BYGGFORSK
Norwegian Building Research Institute

NORWEGIAN UNIVERSITY OF
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Department of Building and Construction
Engineering

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Moisture conditions in timber frame roof and wall structures

Test house measurements for verification of heat-, air and moisture transfer models

273 Project report 2000

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PREFACE

This report presents a part of the work that was carried out within the Strategic Research Programme «Moisture in Building Materials and Constructions». The programme was carried out in a four year period 1993-1997 as a cooperation between the Norwegian Building Research Institute (NBI) and Department of Building and Construction Engineering, Norwegian University of Science and Technology (NTNU). The programme was mainly funded by the Norwegian Research Council, and additionally by internal funding from the participating institutions.

The programme included the following projects:

0. General activities and programme management
1. Literature survey
2. Moisture physics
3. Calculation programs
4. Material properties
5. Verification
6. Dr.ing. (PhD) studies
7. International cooperation

The work presented in this report has been carried out within project 5 "Verification". The test house measurements were made in the period 1994-98. Since 1998 extensive analysis work and additional measurements have been performed.

Trondheim, March 2000

Stig Geving Sivert Uvsløkk

CONTENTS

1 INTRODUCTION

As a part of the research programme "Moisture in Building Materials and Constructions" (1993-97), experiments have been performed on different building envelope structures at a test house in Trondheim, Norway. Most of the test elements were lightweight timber frame constructions. The roof elements were all horizontal with a high degree of one-dimensionality. The timber frame walls had different combinations of vapour retarders and wind barriers. The external surfaces were exposed to the ambient climate, while the indoor climate in the house was controlled at 23 °C and 50 % RH. The outdoor climate was monitored by an automatic weather station situated 17 meters from the test house. Moisture and temperature conditions in the elements were monitored continuously in the period 1994-98. Since then extensive analysis work and additional measurements have been performed.

The main purposes of the test house measurements were:

1. Collecting data for comparison with computer simulations of transient moisture transfer in building constructions. The measurement data from this test house are made available for researchers who want to verify computer models for heat, air and moisture transfer through building structures. The data are available on digital format (CD-ROM).
2. Investigate how untraditional combinations of indoor and outdoor vapour resistance (vapour barrier and wind barrier) influence the moisture conditions of a timber frame wall.

This report gives a description of the data that are available for verification purposes from the test house. The report comprises descriptions of :

- Test house
- Wall and roof elements investigated
- Instrumentation of the elements
- Boundary conditions
- Outdoor climatic parameters measured
- Measured material properties
- Some measurement results from wall and roof elements

2 DESCRIPTION OF THE TEST HOUSE

2.1 General

The test house is located on a field station belonging to the Norwegian Building Research Institute and Department of Building and Construction Engineering, NTNU. The field station is located on an open field at Voll (Jonsvannsveien 159) in Trondheim, approximately 6 km south-east of the centre of the city. The exact location is N63°25' E10°28'. The field station consists of a test house with removable roof and wall elements (which is described in this report), another test house which can be rotated for wind pressure studies, an automatic weather station (also described in this report) and a small measurement house in connection with the weather station, see figure 1. The test house is shown in Figure 2.

The roof and facades of the test house consist of prefabricated sections fixed to the outside of a steel frame structure, see figure 3. The test house is orientated in north-south direction and has the following indoor dimensions: length 10.7 m, width 3.45 m and height 3.5 m. The roof sections span from facade to facade, and have a 1:40 slope. All sections are 1,2 m wide and they are separated from each other regarding air and moisture transfer, by use of polyethylene foil. The sections may be changed individually without disturbing the neighbour sections. There are a total of 16 wall sections on the western and eastern facades and 8 roof sections, see figure 4. The test house is equipped with a low temperature electric floor heating system, balanced mechanical ventilation with heat recovery and an automatic air humidifying system.

