the three variants of cellulose-fibres, no moisture related material properties currently exist that make it possible to distinguish between the variants. Therefore, only constructions containing hammer milled cellulose fibres are considered as material data for this variant is available. Further on in the report, the term cellulose fibres will refer to this variant of insulation unless otherwise stated.

Material properties and moisture conversion factors for hemp, sheeps wool, straw and in-situ cellular concrete are not currently available in the literature, so even though the materials may be used in building envelope components, their implementation has not been shown. However, as data on the material properties of these materials becomes available, assessment of construction insulated with these materials should also be performed.

One by one, the construction types are described in the following sections. For each construction type only a few variants are included in the descriptions.

For the same basic design, several different insulation thicknesses are normally possible. In all calculations, the insulation level is determined by the current Danish Building Regulation (1995). However, to see the influence of increasing the insulation thickness, calculations are also made for an example of two constructions that are similar in all aspects except the insulation thickness. Here, one construction just fulfills the current requirements in the Danish Building Regulations whereas the other construction should at least fulfill the requirements of what is expected from the next Danish Building Code in year 2005 - a 33% increase in insulation thickness.

4.1 Deck above crawl space

The thermal transmission coefficient for decks above crawl space must not exceed 0.2 W/m^{2}K according to the current building regulations. Generally this implies that the total thickness of insulation material should be around 175 mm if the thermal conductivity of the insulation material is 0.039 W/mK.

The floor construction, which is the upper part of the deck, may be a carpet on a concrete slab or it may be wooden planks on joists. However, the influence of the floor construction may not be noticeable on the U-value as the floor is placed above the insulation material. Instead, the major influence will be from the light weight deck or heavy weight deck used in the construction as they have an influence on the ventilation rate of the crawl space. If organic materials are used in a crawl space construction, the ventilation rate should be higher than for constructions using in-organic building materials. As the boundary conditions for these two types of deck differ, both types are included in the calculations.

Construction 1.1	Wooden planks on joists, 50 mm insulation, vapour retarder, 200 mm light-weight aggregate concrete, 125 mm insulation
Construction 1.2	Wooden planks on joists, vapour retarder, 125 mm insulation between joists, 75 mm structural mineral wool panels

Construction 1.1 is modelled with mineral wool as lower insulation layer. The upper insulation layer may be mineral wool, perlite (expanded stone material), cellulose fibre or flax (the vapour retarder should have a Z-value of 10 GPam^{2}s/kg when cellulose fibre or flax is used (DBI 2000)). If construction 1.2 is used, cellulose fibre insulation or flax insulation may be used. In this case, the vapour retarder should have a Z-value around 10 GPam^{2}s/kg (DBI 2000). Furthermore, the insulation thickness should be increased to 150 mm to fulfill the thermal requirements. A vapour retarder is to be used when mineral wool is used as insulation material, however, no specific demands regarding its vapour permeability is given.
Several types of insulation materials are usable in both of these constructions. Table 4.1 and 4.2 give an overview of which types of insulation materials can be used in the constructions.

Table 4.1 Use of insulation types for construction: “Planks on joists and use of cellular aggregate concrete”. Figure from (SBI 1995)

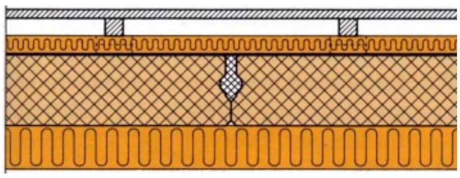
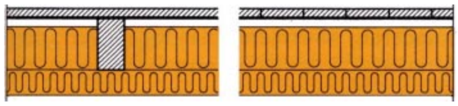
Construction 1.1 							
Construction details: 25 mm wooden planks 50 mm insulation (upper) Vapour retarder 200 mm light weight aggregate concrete 125 mm insulation (lower)	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Upper insulation layer	✓				✓	✓	✓
Lower insulation layer	✓						

Table 4.2 Use of insulation types for construction: "Planks on joists with insulation between joists". Figures from (SBI 1995)

Construction 1.2 							
Construction details: 25 mm wooden planks Vapour retarder 150 mm insulation (upper) 75 mm insulation (lower)	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Upper insulation layer	✓					✓	✓
Lower insulation layer	✓						

4.2 Slab on grade

The thermal transmission coefficient for slabs on grade must not exceed 0.2 W/m^2K according to the current building regulations. Such an U-value normally corresponds to 200 mm of insulation material, but as other materials with insulation properties are also found in normal slab on grade constructions, the thickness of traditional insulation materials is around 100-150 mm. The floor construction, which is the upper part of the deck, may be a carpet on a concrete slab or it may be wooden planks on joists. However, from the view of thermal and moisture performance, slab on grade constructions can be divided into two types; those with a concrete deck on top of the thermal insulation and those with a porous deck and a thick membrane to hinder transport of radon through the construction.

Construction 2.1 Wooden planks on joists, 50 mm insulation between joists, vapour retarder, 100 mm concrete, 75 mm structural insulation, 150 mm gravel as capillary break

Construction 2.2 Wooden planks on joists, 50 mm insulation between joists, vapour retarder, 100 mm light weight aggregate concrete, 150 mm loose fill coated light weight aggregate

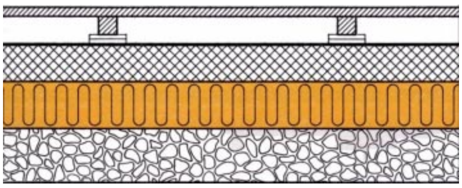
Construction 2.1 is modelled with structural mineral wool or EPS/XPS as the lower insulation layer. The upper insulation layer may be cellulose, flax, mineral wool, perlite (expanded stone material) or EPS/XPS. The Z-value of the vapour retarder should be at least 50 $GPasm^2/kg$ (DBI 2000)

Construction 2.2 is modelled with cellulose, flax, mineral wool, perlite (expanded stone material)

or EPS/XPS as the insulation between the joists. The Z-value of the vapour retarder should be at least 50 GPam^{2}s/kg (SBI 2000).
Several types of insulation materials are usable in both of these constructions. Table 4.3 and 4.4 give an overview of which types of insulation materials to be used in the constructions.

Table 4.3 Use of insulation types for construction: "Concrete slab and planks on joists". Figure from (SBI 1995)

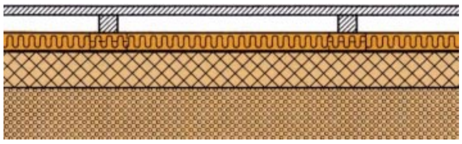
Construction 2.1



Construction details: 25 mm wooden planks 50 mm insulation (upper) Vapour retarder 100 mm concrete 75 mm structural insulation (lower) 150 mm gravel (capillary break)	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Upper insulation layer	✓	✓			✓	✓	✓
Lower insulation layer	✓	✓					

Table 4.4 Use of insulation types for construction: "Light weight aggregate concrete slab and planks on joists with insulation between joists". Figure from (SBI 1995)

Construction 2.2



Construction details: 25 mm wooden planks 50 mm insulation (upper) Vapour retarder 100 mm light weight aggregate concrete 150 mm loose fill coated light weight aggregate (lower)	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Upper insulation layer	✓	✓			✓	✓	✓
Lower insulation layer	✓	✓		✓			

4.3 Basement outer walls

The thermal transmission coefficient for basement outer walls must not exceed 0.3 W/m^2K according to the current building regulations. Generally this implies that some insulation material should be used. However, the amount of insulation material depends on what other materials that are used in the construction.

The thermal insulation may either be placed on the inside or the outside of the construction. If the insulation is placed on the outside, it is made with draining capabilities to drain soil water away from the basement wall.

Besides thermal insulation, the walls are normally made of either concrete or light weight aggregate concrete. The material layers (specified from outside and in) in basement outer walls are:

Construction 3.1	permeable membrane, 125 mm insulation with draining capabilities, 300 mm concrete
Construction 3.2	drainage layer, rendering, asphalt impregnation, 300 mm concrete, 75 mm insulation, 75 mm cellular concrete

Construction 3.1 is modelled with mineral wool or EPS as the insulation layer, both which should have drainage capabilities. The water permeable membrane is omitted from the model as its function is to keep the soil away from the drainage grooves.

In construction 3.2 mineral wool or EPS insulation may be used. as insulation material In the model, the rendering is omitted as its impact on the thermal and moisture conditions is very low.

Several types of insulation materials are usable in both of these constructions. Table 4.5 and 4.6 give an overview of which types of insulations materials to be used in the constructions.

Table 4.5 Use of insulation types for construction: “Basement concrete wall with exterior insulation”. Figure from (SBI 1995)

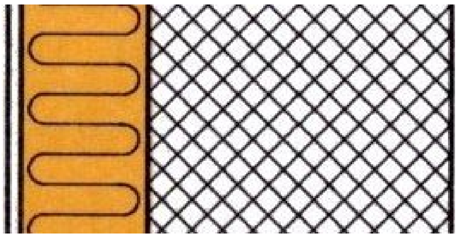
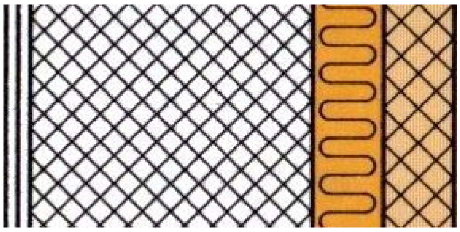
Construction 3.1							
Construction details: 125 mm insulation 300 mm concrete	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓	✓		✓			

Table 4.6 Use of insulation types for construction: “basement concrete wall with interior insulation”. Figure from (SBI 1995)

Construction 3.2							
Construction details: Drainage layer Asphalt impregnation 300 mm concrete 75 mm insulation 75 mm cellular concrete	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓	✓					

4.4 Solid outer walls with exterior insulation

The thermal transmission coefficient for outer walls must not exceed 0.2 W/m^{2}K or 0.3 W/m^{2}K depending on the average density of the wall construction. Aiming at a thermal transmission coefficient of 0.2 W/m^{2}K, the demand can be fulfilled by using approximately 200 mm of

insulation on the outside of the load bearing construction.
The solid outer wall can basically be constructed in two different ways, either with an outside rendering or with a ventilated air gap and cladding. Besides these variation, the wall types can be treated as almost similar from a hygro-thermal point of view.
A third variation is also examined here. This type of wall is made of a massive block of cellular concrete. In the outer wall made out of cellular concrete, no extra thermal insulation is used as the cellular concrete has sufficient thermal insulation properties if large thicknesses are used.

Construction 4.1	stucco, 200 mm structural insulation, 100 mm cellular concrete
Construction 4.2	cladding, ventilated air gap, wind tight vapour permeable layer, 200 mm insulation placed between wooden posts, 100 mm cellular concrete
Construction 4.3	500 mm massive cellular concrete

Construction 4.1 is modelled with mineral wool as the insulation layer.
If construction 4.2 is used, cellulose fibre, flax or mineral wool may be used as insulation material.
Several types of insulation materials are usable in both of these constructions. Table 4.7, 4.8 and 4.9 give an overview of which types of insulation materials to be used in the constructions.

Table 4.7 Use of insulation types for construction: “Solid wall with exterior insulation and stucco”. Figure from (SBI 1995)

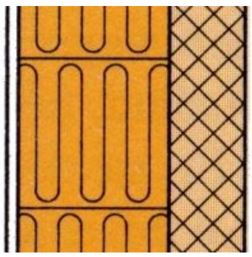
Construction 4.1 							
Construction details: 12 mm stucco 200 mm structural insulation 100 mm cellular concrete or light weight aggregate concrete	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓	✓					

Table 4.8 Use of insulation types for construction: “Solid wall with exterior insulation and cladding”. Figure from (SBI 1995)

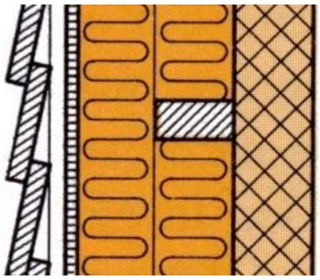
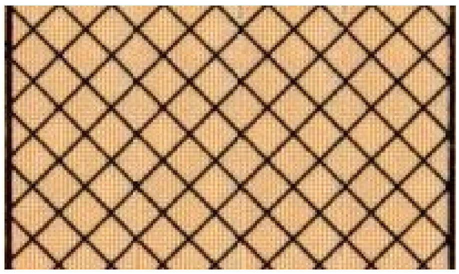
Construction 4.2 							
Construction details: Cladding Ventilated air gap Wind tight layer 200 mm insulation 100 mm cellular concrete or light weight aggregate concrete	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓					✓	✓

Table 4.9 Use of insulation types for construction: “Massive cellular concrete”

Construction 4.3 							
Construction details: 500 mm cellular concrete	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer			✓				

4.5 Solid outer walls with interior insulation

The thermal transmission coefficient for outer walls must not exceed 0.2 W/m^2K or 0.3 W/m^2K depending on the average density of the wall construction. Aiming at a thermal transmission

coefficient of 0.2 W/m^{2}K, the demand can be fulfilled by using approximately 200 mm of insulation on the inside of the load bearing construction.
The solid outer wall with interior insulation is constructed with an outside rain screen which may consist of a brick wall, wooden sheeting, metal profiles or corrugated cementitious sheeting. Behind the different types of cladding material, a ventilated air gap is established to facilitate removal of rain which may penetrate the rain screen. Due to the ventilated air gap, the influence from the rain screen on the thermal and moisture conditions in the insulation does not differ from one type of rain screen to the other. Instead, a difference between the different types of walls with interior insulation may be found in the location of the vapour retarder. In some designs, the vapour retarder is placed behind the inner gypsum layer and in other designs the vapour retarder is located inside the insulation layer.

Construction 5.1	brick wall, ventilated air gap, windtight layer, 200 mm insulation supported by wooden beams and posts, vapour retarder, inner sheet
Construction 5.2	brick wall, ventilated air gap, windtight layer, 150 mm insulation supported by beams and posts, vapour retarder, 50 mm insulation, inner sheet
Construction 5.3	brick wall,100 mm internal insulation, vapour retarder, inner sheet (does not fulfill thermal requirements, but is a typical example on retrofit of an existing construction)

Construction 5.1 is modelled with mineral wool, cellulose or flax as the insulation layer. The Z-value of the vapour retarder should be at least 10 GPa·s·m^2/kg. (DBI 2000)
Construction 5.2 and 5.3 are modelled with mineral wool.
Several types of insulation materials are usable in both of these constructions. Table 4.10, 4.11 and 4.12 give an overview of which types of insulation materials to be used in the constructions.

Table 4.10 Use of insulation types for construction: “Light weight wall with interior insulation and interior vapour retarder”. Figure from (SBI 1995)

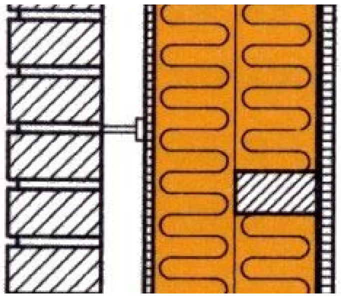
Construction 5.1 							
Construction details: 108 mm brick wall Ventilated air gap 200 mm insulation Vapour retarder 13 mm gypsum board	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Inner insulation layer	✓					✓	✓
Outer insulation layer	✓					✓	✓

Table 4.11 Use of insulation types for construction: “Light weight wall with interior insulation and vapour retarder embedded in insulation”. Figure from (SBI 1995)

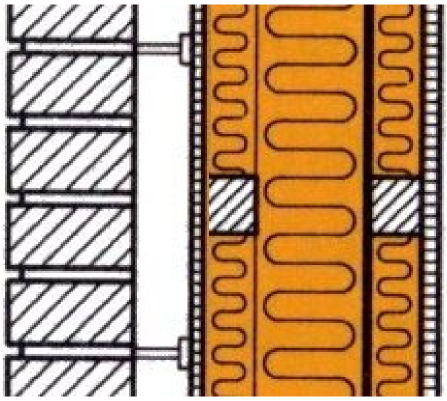
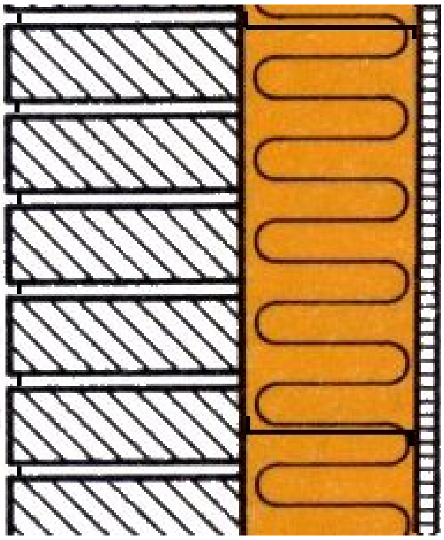
Construction 5.2 							
Construction details: 108 mm brick wall Ventilated air gap 150 mm insulation (outer) Vapour retarder 50 mm insulation (inner) 13 mm gypsum board	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Inner insulation layer	✓					✓	✓
Outer insulation layer	✓					✓	✓

Table 4.12 Use of insulation types for construction: “Brick wall with internal insulation”. Figure from (SBI 1995)

Construction 5.3



Construction details: 230 mm brick wall, 100 mm insulation, Vapour retarder, 13 mm gypsum board fastened by steel profiles	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓	✓					

4.6 Cavity walls

The thermal transmission coefficient for cavity walls must not exceed 0.3 W/m^{2}K according to the current building regulations. Generally this demand can be fulfilled if the cavity is filled with insulation and if the width of the cavity exceeds 125-200 mm depending on the thermal conductivity of the used insulation material.

The cavity wall is normally constructed with an outside leaf of brick and an inner leaf of brick, concrete, light weight concrete, or light weight aggregate concrete. Thermal insulation is placed between the inner and the outer leaf. To improve the structural properties of these types of constructions, wall ties are used to connect the two leafs.

The insulation used in these types of constructions may either be structural insulation or loose-filled insulation which fills either part or the whole of the cavity. All three designs are included in the description.

Construction 6.1 108 mm brick, 200 mm structural insulation, 108 mm brick

Construction 6.2 108 mm brick, 200 mm loose fill insulation, 108 mm brick

Construction 6.3 108 mm brick, ventilated air cavity, wind-tight layer, 200 mm loose fill insulation, 108 mm brick

Construction 6.1 is modelled with mineral wool as the insulation material.
In construction 6.2, mineral wool or perlite (expanded stone material) as loose fill is used as the insulation material. Organic insulation material may not be used here as water can be transported through the porous outer brick leaf.
If construction 6.3 is used, mineral wool, cellulose fibre or flax as loose fill may be used as insulation material.
Several types of insulation materials are usable in both of these constructions. Table 4.13, 4.1 and 4.15 give an overview of which types of insulation materials to be used in the constructions.

Table 4.13 Use of insulation types for construction: "Cavity wall insulated with structural insulation". Figure from (SBI 1995)

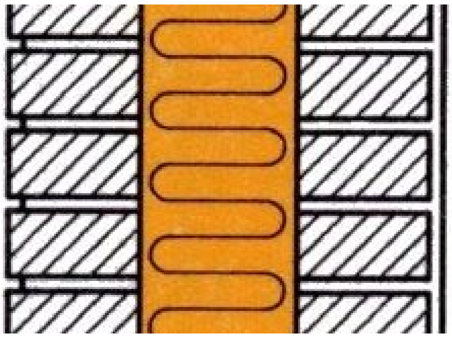
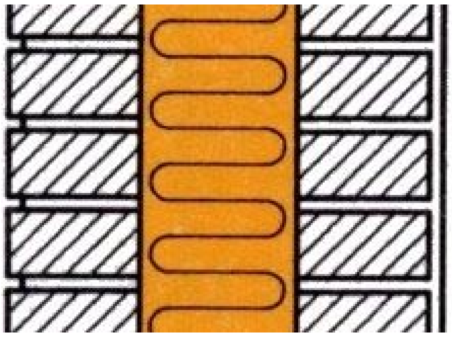
Construction 6.1 							
Construction details: 108 mm brick 200 mm structural insulation 108 mm brick wall	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓						

Table 4.14 Use of insulation types for construction: "Cavity wall insulated with loose-fill insulation material". Figure from (SBI 1995)

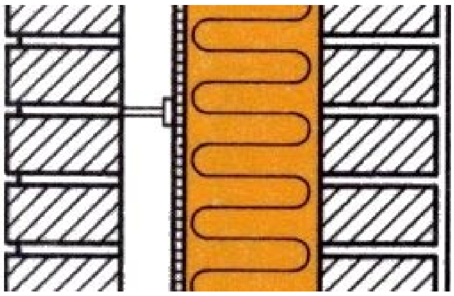
Construction 6.2



Construction details: 108 mm brick 200 mm loose-fill insulation 108 mm brick wall	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓				✓		

Table 4.15 Use of insulation types for construction: "Cavity wall with loose-fill insulation material (partly filled)". Figure from (SBI 1995)

Construction 6.3



Construction details: 108 mm brick Ventilated air gap Wind-tight layer 200 mm loose-fill insulation 108 mm brick wall	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓					✓	✓

4.7 Light-weight outer walls

The thermal transmission coefficient for light-wight outer walls must not exceed 0.2 W/m^{2}K according to the current building regulations. Generally, this implies that the total thickness of insulation material should be around 200 mm if the thermal conductivity of the insulation material is 0.039 W/mK.

Light-weight outer walls may either be constructed using wooden beams and posts or steel profiles as the load-bearing construction with thermal insulation in-between.

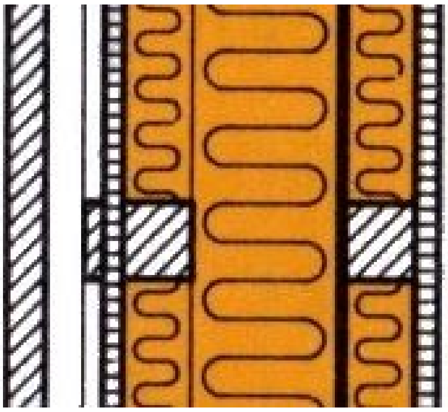
The insulation used in these types of constructions is applied in batts or as loose-fill material. When batts are used, the insulation may be protected from the exterior climate by a light-weight rain screen or a brick veneer both with a ventilated air gap between the rain screen and the insulation.

Construction 7.1	light-weight rain screen, ventilated air gap, wind tight layer, 150 mm insulation, vapour retarder (Z=10 GPa·m^{2}s/kg), 50 mm insulation, inner gypsum sheeting,
Construction 7.2	light-weight rain screen, ventilated air gap, wind tight layer, 150 mm insulation, vapour barrier (Z=125 GPa·m^{2}s/kg), 50 mm insulation, inner gypsum sheeting

Construction 7.1 is modelled with mineral wool, cellulose fibre or flax as the insulation material.
Construction 7.2 is modelled with mineral wool as the insulation material.
Several types of insulation materials are usable in some of these construction. Table 4.16 and 4.17 give an overview of which types of insulation materials to be used in the constructions.

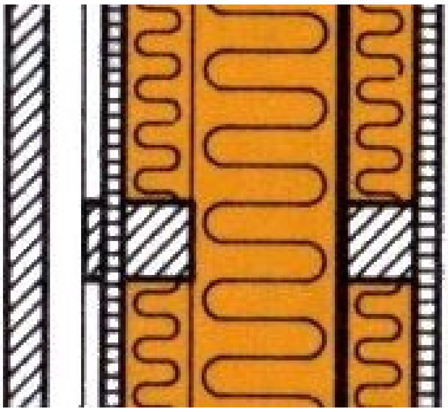
Table 4.16 Use of insulation types for construction: "Light weight wall with vapour retarder and a light weight rain screen"

Construction 7.1



Construction details: Cladding Ventilated air gap 150 mm insulation Vapour retarder (Z=10 GPa·m²s/kg) 50 mm insulation 2 x 13 mm gypsum	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓					✓	✓

Table 4.17 Use of insulation types for construction: “Light weight wall with vapour barrier and a light weight rain screen”

Construction 7.2 							
Construction details: Cladding Ventilated air gap 150 mm insulation Vapour barrier (Z=125 GPa·m²s/kg) 50 mm insulation 2 x 13 mm gypsum	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓						

4.8 Concrete sandwich elements

The thermal transmission coefficient for concrete sandwich elements must not exceed 0.3 W/m^2K, a demand that can be fulfilled using 200 mm of insulation.

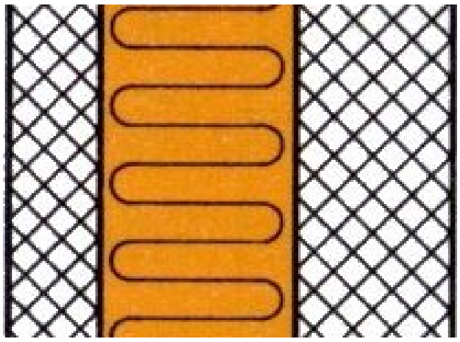
In concrete sandwich elements, insulation is placed between two concrete layers. At the edge of the elements, this insulation thickness is somewhat lower. However, here only the middle part of the sandwich element utilizing the full insulation thickness is included here.

Construction 8.1 70 mm concrete, 200 mm insulation, 80 mm concrete

Two types of insulation are used in the concrete sandwich elements, mineral wool or EPS. This is shown in Table 4.18.

Table 4.18 Use of insulation types for construction: "Concrete sandwich element"

Construction 8.1



Construction details: 70 mm concrete 200 mm insulation 80 mm concrete	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓	✓					

4.9 Unventilated roof

The thermal transmission coefficient for unventilated (flat or sloped) roofs must not exceed 0.20 W/m^{2}K according to the current building regulations. This can generally be fulfilled using insulation with an average thickness of 200 mm.

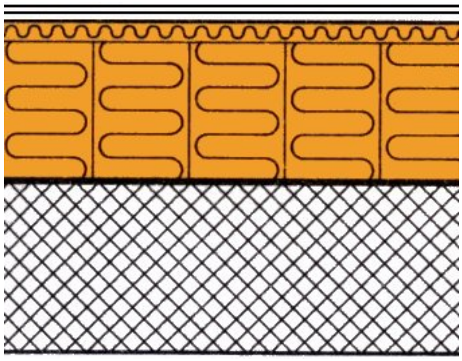
The unventilated roof is normally constructed with a load bearing deck, a vapour retarder, an insulation layer and a roofing membrane. Structural insulation is used on unventilated roofs as it should be able to withstand physical loads without deformation.

Construction 9.1 roofing membrane, 200 mm insulation, vapour retarder, 200 mm concrete deck

Construction 9.1 is modelled with either mineral wool or a combination of EPS and mineral wool as insulation material. The combination of EPS and mineral wool is a standard solution to avoid the risk of fire both during application of the roofing membrane and during use.

Table 4.19 provide an overview of the different types of insulation materials which are used in the construction.

Table 4.19 Use of insulation types for construction: “Unventilated roof”

Construction 9.1 							
Construction details: 8 mm modified bitumen 200 mm insulation Vapour retarder 200 mm concrete	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Insulation layer	✓	✓					

4.10 Ventilated roof

The thermal transmission coefficient for roofs must not exceed 0.15 W/m^{2}K unless when so-called parallel roofs are considered. In this case the thermal transmission coefficient must not exceed 0.20 W/m^{2}K. The demand is generally fulfilled if 200 mm or more of insulation is applied in the constructions.

A ventilated roof may either be sloped or low-sloped.

A low-sloped ventilated roof is typically constructed with wooden trusses and the insulation placed between the trusses. A vapour retarder is placed below the insulation or placed up to one third into the insulation layer, and above the insulation layer a ventilated air gap is constructed. The roof is sealed off with a roofing membrane on a wooden deck.

In a sloped roof construction the insulation is also placed between trusses. A vapour retarder is placed in the insulation layer, at the warm side normally one-fourth into the layer. Above the insulation layer, a 75 mm ventilated air gap is constructed and the roof is sealed of with e.g. roofing tiles.

Construction 10.1	roofing membrane, wooden deck, 95 mm ventilated air gap, 150 mm insulation, vapour retarder (Z=50 GPa·m^{2}s/kg), 50 mm insulation, ceiling
Construction 10.2	roofing tiles, 75 mm ventilated air gap,150 mm insulation, vapour retarder(Z=10 GPam^{2}s/kg if organic insulation materials are used Z=50 GPa·m^{2}s/kg if mineral wool is used), 50 mm insulation, ceiling

Construction 10.1 or 10.2 is modelled with mineral wool, cellulose fibre or flax as insulation material. The Z-value of the vapour retarder should be at least 10 GPa·m^{2}s/kg if organic insulation materials are used, otherwise at least 50 Gpa·m^{2}s/kg (SBI 1995). Construction 10.1 and 10.2 may also be insulated with perlite (expanded stone material). For construction 10.1 the lowest insulation should be mineral wool according to (DBI 2000).
Several types of insulation materials are usable in both of these constructions. Table 4.20 and 2.21 give an overview of which types of insulation materials to be used in the constructions.

Table 4.20 Use of insulation types for construction: "Low-sloped ventilated roof"

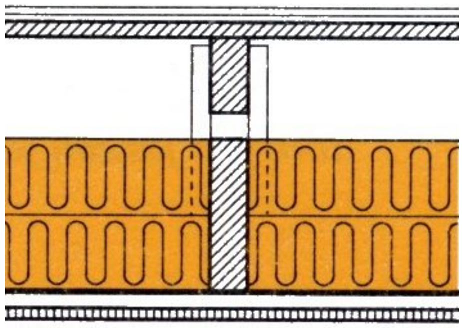
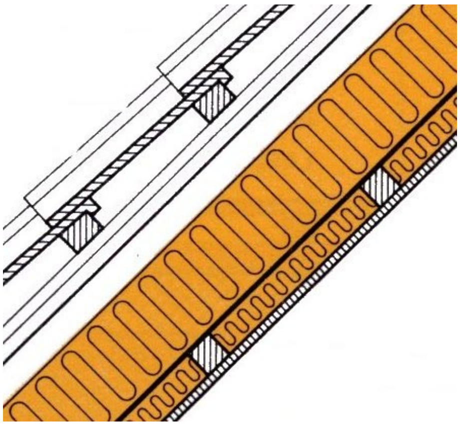
Construction 10.1							
Construction details: 8 mm modified bitumen Wooden deck 95 mm ventilated air gap 150 mm insulation (upper) Vapour retarder Z= 10 or 50 GPa·m^{2}s/kg 50 mm insulation (lower) 2 x 13 mm gypsum	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose fibre	Flax
Lower insulation layer	✓				✓		
Upper insulation layer	✓				✓	✓	✓

Table 4.21 Use of insulation types for construction: "45° Sloped ventilated roof"

Construction 10.2



Construction details: Roofing tiles Diffusion tight underroof 75 mm ventilated air gap 150 mm insulation (upper) Vapour retarder Z=10 or 50 GPa·m²s/kg 50 mm insulation (lower) 2 x 13 mm gypsum	Mineral wool	EPS and XPS	Light weight concrete	Light weight aggregate	Expanded stone material	Cellulose	Flax
Lower insulation layer	✓					✓	✓
Upper insulation layer	✓					✓	✓

5. MATERIAL PROPERTIES

As seen in the previous chapter, calculation of moisture conditions and design value of the thermal conductivity should be performed for a number of insulation materials. Besides construction of models which represent the different building envelope constructions it is also necessary to determine the moisture related material properties for each of the insulation materials which are found in the constructions shown in the previous chapter.

The following insulation materials are found in the constructions of the previous chapter:

Mineral wool
Expanded Polystyrene
Light weight concrete
Light weight aggregate concrete
Perlite (expanded stone material)
Cellulose fibre
Flax

For each of the materials, a number of material properties of importance in this context, are reported here. These material properties include:
Density
Sorption isotherm
Capillary suction
Vapour permeability
Moisture conversion coefficient (mass-by-mass or volume-by-volume).

Properties of the different materials are organized in Table 5.1 and Figure 5.1. Some important comments regarding the use of some of the material parameters are given afterwards.

Table 5.1 Density, vapour permeability, moisture conversion coefficient, moisture content at reference conditions and thermal conductivity for investigated insulation materials. [(1)] material library supplied with calculation tool (Pedersen 1990), [(2)] (Hansen et al. 1999), [(3)] (EN 12524 2000), [(4)] (FIW 2000)

Material	Density [kg/m^3]	Vapour permeability [kg/m·s·Pa]·10^{-12}	Moisture conversion coefficient	MC at 23°C, 50% RH	Thermal conductivity [W/mK]
Mineral wool	30 [(1)]	157 [(1)]	4 m^3/m^3 [(3)]	0 kg/kg [(3)]	0.039
Mineral wool (structural)	170 [(1)]	113 [(1)]	4 m^3/m^3 [(3)]	0 kg/kg [(3)]	0.039
Expanded polystyrene	20 [(1)]	5 [(1)]	4 m^3/m^3 [(3)]	0 kg/kg [(3)]	0.039
Light weight concrete	625 [(1)]	30 [(1)]	4 kg/kg [(3)]	0.026 kg/kg [(3)]	0.17
Light weight aggregate con-crete	170 [(1)]	66 [(1)]	4 kg/kg [(3)]	0 kg/kg [(3)]	0.075
Perlite	85 [(2)]	100 [(2)]	3 kg/kg [(3)]	0.01 kg/kg [(3)]	0.039
Cellulose fibre	40 [(2)]	200 [(2)]	0.5 kg/kg [(3)]	0.11 kg/kg [(3)]	0.039
Flax	30 [(2)]	150 [(2)]	0.5 kg/kg [(4)]	0.06 kg/kg [(4)]	0.039

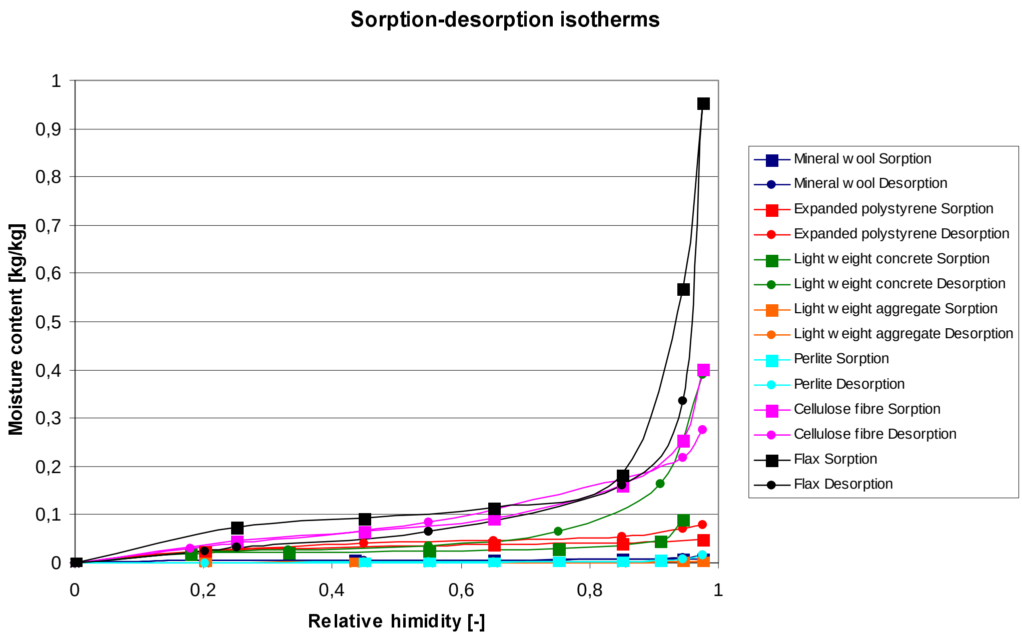


Figure 5.1 Sorption and desorption isotherms for investigated materials. Values for mineral wool, expanded polystyrene, light weight concrete and light weight aggregate concrete are reported in the material library supplied with the calculation tool (Pedersen 1990). Values for perlite, cellulose fibre and flax are from Hansen et al (1999).

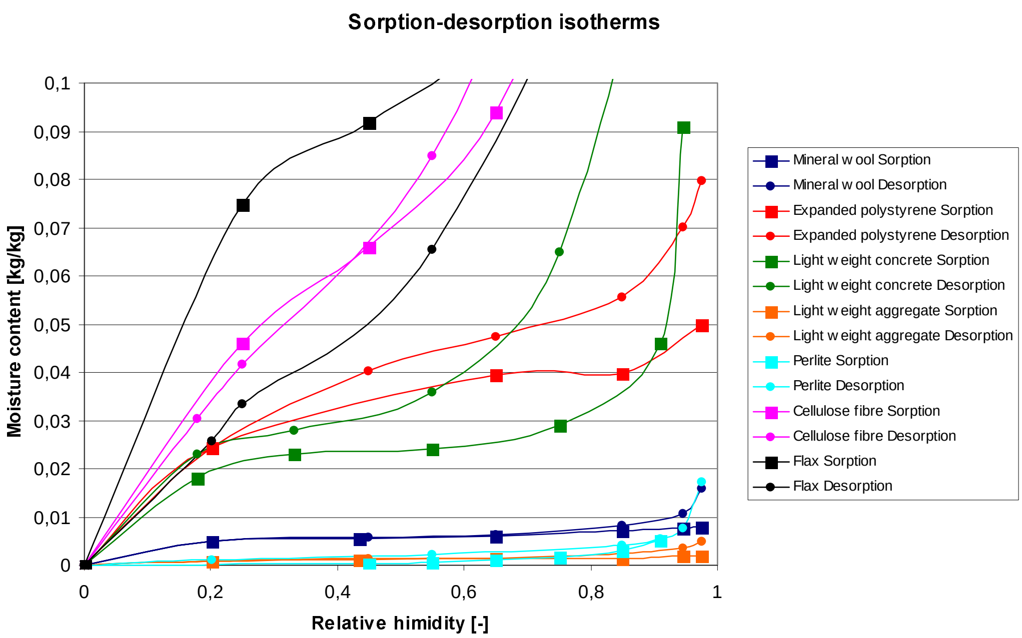


Figure 5.2 Extract of Figure 5.1 giving a better view of the region containing the lower values of moisture content. References for material data are equal to Figure 5.1.