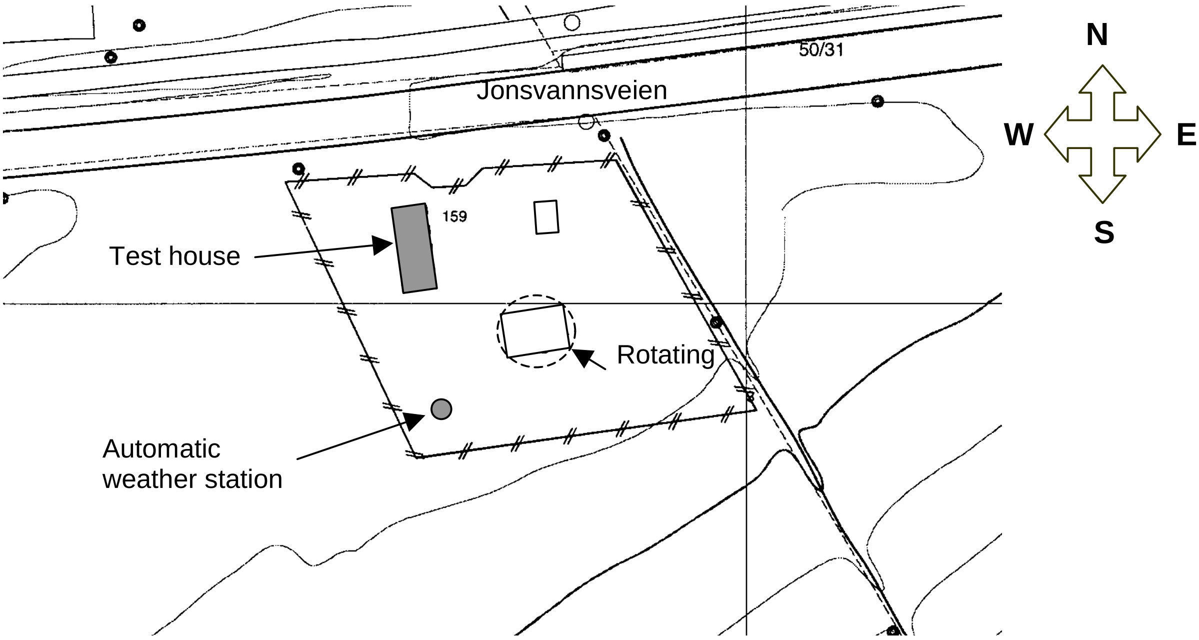


Figure 1 A map showing the field station

Figure 2 The northeast side of the test house.