The influence of choosing different values of the moisture content at reference conditions (23 °C, 50% RH) will be examined in Chapter 7 following the results of the calculations.

6. CONSTRUCTION OF MODELS FOR CALCULATING MOISTURE CONDITIONS

Models are simplified representations of reality, in this case of building constructions and boundary conditions. During construction of the models, simplifications of construction and/or boundary conditions are performed. The simplifications differ from construction to construction, and there may therefore be a need for an overview showing the simplifications of the different models, i.e. computerized representations of the different physical constructions. Such an overview is provided in the following.

1. Most multi-dimensional effects are omitted from all the models, with the only exception being the heat, air and moisture flow in the ventilated claddings of some of the constructions. The reason for this simplification is that the heat and moisture transfer model (Rode 1990) is only usable for solving one-dimensional problems. An exception has been made in the case of ventilated cladding which is modelled using an add-on to the model. This aspect is treated in issue no. 5 of this overview.
2. Slab on grade models are made with inclusion of the boundary conditions from the ground. The ground is modelled as having a constant temperature of 10°C and a constant relative humidity of 100%. Free water in the soil volume is omitted from the models for construction 2.1 (Concrete slabs and planks on joists) as the gravel layer acts as a capillary barrier which hinder the existence of a liquid water volume just below the lower insulation layer.

   In the models representing construction 2.2 (Light weight aggregate concrete slab and planks on joists with insulation between joists), a layer acting as a capillary barrier is not found, except the insulation layer which acts as a capillary barrier. It is therefore necessary to include the effect of liquid water from the soil volume below the construction. In these models, the soil is modelled as having a constant relative humidity of 100%.

   As the moisture level at the interior surface cannot be expressed relative to the exterior climate (the soil volume) as it was mentioned in section 3.1, another indoor reference climate is specified. The indoor temperature is kept at 23°C during summer and 21°C during winter. The indoor relative humidity is given as monthly values and has the following values in the period from January to December: 42%, 40%, 43%, 51%, 56%, 56%, 59%, 62%, 66%, 61%, 52% and 46%.
3. Models representing the basement outer walls are made with the inclusion of boundary conditions from the ground. The ground is modelled as having a constant temperature of 10°C and having a constant relative humidity of 95%. Free water is omitted from the soil volume as the two types of basement outer wall constructions have sufficient water drainage capabilities. The indoor climate is kept at a temperature between 21°C (winter) and 23°C (summer) and a relative humidity of 40%.

   If higher moisture levels are specified for the indoor climate, the result is a high internal partial vapour pressure compared to the external conditions. The partial vapour pressure will initiate a transport of water vapour through the construction. The end result of a calculation where a high partial vapour pressure is maintained at the interior surface is that the insulation will be totally water saturated. It must therefore be stressed that the results which are obtained by using the model are very sensitive to changes in the boundary conditions. If a continuous partial vapour pressure difference exists across the construction, the inevitable result is a water saturated construction. This small continuous partial vapour pressure difference requires just a small increase above the 40% relative humidity for the internal boundary conditions (both summer and winter).

4. Models which represent either of the wall constructions, i.e. solid outer walls with exterior or interior insulation, cavity walls, light-weight outer walls or concrete sandwich elements are made to include the effect of driving rain on the moisture performance. Data describing driving rain is made on basis of measured data from Danish Meteorological Institute from 1991. The data is reported by Kragh (1998). Transformation of free rain, which is reported in the measured data, into driving rain requires detailed information regarding the topography of the surrounding landscape, design of the buildings and many other factors. An amount of driving rain which is on the safe side (more than what may actually be measured and therefore usable in a design situation) is obtained by multiplying the amount of free rain by 0.5. The driving rain is added to the outermost material layer in the construction.
5. Models which represent wall constructions with a ventilated air gap are made to include the effect of the gap. Description of the parameters needed to include the effect of a ventilated air gap in a model is described in an add-on to the documentation for the heat and moisture calculation tool by Pedersen (1990).
6. Models which represent ventilated roof constructions are made to include the effect of a ventilated air gap in the construction. Description of the parameters to include the effect of the ventilated air gap is found in the literature according to item 5 of this overview.
7. The initial moisture conditions in the models of the unventilated low slope roofing constructions are made to be in equilibrium with air having a relative humidity of 85%. The initial moisture content is very important for this type of construction as the insulation, and the moisture if present, is placed between two water- and vapour-tight membranes making it almost impossible for the moisture to escape once it has entered the construction.

   It must therefore be stressed that the results of the later calculations are only valid for constructions with the same moisture content. Having a higher initial moisture content will result in a high moisture content throughout the life of the construction with a very high thermal conductivity. Assessment of the level of moisture intrusion and the effect on the thermal performance is outside the scope of this investigation.

7. CALCULATION RESULTS

Based on the descriptions of the constructions (Chapter 4), the material data (Chapter 5) and a combination of the modelling techniques and boundary conditions (Chapter 4 and 6), the calculations of the design value of the thermal conductivity for insulation materials under climatic specific conditions is performed.

Results are reported for different insulation materials in the different constructions. The results are given both as absolute values of the design value of the thermal conductivity and as value relative to the declared value.

The results are shown in Table 7.1, 7.2 and 7.3 on the following pages. The results are given in a spreadsheet with the following information.

Construction	Number linked to the construction according to the list in Chapter 4
Description	A short description presenting the type of construction
Insulation material	Type of insulation material
F_m	Moisture conversion factor as defined in EN ISO 10456 (1999). The design value of the thermal conductivity (taking into account moisture) is the moisture conversion factor multiplied with the declared value
%	Percent difference between declared and design value. A positive value is stated when the design value is higher than the declared.
Secondary insulation	In case there is more than one insulation material in the construction, the type of insulation material is given

Table 7.1 Moisture conversion factor and increase in thermal conductivity for insulation materials

Construction	Description	Insulation material	F_m	%	Secondary insulation	F_m	%
1.1	Light weight aggregate concrete deck above crawl space	Mineral wool	1.0007	0.1	Mineral wool	1.0007	0.1
		Perlite (expanded stone material)	0.9749	-2.5	Mineral wool	1.0007	0.1
		Cellulose fibre	0.9854	-1.5	Mineral wool	1.0007	0.1
		Flax	1.0033	0.3	Mineral wool	1.0007	0.1
1.2	Insulation between joists above crawl space	Mineral wool	1.0007	0.1	Mineral wool	1.0007	0.1
		Cellulose fibre	0.9764	-2.4	Mineral wool	1.0007	0.1
		Flax	0.9954	-0.5	Mineral wool	1.0007	0.1
2.1	Concrete slab on grade	Mineral wool	1.0007	0.1	Mineral wool (structural)	1.0049	0.5
		Expanded Polystyrene	1.0033	0.3	Mineral wool (structural)	1.0049	0.5
		Perlite (expanded stone material)	0.9766	-2.3	Mineral wool (structural)	1.0049	0.5
		Cellulose fibre	0.9956	-0.4	Mineral wool (structural)	1.0049	0.5
		Flax	1.0134	1.3	Mineral wool (structural)	1.0049	0.5
		Mineral wool	1.0008	0.1	Expanded Polystyrene	1.0041	0.4
		Expanded Polystyrene	1.0033	0.3	Expanded Polystyrene	1.0041	0.4
		Perlite (expanded stone material)	0.9763	-2.4	Expanded Polystyrene	1.0041	0.4
		Cellulose fibre	0.9945	-0.5	Expanded Polystyrene	1.0041	0.4
		Flax	1.0123	1.2	Expanded Polystyrene	1.0041	0.4
2.2	Light weight aggregate concrete slab on grade	Mineral wool	1.0007	0.1	Light weight aggregate	1.0014	0.1
		Expanded Polystyrene	1.0033	0.3	Light weight aggregate	1.0014	0.1
		Perlite (expanded stone material)	0.9761	-2.4	Light weight aggregate	1.0014	0.1
		Cellulose fibre	0.9940	-0.6	Light weight aggregate	1.0014	0.1
		Flax	1.0121	1.2	Light weight aggregate	1.0014	0.1
3.1	Basement wall w. ext. insulation	Mineral wool (structural)	1.0046	0.5			
		Expanded Polystyrene	1.004	0.4			
3.2	Basement wall w. int. insulation	Mineral wool (structural)	1.0043	0.4			
		Expanded Polystyrene	1.0036	0.4			

Table 7.2 Moisture conversion factor and increase in thermal conductivity for insulation materials

Construction	Description	Insulation material	F_m	%	Secondary insulation	F_m	%
4.1	External insulation with stucco	Mineral wool (structural)	1.0043	0.4			
4.2	External wall insulation with cladding	Mineral wool	1.0007	0.1			
		Cellulose fibre	0.9909	-0.9			
		Flax	1.0113	1.1			
4.3	Massive cellular concrete wall	Cellular concrete	1.0862	8.6			
5.1	Internal insulation with interior vapour retarder	Mineral wool	1.0007	0.1			
		Cellulose fibre	0.9860	-1.4			
		Flax	1.0058	0.6			
5.2	Internal insulated wall with embedded vapour retarder	Mineral wool	1.0007	0.1			
		Cellulose fibre	0.9889	-1.1			
		Flax	1.0089	0.9			
5.3	Wall with Internal insulation	Mineral wool	1.0007	0.1			
6.1	Cavity wall with HD insulation	Mineral wool (structural)	1.0053	0.5			
6.2	Cavity wall with loose-fill-insulation	Mineral wool (structural)	1.0019	0.2			
		Perlite (expanded stone material)	0.9844	-1.6			
6.3	Cavity wall with partly filled loose-fill insulation	Mineral wool	1.0007	0.1			
		Cellulose fibre	0.9889	-1.1			
		Flax	1.0093	0.9			
7.1	Light weight wall with vapour retarder and light rain screen	Mineral wool	1.0007	0.1			
		Cellulose fibre	0.9889	-1.1			
		Flax	1.0084	0.8			
7.2	As 7.1 with vapour barrier	Mineral wool	1.0007	0.1			
8.1	Concrete sandwich element	Mineral wool	1.0017	0.2			
		Expanded Polystyrene	1.0034	0.3			

Table 7.3 Moisture conversion factor and increase in thermal conductivity for insulation materials

Construction	Description	Insulation material	F_m	%	Secondary insulation	F_m	%
9.1	Unventilated roof	Mineral wool (structural)	1.0077	0.8			
		Expanded Polystyrene	1.0032	0.3			
10.1	Ventilated low-slope roof	Mineral wool	1.0009	0.1			
		Perlite (expanded stone material)	0.9756	-2.4			
		Cellulose fibre	0.9926	-0.7			
		Flax	1.0120	1.2			
10.2	Ventilated sloped roof	Mineral wool	1.0007	0.1			
		Cellulose fibre	0.9769	-2.3			
		Flax	0.9955	-0.5			

As seen from Table 7.1 to 7.3, the effect of moisture levels above standard conditions (23°C, 50% RH) is a change in thermal conductivity between -2.5% and +8.6%. The negative correction, i.e. where the moisture content of the insulation is lower than that of the reference conditions, is mainly found for perlite (expanded stone material) and most constructions with cellulose fibre insulation. The positive corrections are generally found for the massive cellular concrete wall and, with smaller corrections, for mineral wool, polystyrene and flax insulation.

7.1 Effect of moisture content at reference conditions

The change in thermal conductivity depends on the moisture content of the insulation materials at reference conditions (23°C and 50% relative humidity). In the literature it is possible to find several different values for the moisture content at reference climatic conditions for the same type of insulation material. As this moisture content has a large influence on the results of the calculations, it was decided to search for alternative values reported in the literature. Two materials were of special interest here, namely insulation materials based on cellulose fibre or flax.

The search for literature resulted in the following values for the moisture content at reference climatic conditions.

Cellulose fibre insulation	**Flax**
0.110 kg/kg is reported by EN 12524 (2000)	0.060 kg/kg is reported by FIW (2000)
0.075 kg/kg is reported by Hansen et al (1999)	0.080 kg/kg is reported by Hansen et al (1999)

The results of the search for literature show that large differences exist for the moisture content of cellulose insulation. The raw data which lies behind the value that is reported in EN 12524 (2000) is not referenced and it is therefore not possible to make a scientific comparison of the two sets of raw data. However, as the measurements which are reported by Hansen et al (1999) is made on materials that are available and sold in Denmark, a series of calculations are also made for this set of data.

The values of moisture content at reference conditions, which have been reported by Hansen et al (1999) corresponds to the sorption isotherm which is used by the calculation tool during the modelling of heat and moisture transfer. The sorption isotherm for cellulose fibre is shown in Figure 7.1. Figure 7.1 also shows the moisture content at reference climatic conditions for cellulose fibre as specified by EN 12524 (2000).

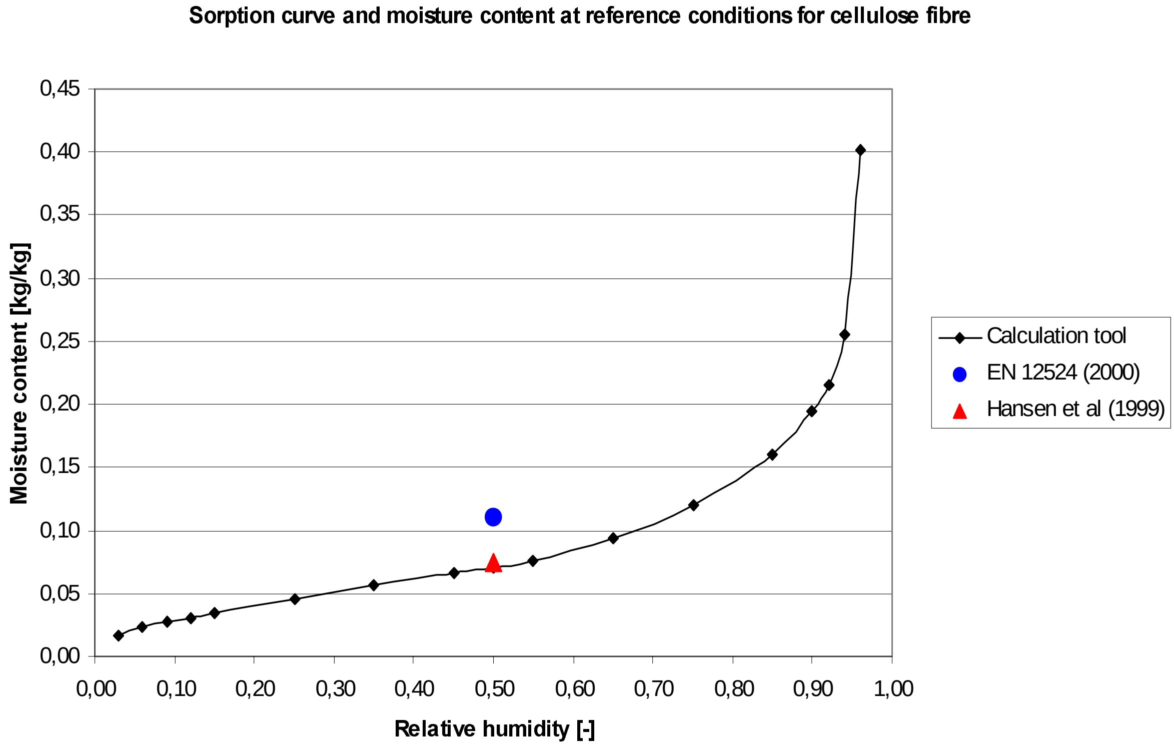


Figure 7.1 Sorption curve and moisture content at reference climatic conditions for cellulose fibre

Figure 7.1 shows that the sorption curve which is used by the calculation tool lies significantly lower than the moisture content under reference climatic conditions which is reported in EN 12524 (2000). However, for other materials the situation might be the opposite with the value from EN 12524 (2000) falling below the values of the sorption isotherm used in the calculation tool. This situation is not shown in Figure 7.1.

An almost similar situation is seen when examining the results from the models containing perlite as insulation materials. In EN 12524 (2000), perlite has a moisture content at reference conditions of 0.01 kg/kg. However, the sorption curve which is used in the calculation tool shows perlite to have a moisture content of below 0.001 kg/kg. This difference is the cause of the negative corrections for perlite that are presented in Tables 7.1 to 7.3.

The results of the extra calculations are reported in Table 7.4, 7.5 and 7.6. Only values that have been changed compared to the results in Table 7.1 to 7.3 are presented in Tables 7.4 to 7.6.

Table 7.4 Moisture conversion factor and increase in thermal conductivity using material data provided by Hansen et al (1999)

Construction	Description	Insulation material	F_m	%	Secondary insulation	F_m	%
1.1	Light weight aggregate concrete deck above crawl space	Cellulose fibre	1.0028	0.3	Mineral wool	1.0007	0.1
		Flax	0.9933	-0.7	Mineral wool	1.0007	0.1
1.2	Insulation between joists above crawl space	Cellulose fibre	0.9937	-0.6	Mineral wool	1.0007	0.1
		Flax	0.9855	-1.5	Mineral wool	1.0007	0.1
2.1	Concrete slab on grade	Cellulose fibre	1.0132	1.3	Mineral wool (structural)	1.0049	0.5
		Flax	1.0033	0.3	Mineral wool (structural)	1.0049	0.5
		Cellulose fibre	1.0121	1.2	Expanded Polystyrene	1.0041	0.4
		Flax	1.0022	0.2	Expanded Polystyrene	1.0041	0.4
2.2	Light weight aggregate concrete slab on grade	Cellulose fibre	1.0116	1.2	Light weight aggregate	1.0014	0.1
		Flax	1.0020	0.2	Light weight aggregate	1.0014	0.1

Table 7.5 Moisture conversion factor and increase in thermal conductivity using material data provided by Hansen et al (1999)

Construction	Description	Insulation material	F_m	%	Secondary insulation	F_m	%
4.2	External wall insulation with cladding	Cellulose fibre	1.0084	0.9			
		Flax	1.0012	0.1			
5.1	Internal insulation with interior vapour retarder	Cellulose fibre	1.0034	0.3			
		Flax	0.9958	-0.4			
5.2	Internal insulated wall with embedded vapour retarder	Cellulose fibre	1.0064	0.6			
		Flax	0.9988	-0.1			
6.3	Cavity wall with partly filled loose-fill insulation	Cellulose fibre	1.0064	0.6			
		Flax	0.9993	-0.1			
7.1	Light weight wall with vapour retarder and light rain screen	Cellulose fibre	1.0063	0.6			
		Flax	0.9984	-0.2			

Table 7.6 Moisture conversion factor and increase in thermal conductivity using material data provided by Hansen et al (1999)

Construction	Description	Insulation material	F_m	%	Secondary insulation	F_m	%
10.1	Ventilated low-slope roof	Cellulose fibre	1.0101	1.0			
		Flax	1.0020	0.2			
10.2	Ventilated sloped roof	Cellulose fibre	0.9942	-0.6			
		Flax	0.9860	-1.4			

Comparing the results reported in Tables 7.1 to 7.3 with the results in Tables 7.4 to 7.6, it is seen that there are differences between the reported values for constructions using cellulose fibre or flax as insulation material. These differences exist because of changes in the moisture content under reference climatic conditions (23°C, 50% RH).