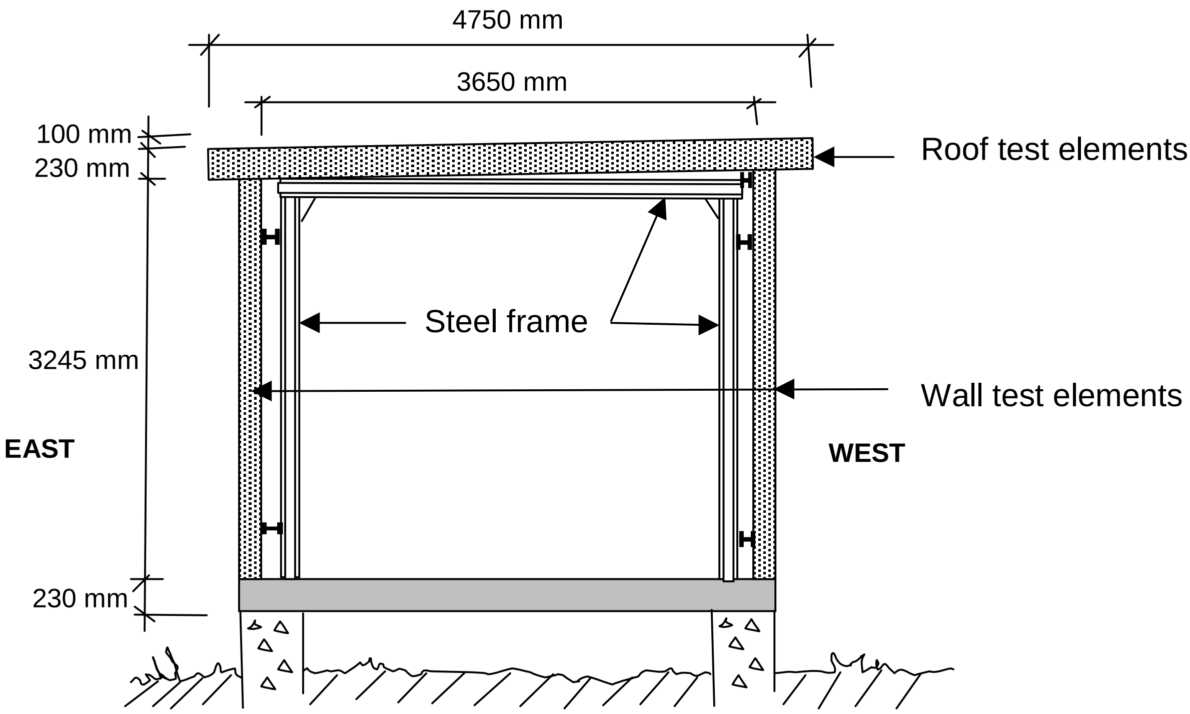


Figure 3 East-west section of the test house showing how the elements are fixed to the steel frame structure.

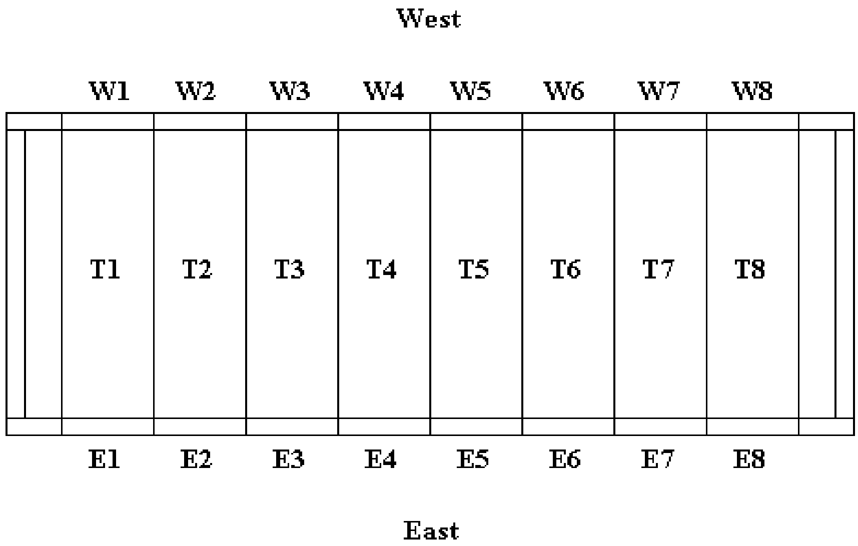


Figure 4 Plan of the test house in Trondheim, showing the location of the wall and roof test elements.

2.2 Logging system

The logging system is a combined system of loggers and communication software on PC. Three loggers (Campbell CR 10) are each connected with the measurement sensors trough a multiplexer (Campbell AM 32 B), see figure 5. For the temperature measurements a common reference was used for each multiplexer. The loggers each have an internal temperature reference, but they were also connected with an external temperature reference (Campbell 10TCRT Thermocouple Reference).
Because of very high electrical resistance (low levels of electrical current) coaxial cables were used for the moisture measurements to avoid that electrical noise from other electrical cables and equipment influenced the measurement signals. To convert the measurement signals (voltage) to moisture content a converter (Delmhorst MT(G) 40) was inserted between the loggers and the multiplexers. This conversion is further described in chapter 4.1. The logging system is more thoroughly described and documented in (Homb, 1998).

2.3 Heating and ventilation

The test house is equipped with a low temperature electric floor heating system, i.e. a Flexel Mark III heating foil with maximum power output of 90 W/m^2. The heating foil is automatically regulated through a thermostat with a temperature sensor in the room air. Throughout the measurement period the temperature of the room was maintained at approximately 23 °C.
The house is ventilated with a balanced mechanical ventilation system (Covent Master CM1) with heat recovery and an automatic air humidifying system. The air flow rate can be controlled between 60-200 m^3/h. The ventilation system will normally give a constant air change rate of 0,5 m^3/m^{3}h. The supply air is heated to the setpoint temperature of the room with an air heater battery. The air supply to the room is through a spiral wound tube with a diameter of 160 mm in the whole length of the house. Holes have been made in the tube to ensure that the supply air is spread evenly in the length of the room, and possibly also in the width and height of the room.

The air humidifying system (Steamatic) automatically adds water vapour to the supply air to maintain the wanted level of relative humidity in the room air. Throughout the measurement period the RH of the room was maintained at approximately 50 %.

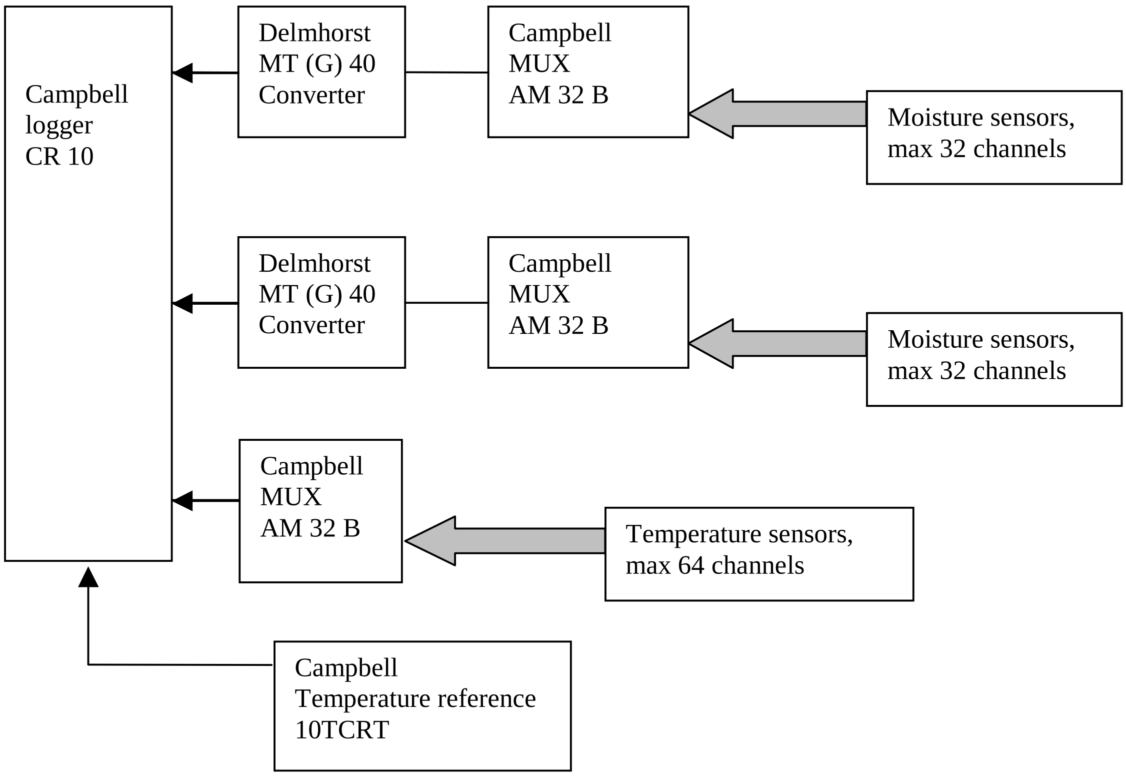


Figure 5 Connection of measurement sensors to one of the three loggers.

2.4 Automatic weather station

Outdoor climatic data are measured by a Milos 500 Vaisala automatic weather station (AWS) located 17 m to the south of the test house, see Figure 1. A picture of the weather station is shown in Figure 6. Hourly values of air temperature, relative humidity, air pressure, wind speed, wind direction, precipitation, global radiation and longwave radiation are recorded. Daily average values of outdoor air temperature, relative humidity and global radiation for the measurement period is shown in figure 7. Occasionally, when weather data are missing they are reconstructed from three other local weather stations (respectively 1, 2 and 40 km from the test house). The sensors used in the Milos 500 Vaisala AWS are shown in Table 1.