Besides the investigation of the influence of the moisture content at reference conditions, other parameters are also to be examined. To see if there is an effect of changing some of the parameters in the models, a variation of parameters and a sensitivity analysis is performed. The sensitivity analysis and variation of parameters is performed for the following parameters.

- Internal boundary conditions
- External boundary conditions
- Sorption isotherm

The sensitivity analysis and variation of parameters is performed for construction 6.3 “Cavity wall with partly filled loose-fill insulation” with cellulose fibre insulation using a declared value of the thermal conductivity of 0.039 W/mK.

7.2 Internal boundary conditions

Besides the model which is already constructed, two more models are made. In the first model the internal moisture addition (compared to the external climate) is lowered by 2 g/m^3 compared to the reference situation, i.e. that the moisture addition varies between 0 g/m^3 and 1 g/m^3 during the year. No other parameters of the model is changed. In the second model the internal moisture addition is increased by 2 g/m^3 compared to the reference situation i.e. the moisture addition varies between 4 g/m^3 and 5 g/m^3. The low moisture addition may be found in storage facilities etc., the average moisture addition may be found in homes and the high moisture addition may be found in some industrial buildings and swimming baths.
The following design values of the thermal conductivity is obtained:

Design value for insulation using model with low moisture addition	0.03851 W/mK
Design value of insulation using model with average moisture addition	0.03857 W/mK
Design value of insulation using model with high moisture addition	0.03862 W/mK

From the design values it can be seen that the effect of the indoor climate on the thermal performance using the given variation of moisture addition result in a change of the thermal conductivity of approximately ±0.14%.

7.3 External boundary conditions

To examine the effect of the external climate two more models are made, one without the effect of driving rain and one model where the intensity of driving rain is doubled, i.e. the amount of driving rain corresponds to the amount of free falling rain.

The following design values of the thermal conductivity is obtained:

Design value for insulation using model with no driving rain	0.038552 W/mK
Design value of insulation using model with average driving rain	0.038568 W/mK
Design value of insulation using model with high driving rain	0.038571 W/mK

From the design values it can be seen that there is an effect of the driving rain on the thermal performance of the insulation material. Still, the effect is small (±0.04%) compared to e.g. the effect of the indoor climate on the thermal performance.

7.4 Sorption isotherm

The influence of the sorption isotherm on the results of the calculations is examined by varying the relationship between the relative humidity and the resulting moisture content of the insulation material.

One calculation is performed using the sorption isotherm with the values shown in Table 5.6. To see the influence of changing the sorption isotherm, the moisture content was first decreased 10% below and later increased 10% above the reference values. The two new sorption isotherms are referenced to as "low sorption isotherm" and "high isotherm".

The following design values of the thermal conductivity is obtained:

Design value for insulation using model with low sorption isotherm	0.038398 W/mK
Design value of insulation using model with average sorption isotherm	0.038568 W/mK
Design value of insulation using model with high sorption isotherm	0.038741 W/mK

The results of the calculations show that a change in the sorption isotherm have a small influence on the thermal conductivity of the insulation material. In this instance, where the values of the sorption isotherm is decreased or increased by 10%, the change in thermal conductivity for the insulation material is ±0.44%.

7.5 Evaluation of results

The results in Table 7.1, 7.2 and 7.3 show that moisture conditions have an influence on the thermal conductivity of insulation materials, in some instances the design value of the thermal conductivity is lower than the declared value and in some instances the design value is higher than the declared value.

Under the defined standard conditions, differences between the declared value and the design value is mostly found for insulation based on perlite (expanded stone material), cellulose and flax. The moisture levels which are found in the insulation materials changes the thermal conductivity by up to 2.5% under specified climatic conditions and material properties.

Although exact results are given for each insulation material in each construction, the thermal conductivity may change if other climatic conditions and material properties are considered. A sensitivity analysis for specific cases shows that the changes in thermal conductivity because of changes in climatic conditions and material properties may amount to:

Indoor boundary conditions:	± 0.14%
Outdoor boundary conditions:	± 0.04%
Material properties:	± 0.44%

These values should be compared with the changes in thermal conductivity just because of the inclusion of moisture in the calculations. As the thermal conductivity of insulation material may be changed by between -2.5% and +8.6% when standard climatic conditions and material properties are used, the above mentioned changes due to uncertainty regarding climate and material properties may seem large. However, of the three aspects, only the first two have to be addressed by a designer. The last of the three aspects should be minimized by performing series of measurements on samples of the different materials.

If only the first two aspects are considered, the uncertainty seems relatively small compared with the changes in thermal conductivity according to Table 7.1, 7.2 and 7.3.

8. CONCLUSION

A method has been developed that makes it possible to estimate both the moisture conversion factor and the design values of the thermal conductivity for a number of insulation materials - including both traditional and so-called alternative products. The method is based on information about the composition of the building envelope constructions and prescribed data regarding material properties and boundary conditions.
Determination of the moisture conversion factor and the design value of the thermal conductivity are performed according to EN ISO 10456. A heat and moisture calculation model is used to calculate the moisture conditions used as input for the method in EN ISO 10456. The moisture conditions in the insulation materials in typical Danish constructions coupled with EN ISO 10456 gives the thermal conductivity of the insulation materials where an average, weighed with the energy used for heating throughout the year, is obtained.
The results of calculations for constructions and conditions chosen for analysis in this project are that, depending on the type of insulation material and its application, the influence from moisture on the thermal conductivity is somewhere between -2.5% and +1.3% for multi-layered, insulated constructions, but +8.6% for a massive outer wall of cellular concrete. In this context it should be noted that the results are quite sensitive to values asserted for the moisture content of the insulation material at reference conditions (23°C, 50% relative humidity). A particular problem arises when the sorption data needed for the calculation model are not consistent with the reference data taken from EN 12524, since this alone will cause a deviation between the calculated moisture contents and the moisture content at reference conditions – and thus result in moisture conversion coefficients different from zero.
For the method developed in this project to be applied in practice, it must strongly be recommended that as exact values as possible of the moisture content at reference conditions are determined for each of the examined insulation materials, and that sorption curves exist which are consistent with the reference conditions. Furthermore, it must be stressed that the results of the calculations can be very sensitive to the boundary conditions.
Consequently, it must be emphasized that the results from the calculations reported in this work are under the assumption of the prescribed boundary conditions, material properties etc. There may exist cases where the prescribed values are not representative or appropriate, and in such cases, a thorough examination of the conditions and the results following calculations, is strongly recommended.

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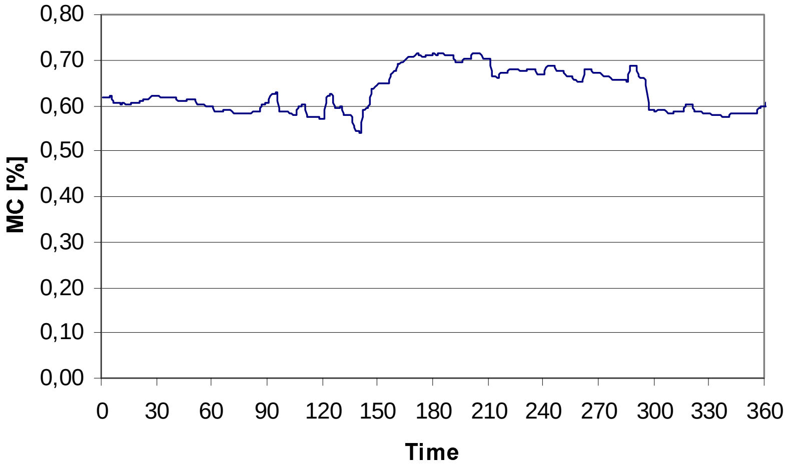
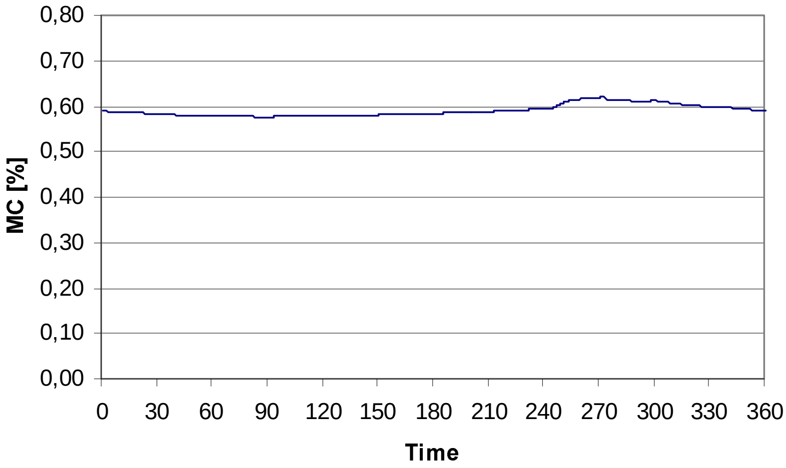
APPENDIX A: DECK ABOVE CRAWL SPACE

Insulation material	Mineral wool (lower layer)
Moisture content at 23°C, 50% RH	0.0 kg/kg (0 m^3/m^3)



Moisture content shown on graph is given in weight-% for lower layer of mineral wool

Insulation material	Mineral wool (upper layer) and mineral wool in lower layer
Moisture content at 23°C, 50% RH	0.0 kg/kg (0 m^3/m^3)

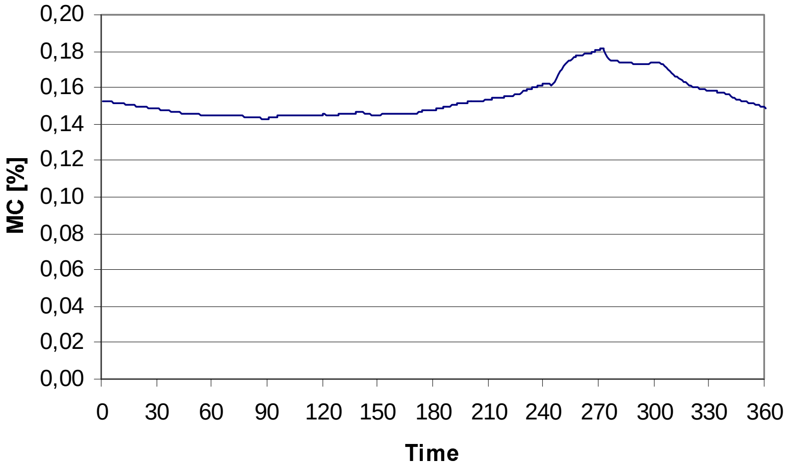


Moisture content for shown in graph is given in weight-% for upper layer of mineral wool

APPENDIX A: DECK ABOVE CRAWL SPACE

Insulation material: Perlite (Expanded stone material) (upper layer) and mineral wool in lower layer

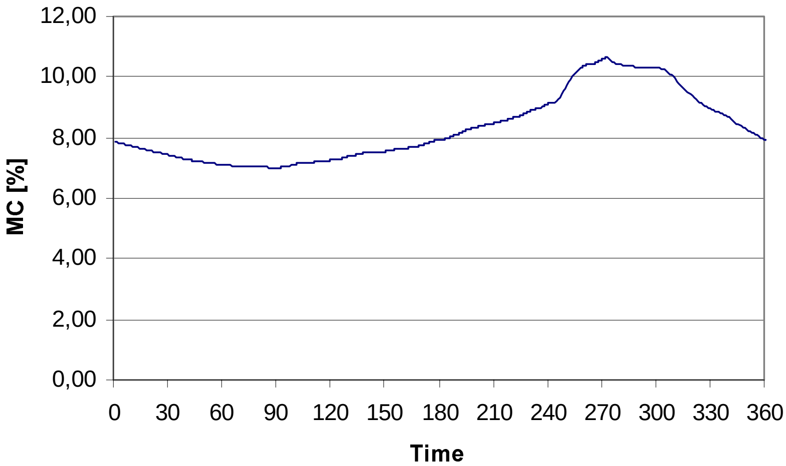
Moisture content at 23°C, 50% RH: 0.01 kg/kg (0.00085 m^3/m^3)



Moisture content shown on graph is given in weight-% for upper layer of perlite

Insulation material: Cellulose fibre (upper layer) and mineral wool in lower layer

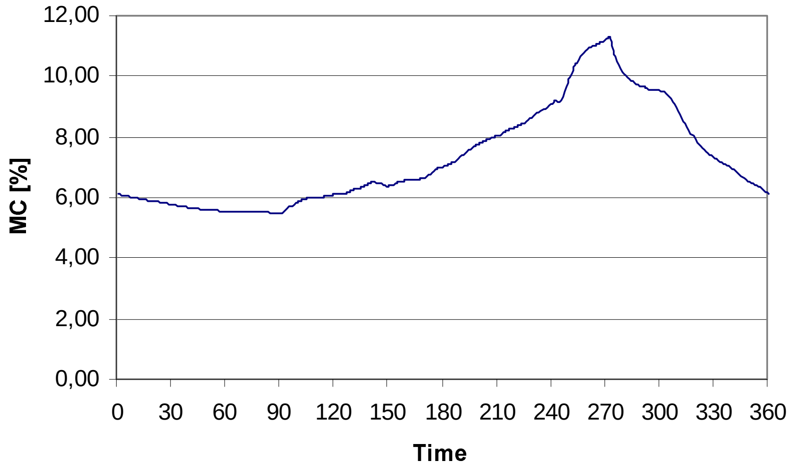
Moisture content at 23°C, 50% RH: 0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of cellulose fibre

APPENDIX A: DECK ABOVE CRAWL SPACE

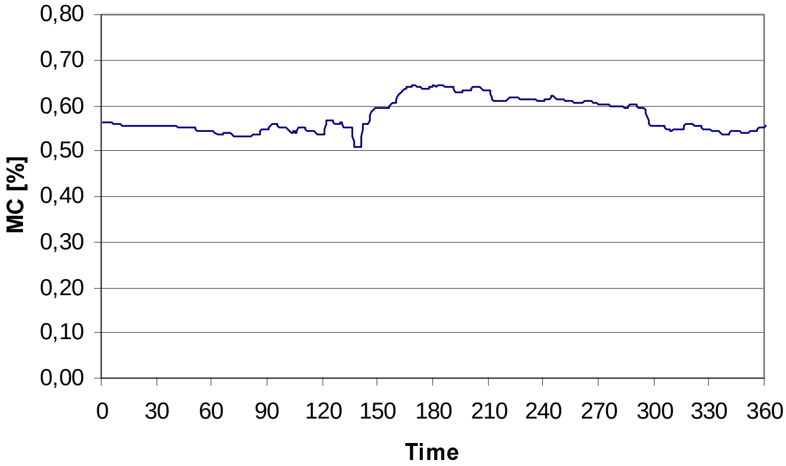
Insulation material	Flax (upper layer) and mineral wool in lower layer
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown on graph is given in weight-% for upper layer of flax

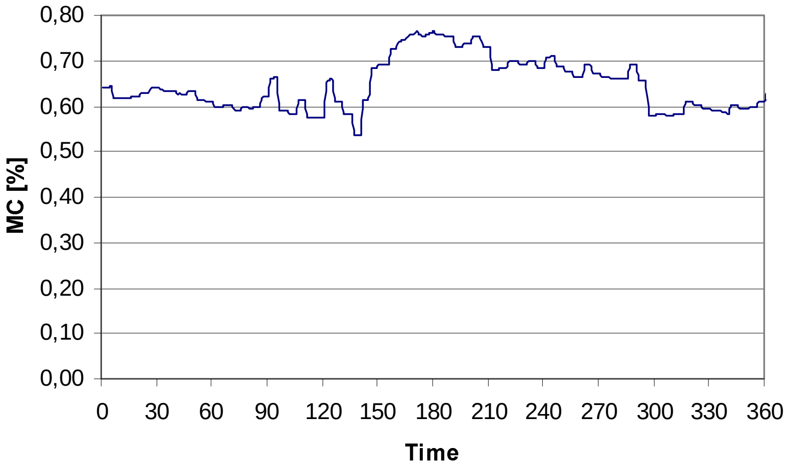
APPENDIX B: INSULATION BETWEEN JOISTS ABOVE CRAWL SPACE

Insulation material	Mineral wool (lower)
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for lower layer of mineral wool

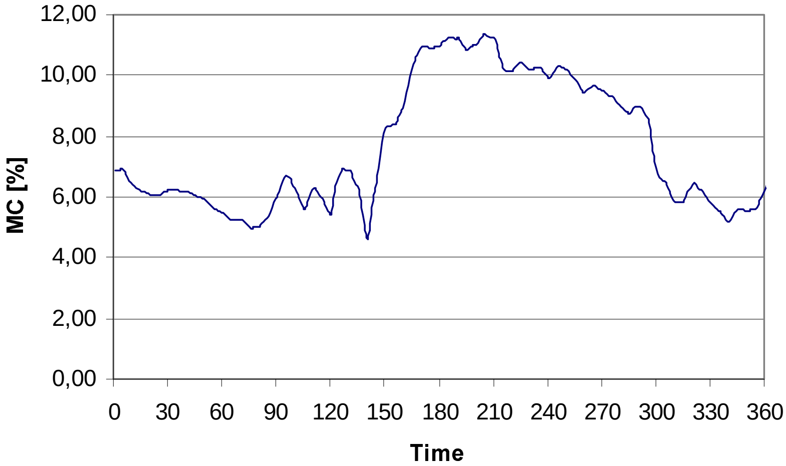
Insulation material	Mineral wool (upper layer) and mineral wool in lower layer
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of mineral wool

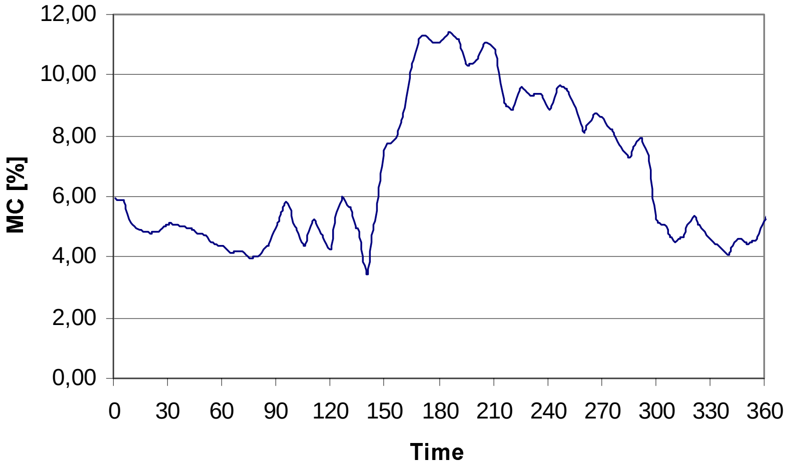
APPENDIX B: INSULATION BETWEEN JOISTS ABOVE CRAWL SPACE

Insulation material	Cellulose fibre (upper layer) and mineral wool in lower layer
Moisture content at 23°C, 50% RH	0.11 kg/kg (00044 m^3/m^3)



Moisture content shown on graph is given in weight-% for upper layer of cellulose fibre

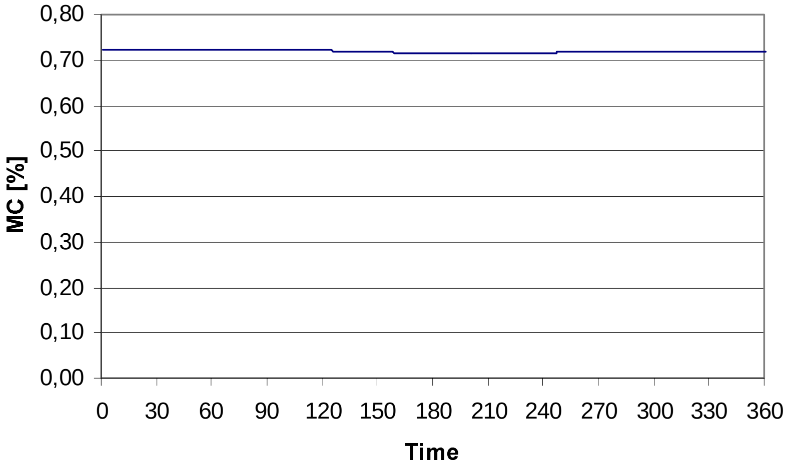
Insulation material	Flax (upper layer) and mineral wool in lower layer
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of flax

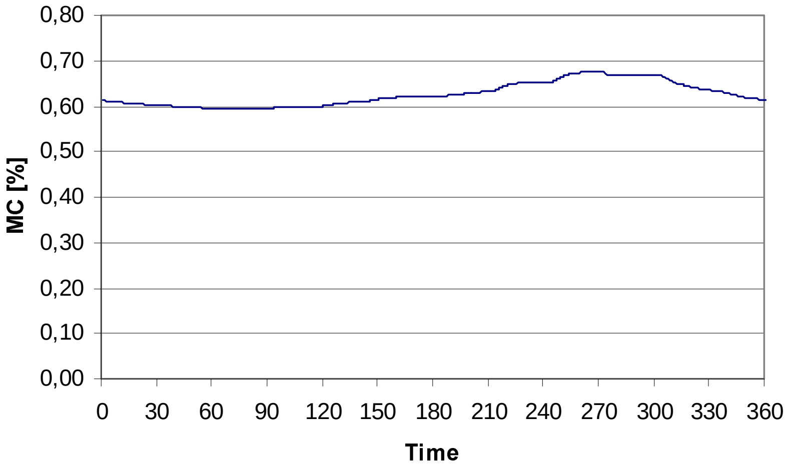
APPENDIX C: CONCRETE SLAB ON GRADE

Insulation material	High density mineral wool (lower layer)
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for lower layer of mineral wool

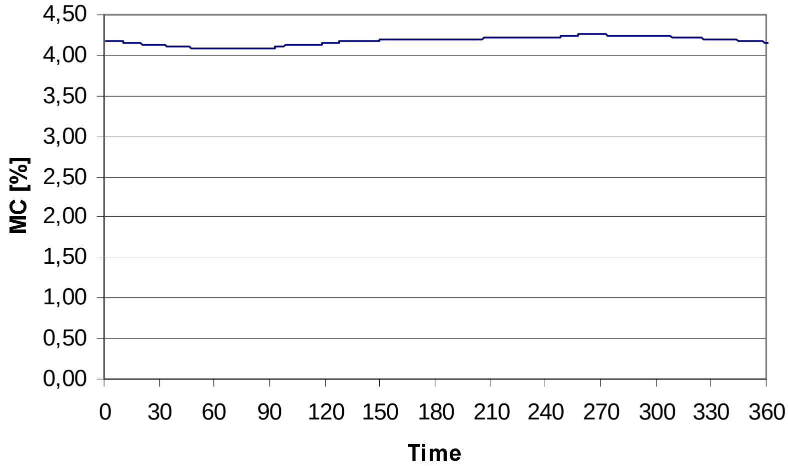
Insulation material	Mineral wool (upper layer) with high density mineral wool in lower layer
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of mineral wool

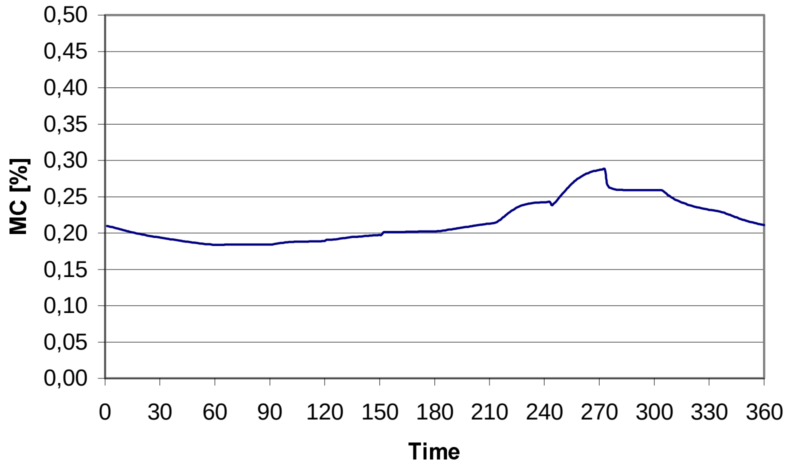
APPENDIX C: CONCRETE SLAB ON GRADE

Insulation material	Expanded polystyrene (upper layer) with high density mineral wool in lower layer
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for upper layer of exp. polystyrene

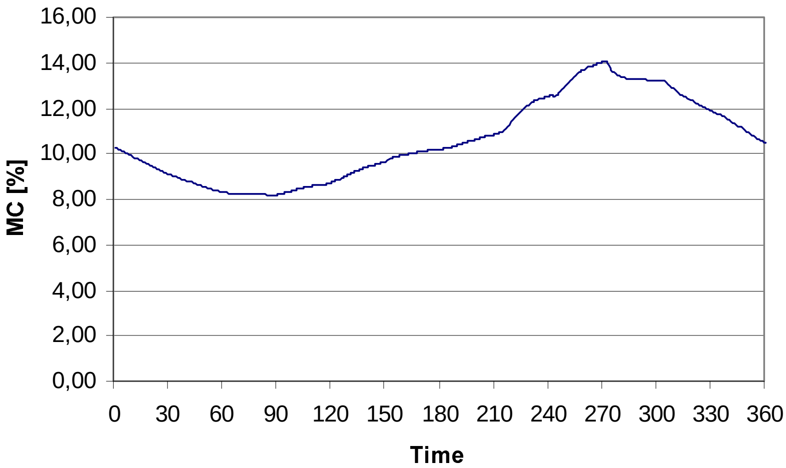
Insulation material	Perlite (Exp.stone material) (upper layer) with high density mineral wool in lower layer
Moisture content at 23°C, 50% RH	0.01 kg/kg (0.00085 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of perlite

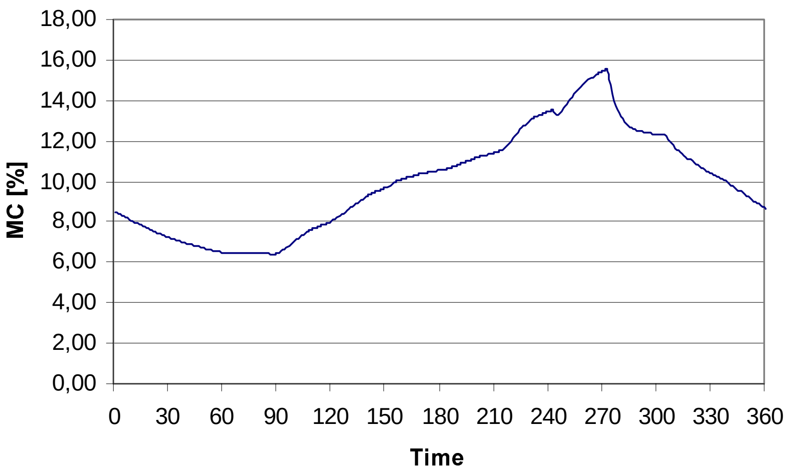
APPENDIX C: CONCRETE SLAB ON GRADE

Insulation material	Cellulose fibre (upper layer) with high density mineral wool in lower layer
Moisture content at 23°C, 50% RH	0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown on graph is given in weight-% for upper layer of cellulose fibre

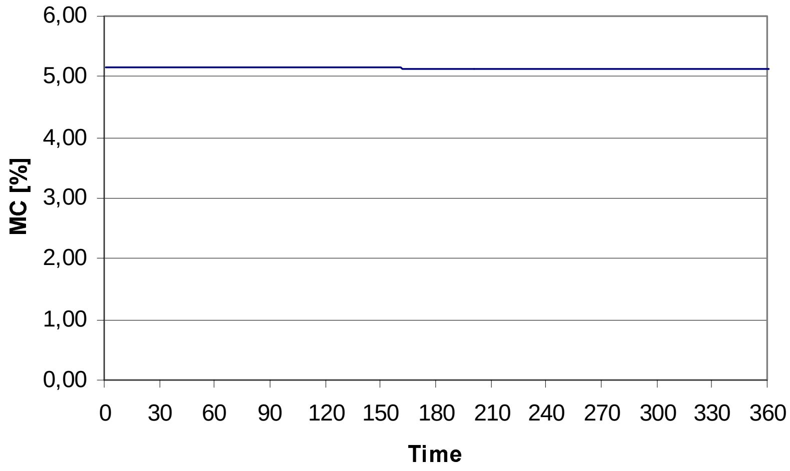
Insulation material	Flax (upper layer) with high density mineral wool in lower layer
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of flax

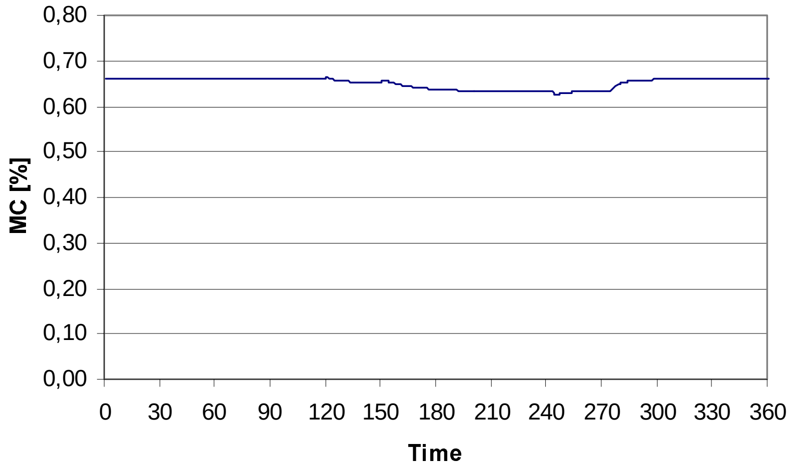
APPENDIX C: CONCRETE SLAB ON GRADE

Insulation material	Expanded polystyrene (lower layer)
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for lower layer of mineral wool

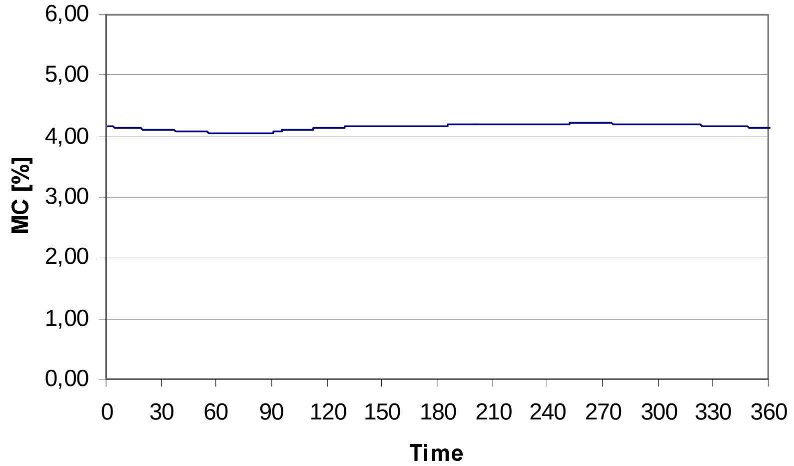
Insulation material	Mineral wool (upper layer) with expanded polystyrene in lower layer
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of mineral wool

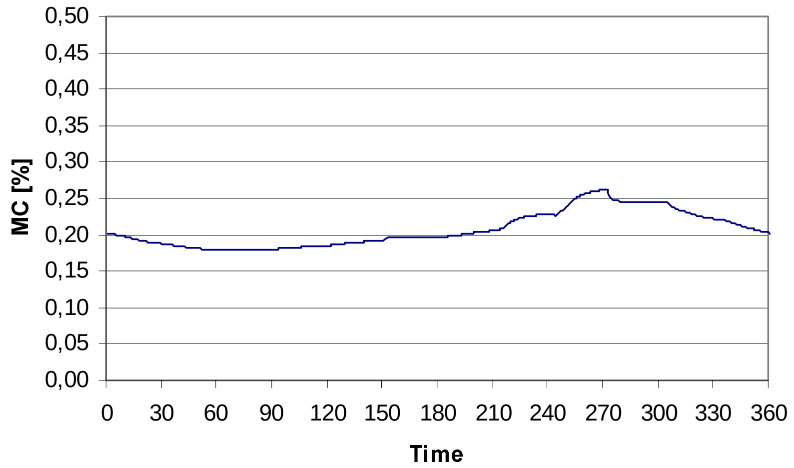
APPENDIX C: CONCRETE SLAB ON GRADE

Insulation material	Expanded polystyrene (upper layer) with expanded polystyrene in lower layer
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for lower layer of exp. polystyrene

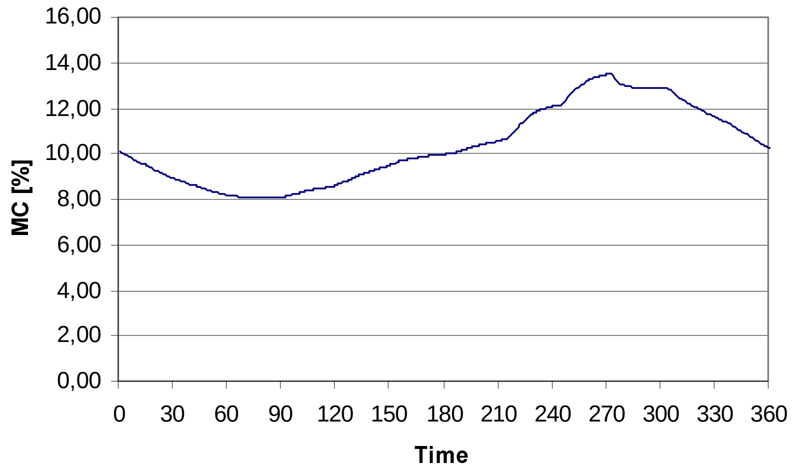
Insulation material	Expanded stone material (upper layer) with expanded polystyrene in lower layer
Moisture content at 23°C, 50% RH	0.01 kg/kg (0.00085 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of exp. polystyrene

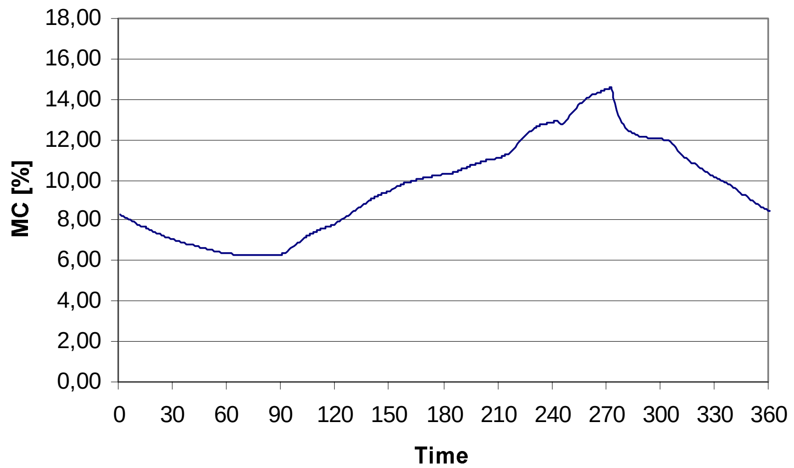
APPENDIX C: CONCRETE SLAB ON GRADE

Insulation material	Cellulose fibre (upper layer) with expanded polystyrene in lower layer
Moisture content at 23°C, 50% RH	0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown on graph is given in weight-% for upper layer of cellulose fibre

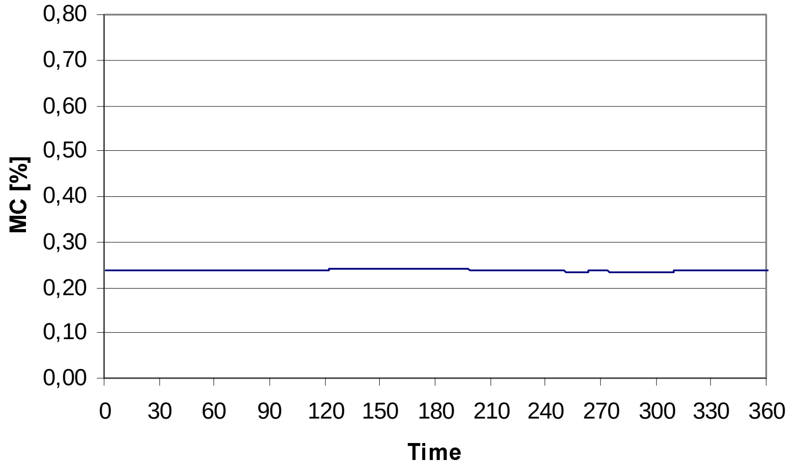
Insulation material	Flax (upper layer) with expanded polystyrene in lower layer
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of flax