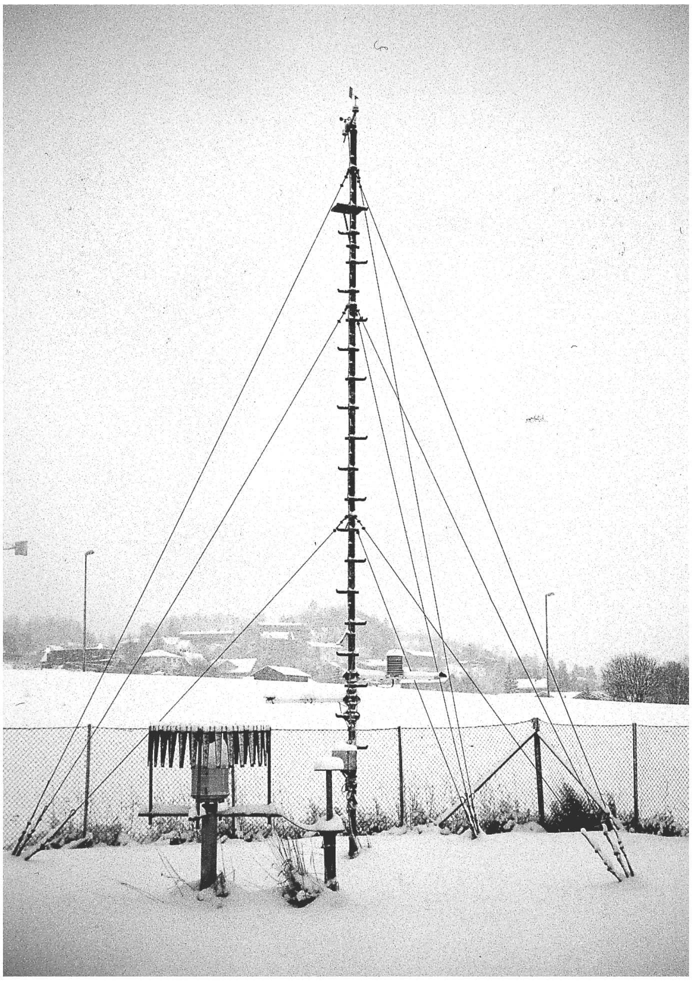


Figure 6 The automatic weather station .

Table 1 Sensors used in the Milos 500 Vaisala AWS

Type	**Trade name**
Air temperature and humidity sensor	Vaisala HMP 35D
Pressure sensor	Vaisala DPA 21
Wind speed sensor	Vaisala WAA 15A
Wind direction sensor	Vaisala WAV 15A
Precipitation amount	Geonor
Precipitation detector	Vaisala DRD 11A
Solar radiation pyranometer	Kipp & Zonen CM 6B
Pyrgeometer	Kipp & Zonen CG 1

The AWS has been operating since 15. March 1995. From 1. March 1996 the Norwegian Meteorological Institute took over the operation of the AWS, ensuring a good quality of the measurements. Since then there is only missing data for a few and short periods. Before 1. March 1996 there were several periods when the AWS was not working. The most serious breakdown took place in the period 15. October 1995 - 29. February 1996 because of serious vandalism on the weather station.
In Table 2 are shown the format of the meteorological parameters measured and recorded since 1. March 1996. These data can be read by a spreadsheet, with the parameters number 1 - 29 in a row, one row for every hour.

Table 2 Format of the meteorological parameters measured and recorded since 1. March 1996