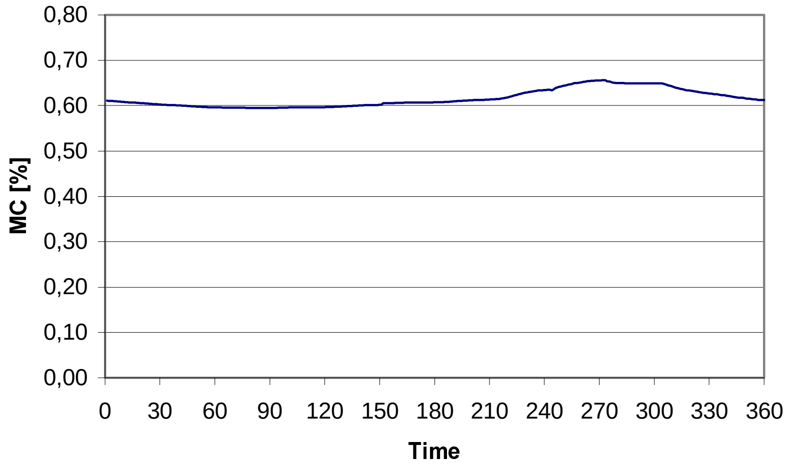
APPENDIX D: LIGHT WEIGHT AGGREGATE CONCRETE SLABS ON GRADE

Insulation material	Light weight aggregate (lower layer)
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for lower layer of LW aggregate

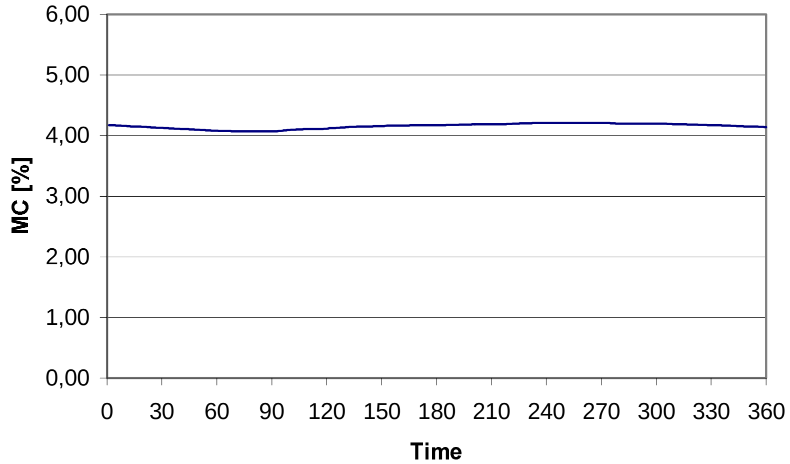
Insulation material	Mineral wool (upper layer) with light weight aggregate as lower layer
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of mineral wool

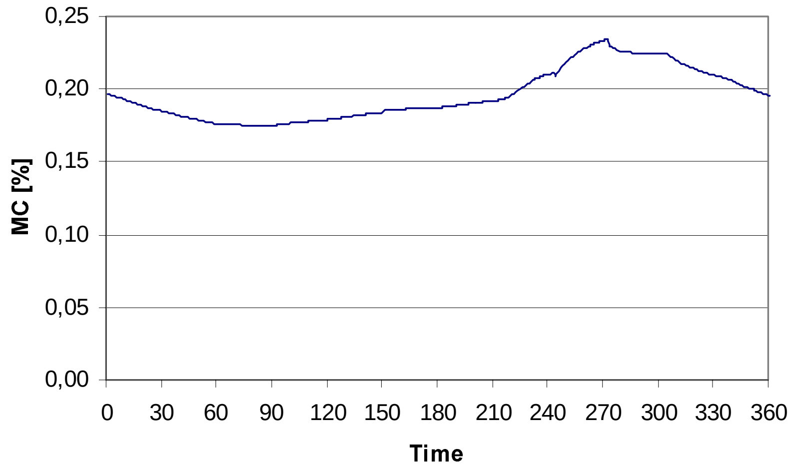
APPENDIX D: LIGHT WEIGHT AGGREGATE CONCRETE SLABS ON GRADE

Insulation material	Expanded polystyrene (upper layer) with light weight aggregate as lower layer
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for upper layer of exp. polystyrene

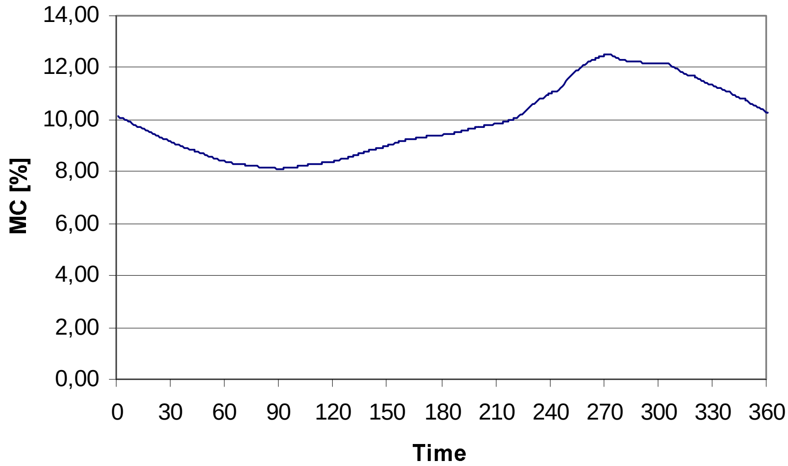
Insulation material	Perlite (Exp. stone material) (upper layer) with light weight aggregate as lower layer
Moisture content at 23°C, 50% RH	0.01 kg/kg (0.00085m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of perlite

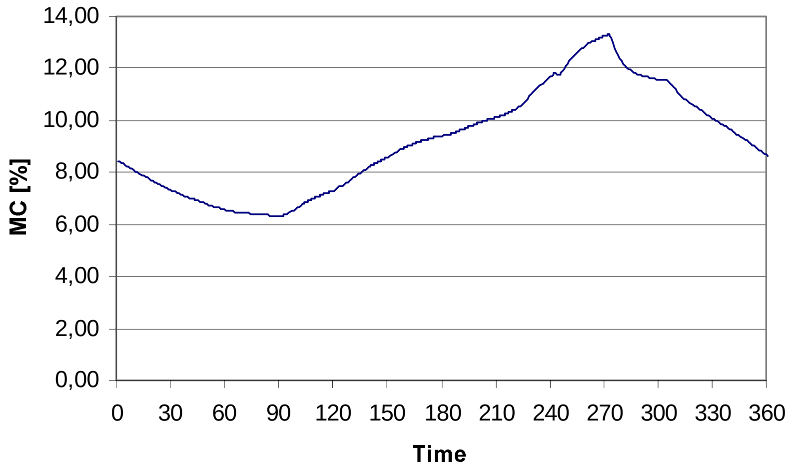
APPENDIX D: LIGHT WEIGHT AGGREGATE CONCRETE SLABS ON GRADE

Insulation material	Cellulose fibre (upper layer) with light weight aggregate as lower layer
Moisture content at 23°C, 50% RH	0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown on graph is given in weight-% for upper layer of cellulose fibre

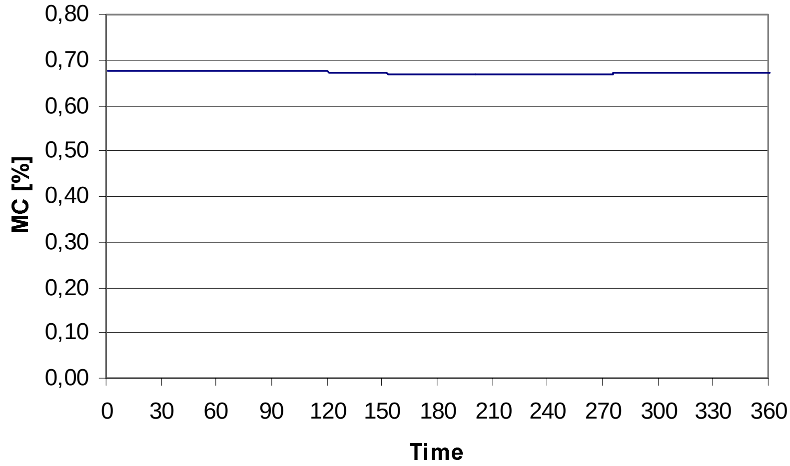
Insulation material	Flax (upper layer) with light weight aggregate as lower layer
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown in graph is given in weight-% for upper layer of flax

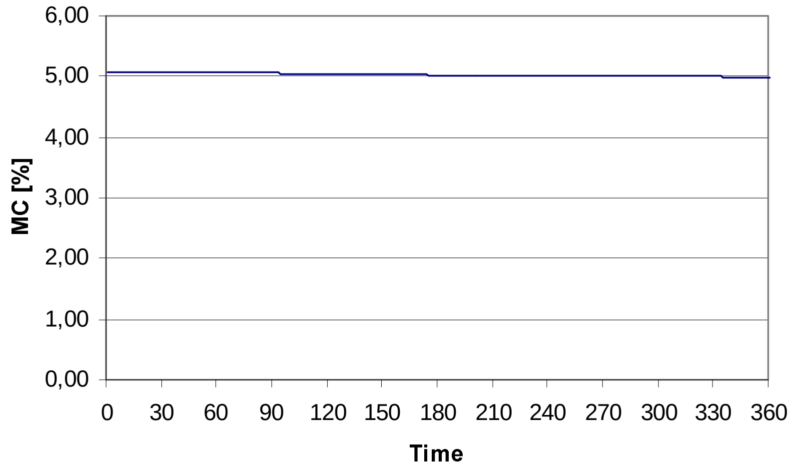
APPENDIX E: BASEMENT WALL WITH EXTERIOR INSULATION

Insulation material	High density mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for high density mineral wool

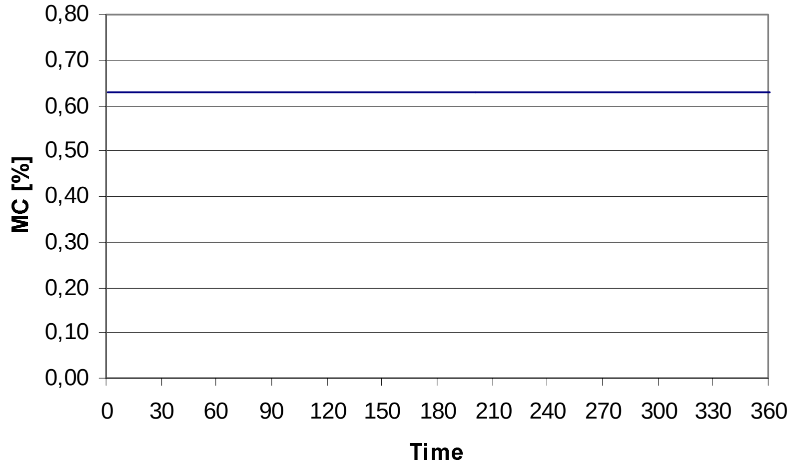
Insulation material	Expanded polystyrene
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown in graph is given in weight-% for expanded polystyrene

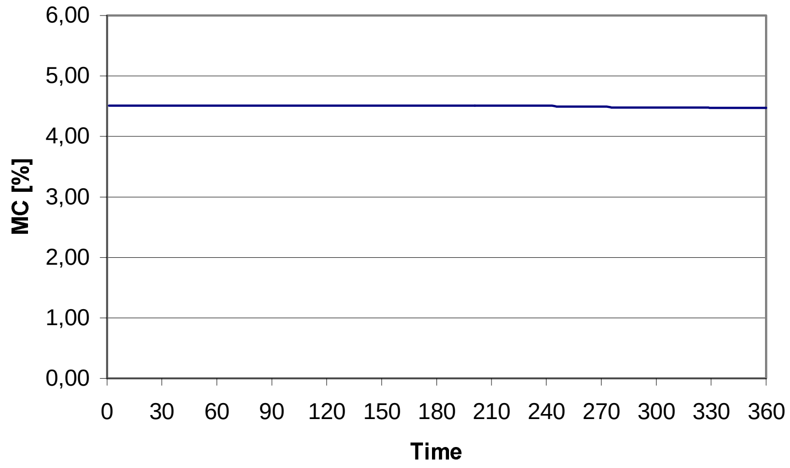
APPENDIX F: BASEMENT WALL WITH INTERIOR INSULATION

Insulation material	High density mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for high density mineral wool

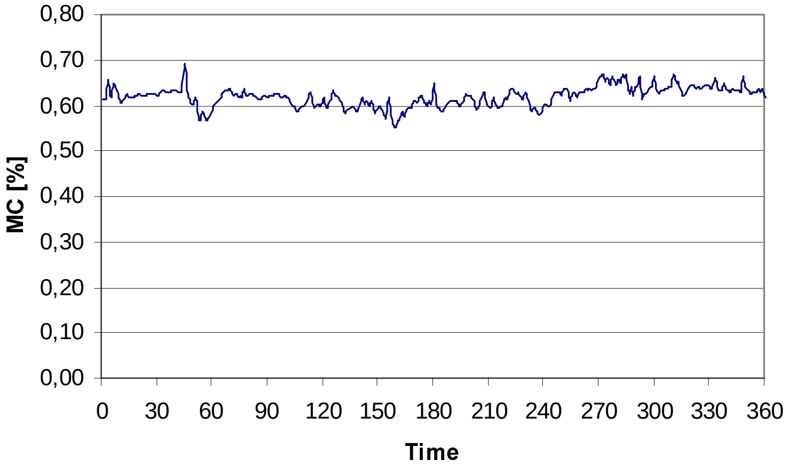
Insulation material	Expanded polystyrene
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown in graph is given in weight-% for polystyrene

APPENDIX G: EXTERNAL INSULATION WITH STUCCO

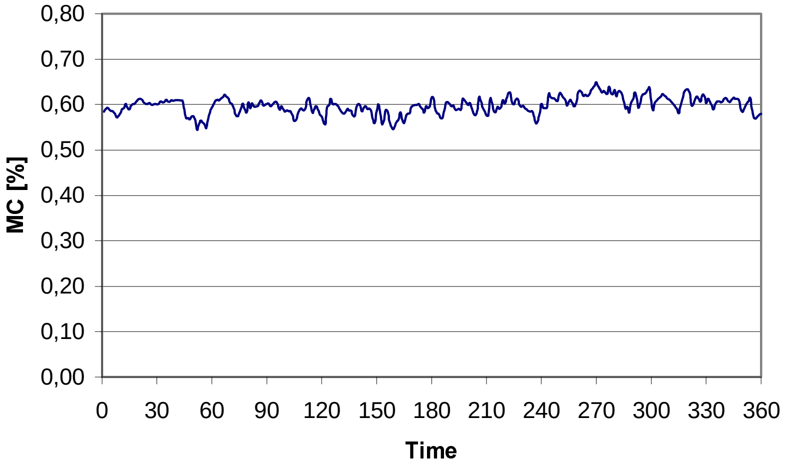
Insulation material	High density mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown in graph is given in weight-% for high density mineral wool

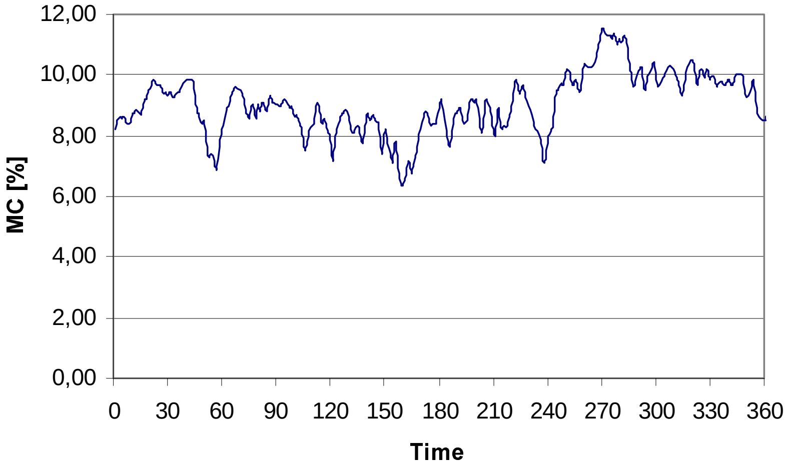
APPENDIX H: EXTERNAL WALL INSULATION WITH CLADDING

Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

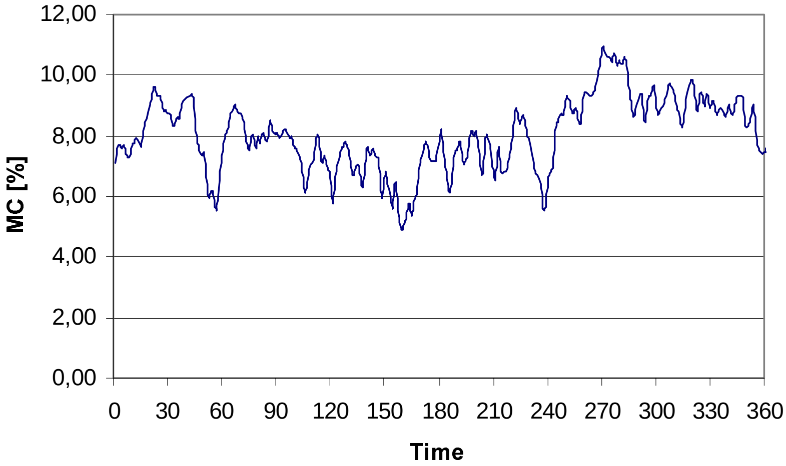
Insulation material	Cellulose fibre
Moisture content at 23°C, 50% RH	0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown in graph is given in weight-% for cellulose fibre

APPENDIX H: EXTERNAL WALL INSULATION WITH CLADDING

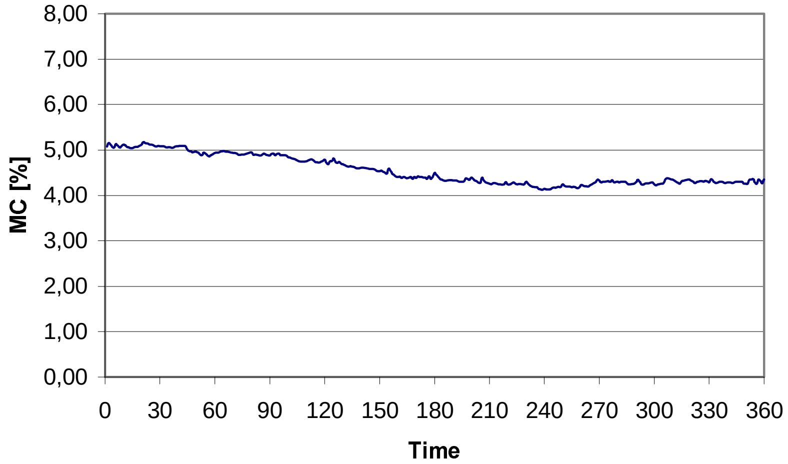
Insulation material	Flax
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown on graph is given in weight-% for flax

APPENDIX I: MASSIVE CELLULAR CONCRETE

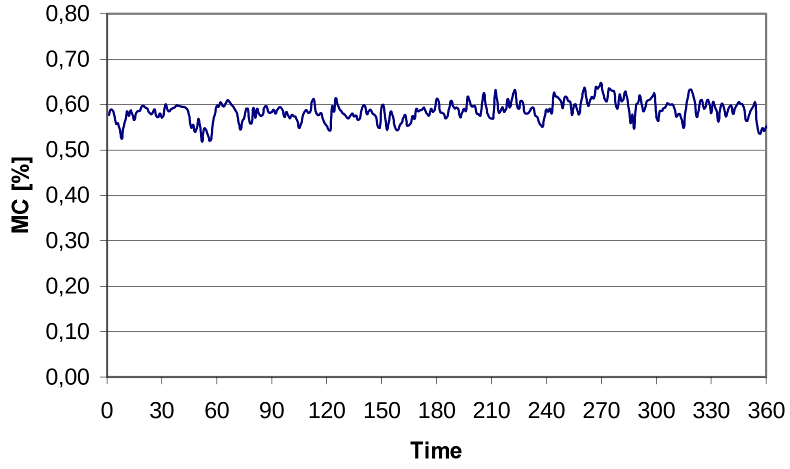
Insulation material	Cellular concrete
Moisture content at 23°C, 50% RH	0.026 kg/kg (0.01625 m^3/m^3)



Moisture content shown on graph is given in weight-% for cellulose fibre

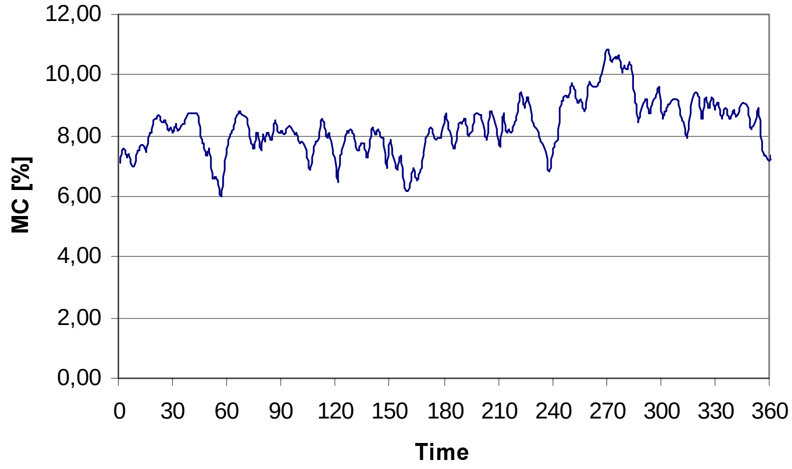
APPENDIX J: INTERNAL INSULATION WITH INTERIOR VAPOUR RETARDER

Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

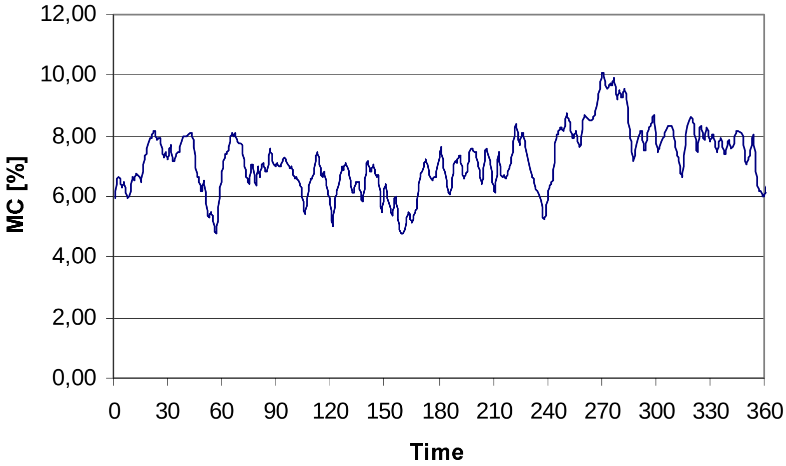
Insulation material	Cellulose fibre
Moisture content at 23°C, 50% RH	0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown in graph is given in weight-% for cellulose fibre

APPENDIX J: INTERNAL INSULATION WITH INTERIOR VAPOUR RETARDER

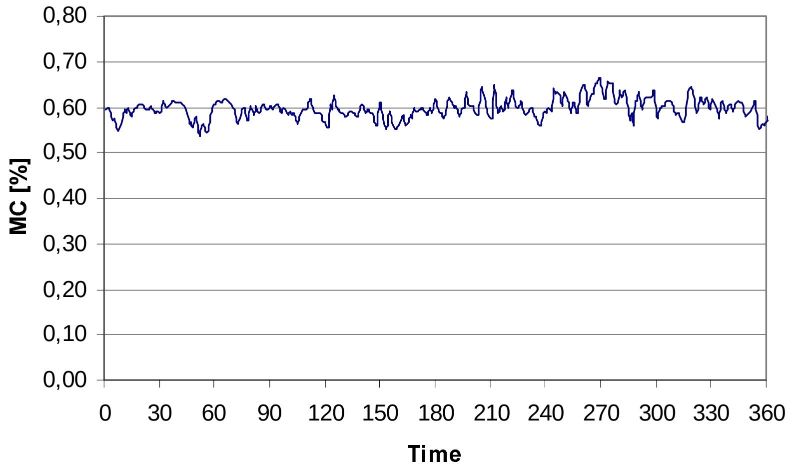
Insulation material	Flax
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown on graph is given in weight-% for flax

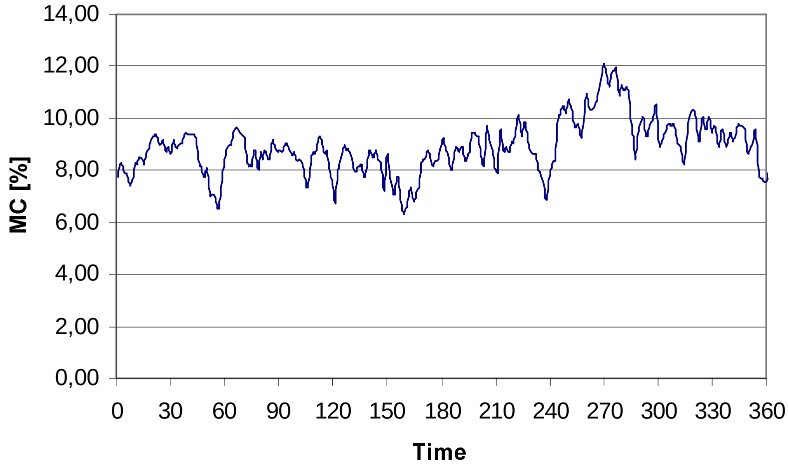
APPENDIX K: INTERNAL INSULATION WITH EMBEDDED VAPOUR RETARDER

Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

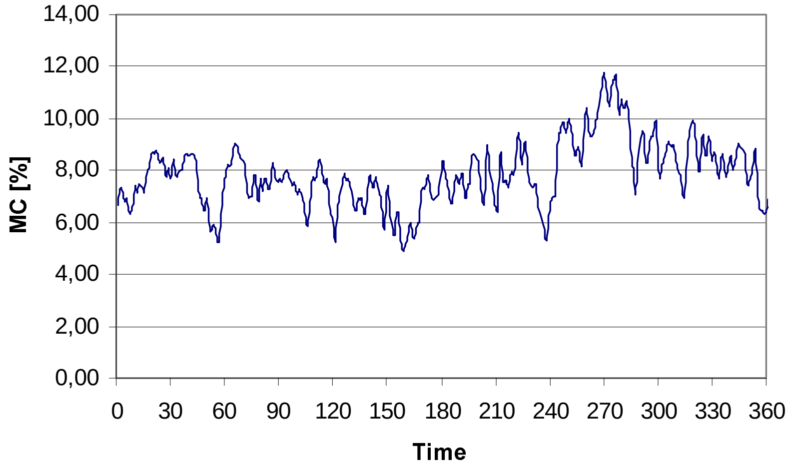
Insulation material	Cellulose fibre
Moisture content at 23°C, 50% RH	0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown in graph is given in weight-% for cellulose fibre

APPENDIX K: INTERNAL INSULATION WITH EMBEDDED VAPOUR RETARDER

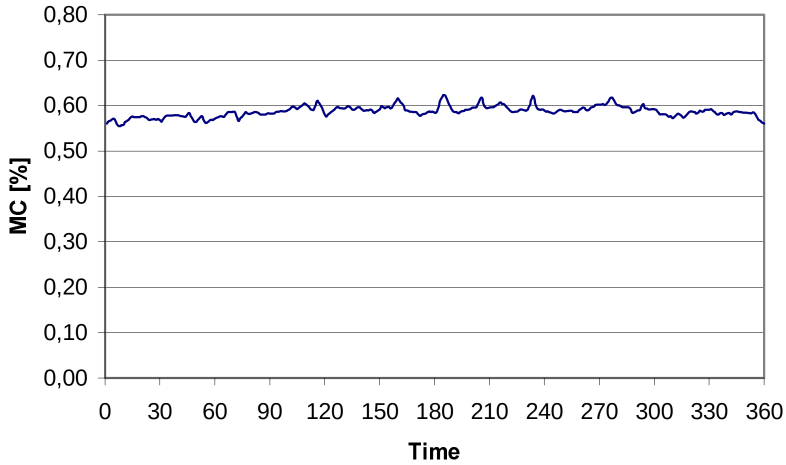
Insulation material	Flax
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown on graph is given in weight-% for flax

APPENDIX L: BRICK WALL WITH INTERNAL INSULATION

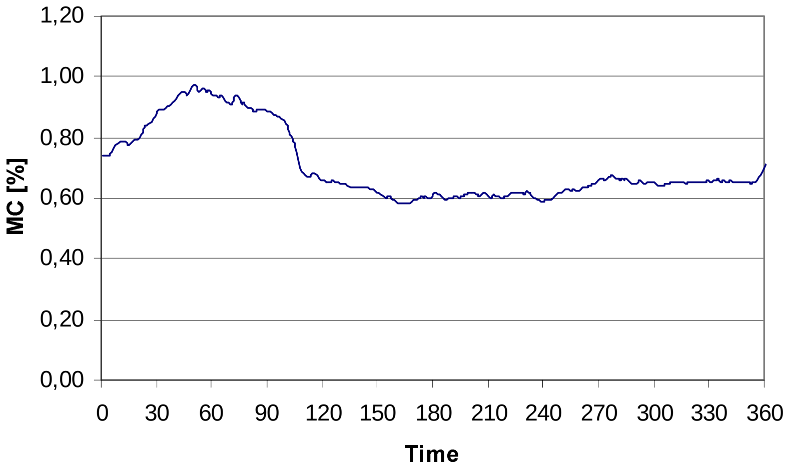
Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

APPENDIX M: CAVITY WALL INSULATED WITH STRUCTURAL INSULATION

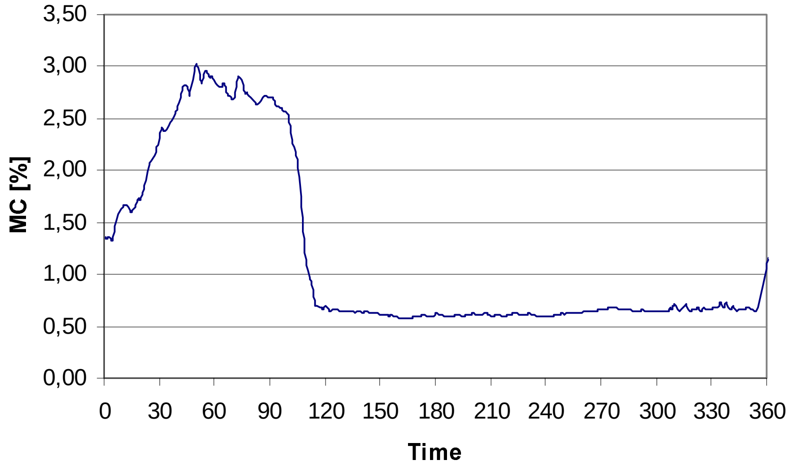
Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

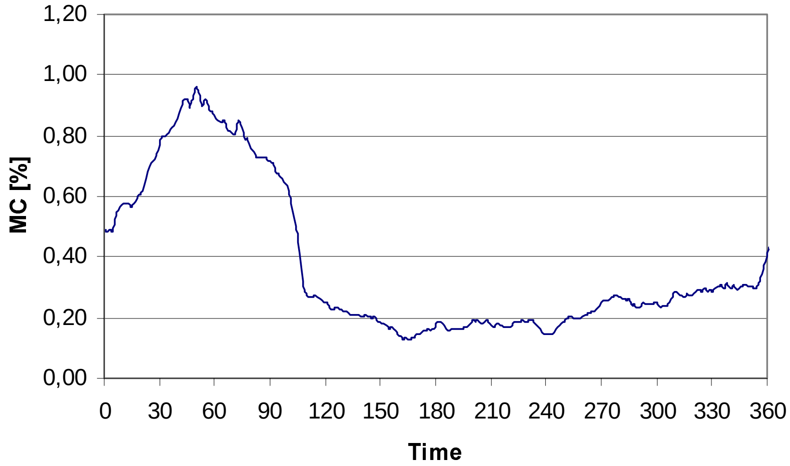
APPENDIX N: CAVITY WALL INSULATED WITH LOOSE-FILL INSULATION

Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

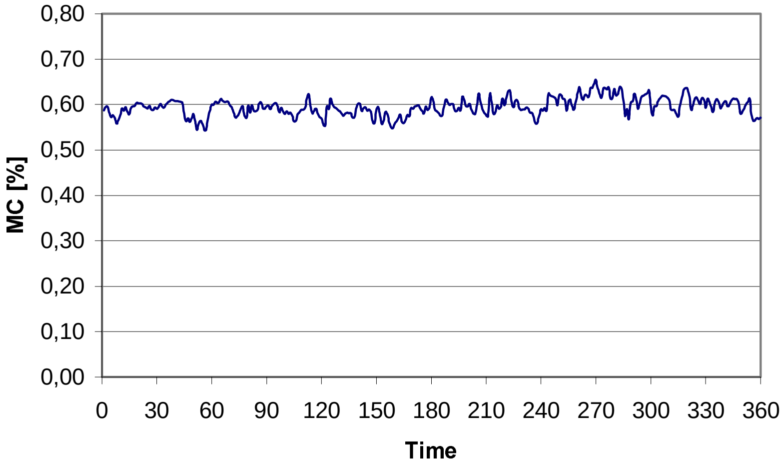
Insulation material	Perlite (Expanded stone material)
Moisture content at 23°C, 50% RH	0.01 kg/kg (0.00085 m^3/m^3)



Moisture content shown in graph is given in weight-% for perlite

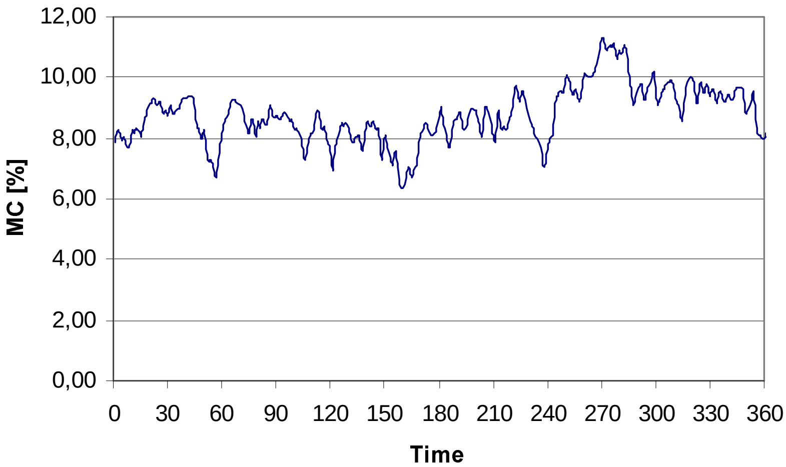
APPENDIX O: CAVITY WALL PARTLY INSULATED WITH LOOSE-FILL

Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

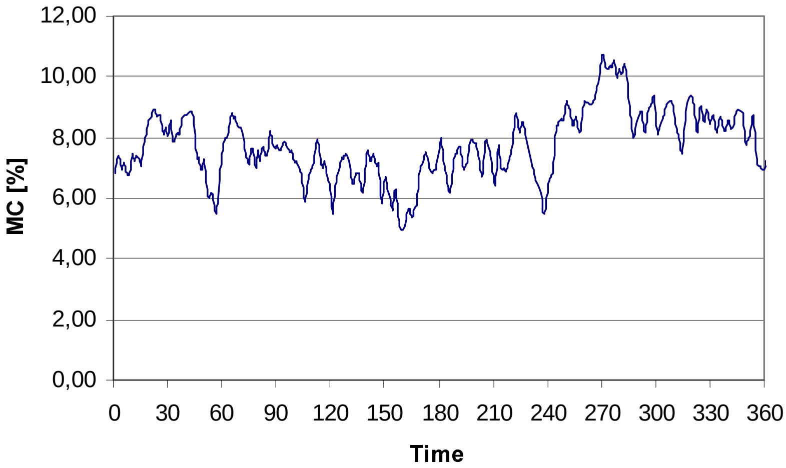
Insulation material	Cellulose fibre
Moisture content at 23°C, 50% RH	0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown in graph is given in weight-% for cellulose fibre

APPENDIX O: CAVITY WALL PARTLY INSULATED WITH LOOSE-FILL

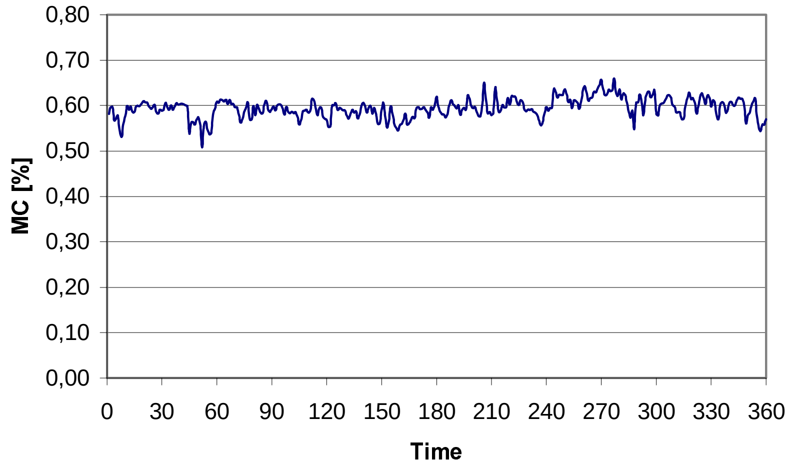
Insulation material	Flax
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown on graph is given in weight-% for flax

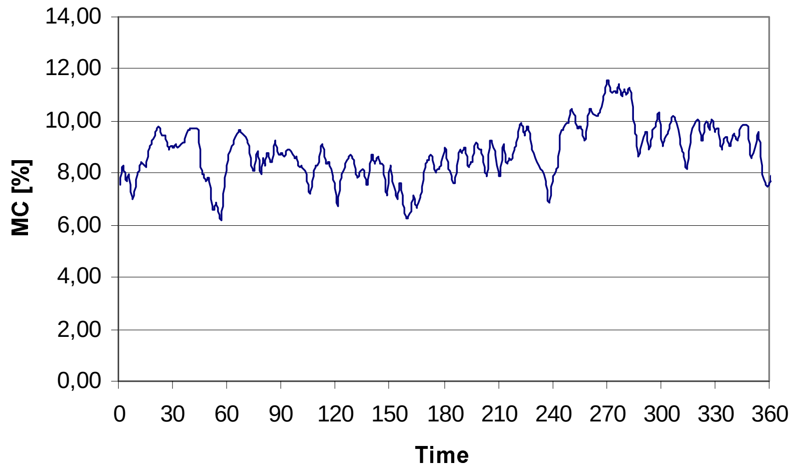
APPENDIX P: LIGHT WEIGHT WALL W/ VAPOUR RETARDER AND CLADDING

Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

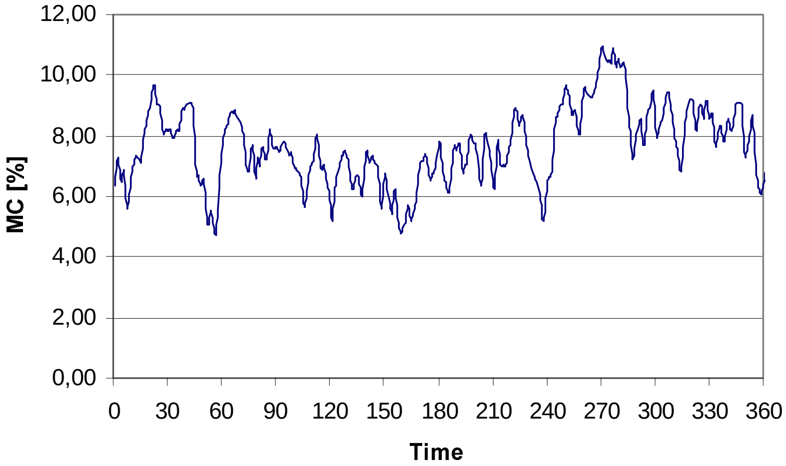
Insulation material	Cellulose fibre
Moisture content at 23°C, 50% RH	0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown in graph is given in weight-% for cellulose fibre

APPENDIX P: LIGHT WEIGHT WALL W/ VAPOUR RETARDER AND CLADDING

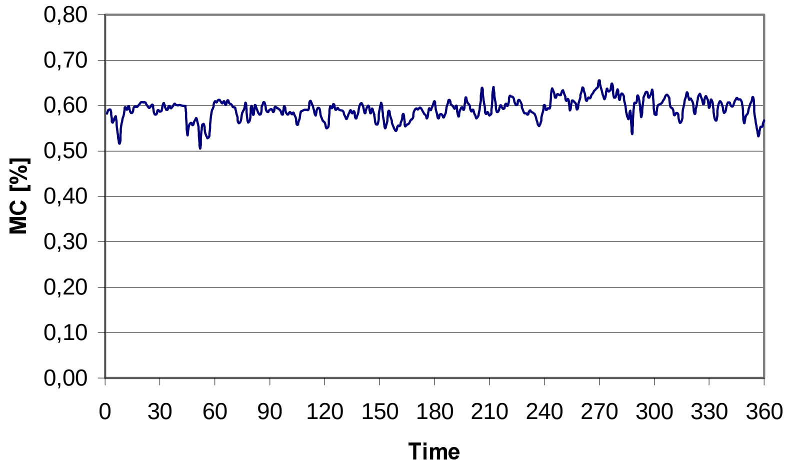
Insulation material	Flax
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown on graph is given in weight-% for flax

APPENDIX Q: LIGHT WEIGHT WALL W/ VAPOUR BARRIER AND CLADDING

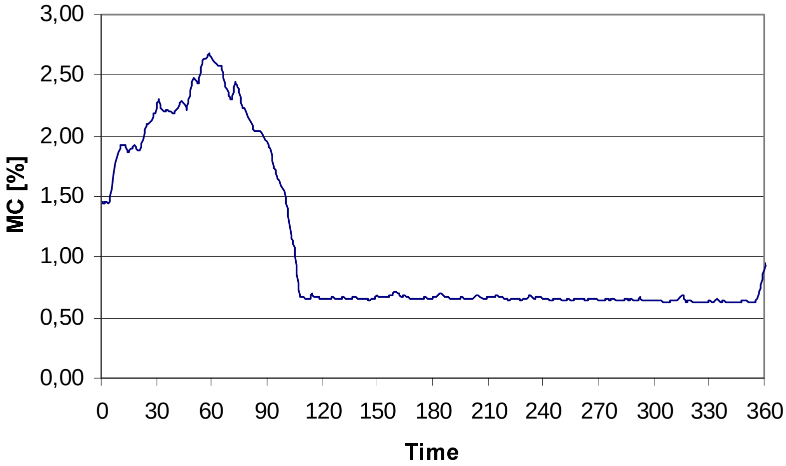
Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown in graph is given in weight-% for mineral wool

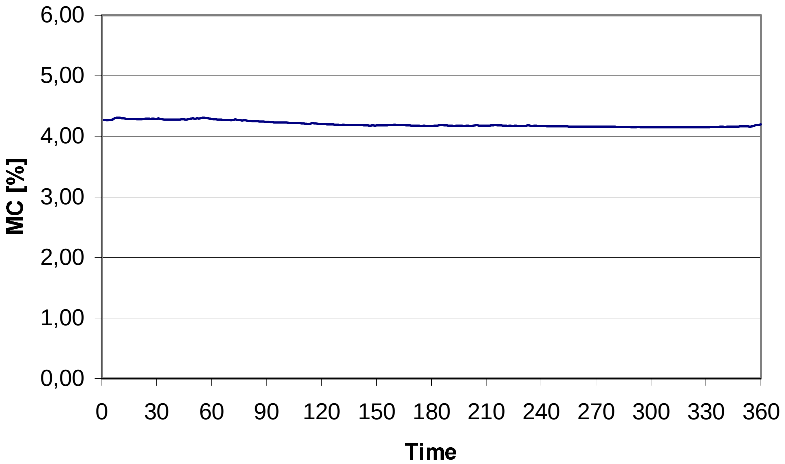
APPENDIX R: CONCRETE SANDWICH ELEMENT

Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

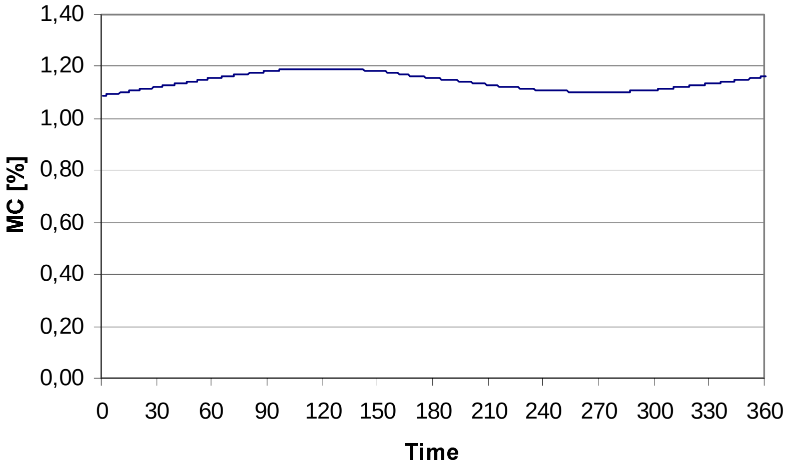
Insulation material	Expanded polystyrene
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown in graph is given in weight-% for expanded polystyrene

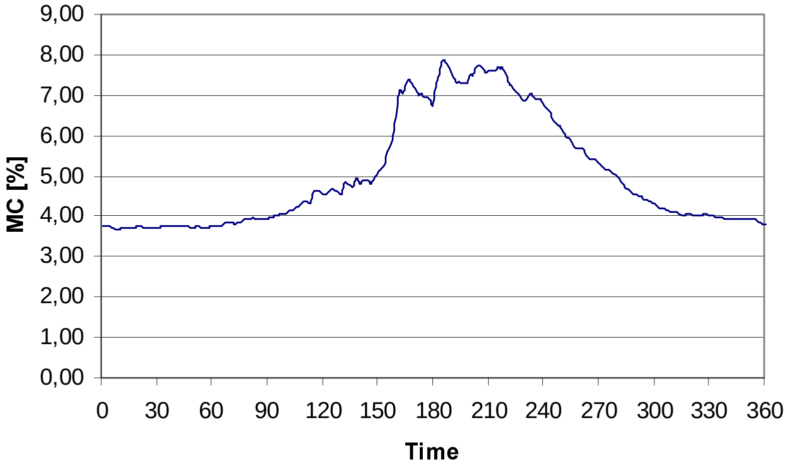
APPENDIX S: UNVENTILATED ROOF LOW-SLOPED ROOF

Insulation material	High density mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for high density mineral wool

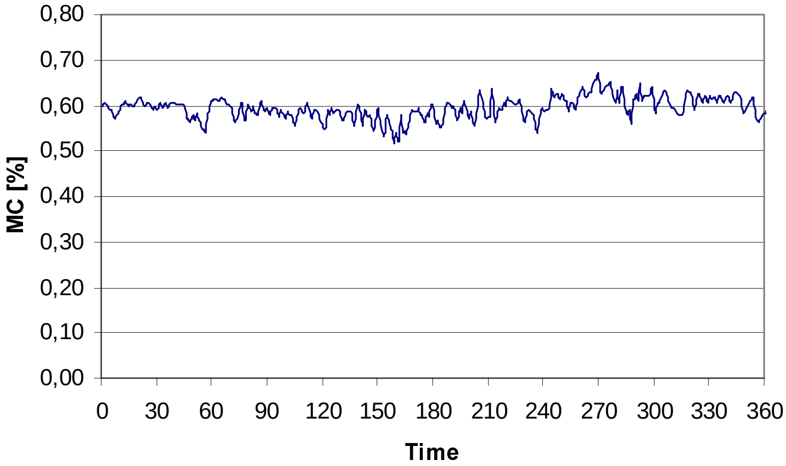
Insulation material	Expanded polystyrene
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown in graph is given in weight-% for expanded polystyrene

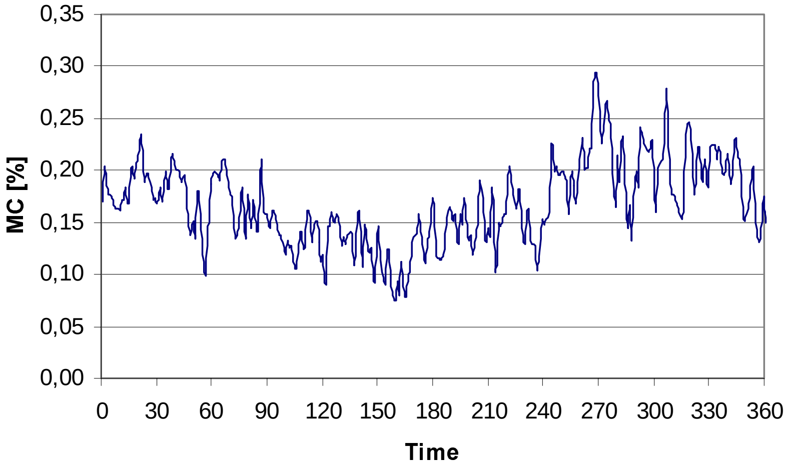
APPENDIX T: VENTILATED LOW-SLOPED ROOF

Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

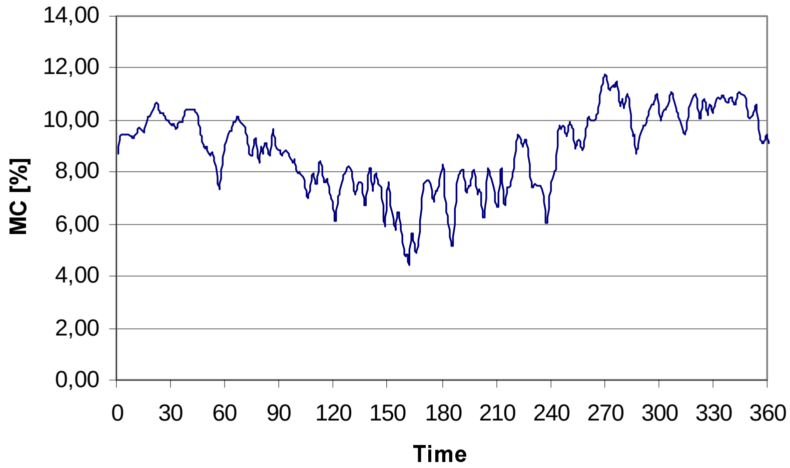
Insulation material	Perlite (Expanded stone material)
Moisture content at 23°C, 50% RH	0.01 kg/kg (0.00085 m^3/m^3)



Moisture content shown in graph is given in weight-% for perlite

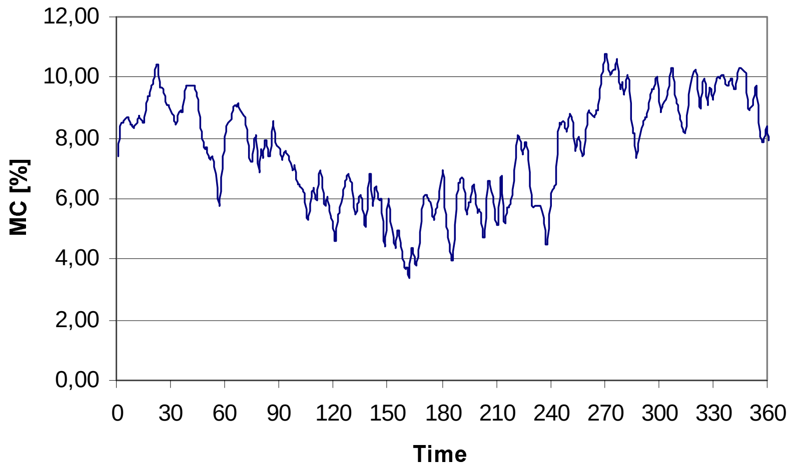
APPENDIX T: VENTILATED LOW-SLOPED ROOF

Insulation material	Cellulose fibre
Moisture content at 23°C, 50% RH	0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown on graph is given in weight-% for cellulose fibre

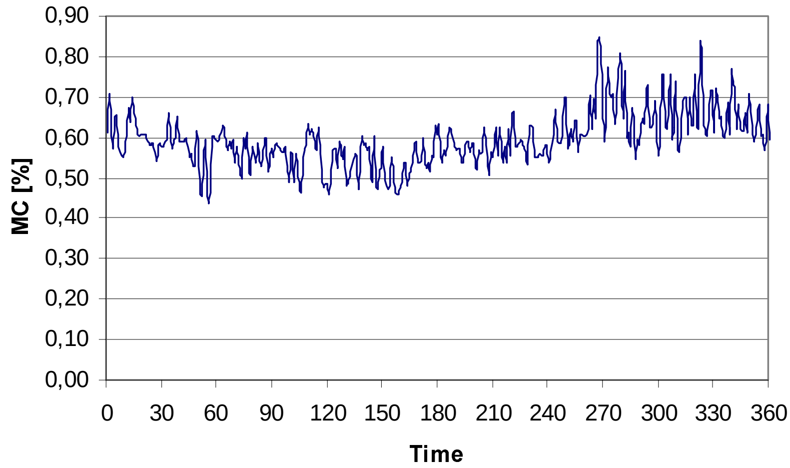
Insulation material	Flax
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown in graph is given in weight-% for flax

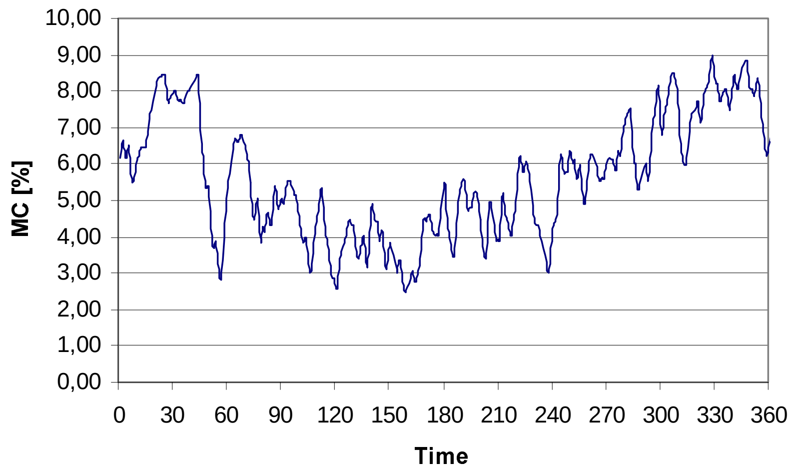
APPENDIX U: VENTILATED SLOPED ROOF

Insulation material	Mineral wool
Moisture content at 23°C, 50% RH	0.0 kg/kg (0.0 m^3/m^3)



Moisture content shown on graph is given in weight-% for mineral wool

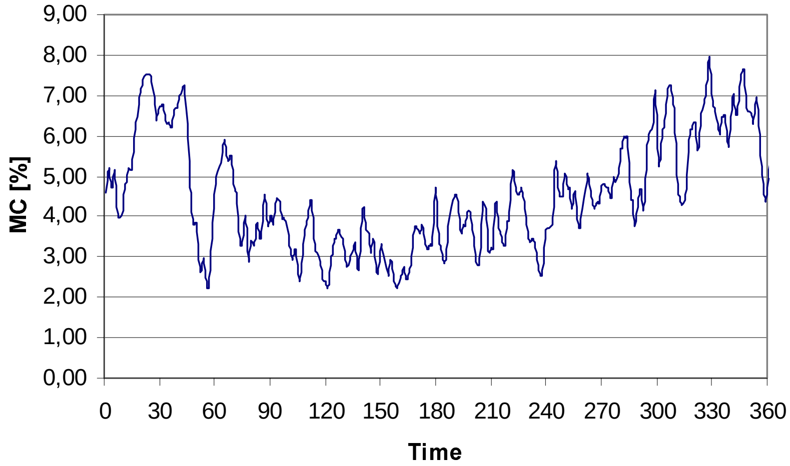
Insulation material	Cellulose fibre
Moisture content at 23°C, 50% RH	0.11 kg/kg (0.0044 m^3/m^3)



Moisture content shown in graph is given in weight-% for cellulose fibre

APPENDIX U: SLOPED VENTILATED ROOF

Insulation material	Flax
Moisture content at 23°C, 50% RH	0.06 kg/kg (0.0018 m^3/m^3)



Moisture content shown on graph is given in weight-% for flax