No.	Symbol	Parameter	Unit
1	TT	Temperature, last minute last hour	°C
2	TTM	Temperature, average last hour	°C
3	TTN	Temperature, minimum last hour	°C
4	TTX	Temperature, maximum last hour	°C
5	UU	Relative humidity, last minute last hour	%
6	UUM	Relative humidity, average last hour	%
7	FF	Wind speed, last 10 minute average last hour	m/s
8	FM	Wind speed, average last hour	m/s
9	FG	Wind speed, 3 seconds max. gust last hour	m/s
10	FX	Wind speed, max. 10 minute running average last hour	m/s
11	DD	Wind direction, belongs to FF (0° = north, 90° = east, etc)	°
12	DM	Wind direction, belongs to FM	°
13	DX	Wind direction, belongs to FX	°
14	RA	Total content in rain gauge	mm
15	RR	Increase in rain gauge last hour	mm
16	RT	Number of minutes precipitation last hour	0 - 60
17	PO	Air pressure in height of station, last minute last hour	hPa
18	POM	Air pressure in height of station, average last hour	hPa
19	PON	Air pressure in height of station, minimum last hour	hPa
20	POX	Air pressure in height of station, maximum last hour	hPa
21	PP	Air pressure, reduced to sea level, standard formulae	hPa
22	PF	Air pressure, reduced to sea level regarding temperature	hPa
23	PT	Air pressure difference, 3 hours	hPa
24	AA	Air pressure characteristics, 3 hours (SYNOP-code)	0 - 8
25	QO	Global radiation, accumulated last hour	W/m^2
26	QOX	Global radiation, maximum last hour	W/m^2
27	QL	Longwave radiation, accumulated last hour	W/m^2
28	QLX	Longwave radiation, maximum last hour	W/m^2
29	SS	Snow depth, last minute last hour	cm

The AWS measures most parameters every five seconds (wind every second). Averages over 60 seconds are calculated (minute values), and these are used to find the hourly values described in Table 2. The hourly values are generated at every shift of hour and consist of:

- Instantaneous value = minute average last minute before shift of hour
- Maximum value = maximum minute average last hour
- Minimum value = minimum minute average last hour
- Average value = average of all minute values last hour

Regarding longwave radiation it should be noted that it is the longwave downward radiation to the instrument (L_{down}) that is measured (QL and QLX in Table 2), and not the net longwave radiation (L_{net}). L_{down} is calculated with the following formulae:

$$L_{down} = \frac{V}{K} + 5.67 \cdot 10^{-8} \cdot T_s^4$$

where V is output of the pyrgeometer (V), K is a calibration factor (Vm^2/W) and T_s is the sensor temperature (K). If net longwave radiation (L_{net}) is wanted the longwave radiation part of the formula above should be subtracted for the specific medium. For example for the sensor L_{net} is calculated as follows:

$$L_{net} = L_{down} - 5.67 \cdot 10^{-8} \cdot T_s^4$$

Climatic data for the period before 1. March 1996 are available, but fewer parameters are available for that period. The period that is available is 1. October 1994 - 1. March 1996. It should be noted that during this period the AWS partly had not started measuring and partly was not working. That means that for some periods we had to reconstruct data from other climatic stations, as shown in Table 3.

Table 3 Main climatic stations used for different periods

Period	Climatic station	Comments
01.10.94-15.03.95	Moholt AWS	
15.03.95-01.09.95	Voll AWS	Many small holes in measurements
01.09.95-01.03.96	Moholt AWS	
01.03.96-	Voll AWS	Operated by DNMI, few holes in measurements

For the period 01.10.94-30.09.95 climatic data from several other stations or measurement sites were employed when data was missing from both Voll AWS and Moholt AWS. These stations/measurement sites were as follows: 1) Risvollan AWS, 2) Værnes airport (main observations by DNMI), 3) Stokkanhøgda (global radiation at a single-family house) and 4) Surface temperatures from test house Voll.

In addition to climatic data for the period 01.03.96 and until today, which are available on the format described in Table 2, climatic data for the whole period 01.10.94 and until today are available on a simplified format described in Table 4. This format that contain only a few parameters have been used to generate climatic files for different heat-, air- and moisture programs.

Table 4 Format of simplified hourly climatic data available for the whole period 01.10.94 and until today (available on EXCEL-format).

No.	Parameter	Unit
1	Temperature, average last hour	°C
2	Relative humidity, average last hour	%
3	Global radiation, accumulated last hour	W/m^2
4	Wind speed, average last hour	m/s
5	Cloud cover (1-8)*	-

* The value is either picked from Værnes airport (01.10.94-30.09.95) or chosen equal to 5.

In addition to global radiation, most heat-, air- and moisture programs also require values for diffuse- and direct solar radiation. A program ("vollfil") was developed that estimated the hourly values of diffuse and direct solar radiation from global radiation. This was based on a method described in (Skartveit and Olseth, 1988). The program reads a climatic file on the format described in Table 4 and is then able to generate climatic files including diffuse- and direct solar radiation on different formats.

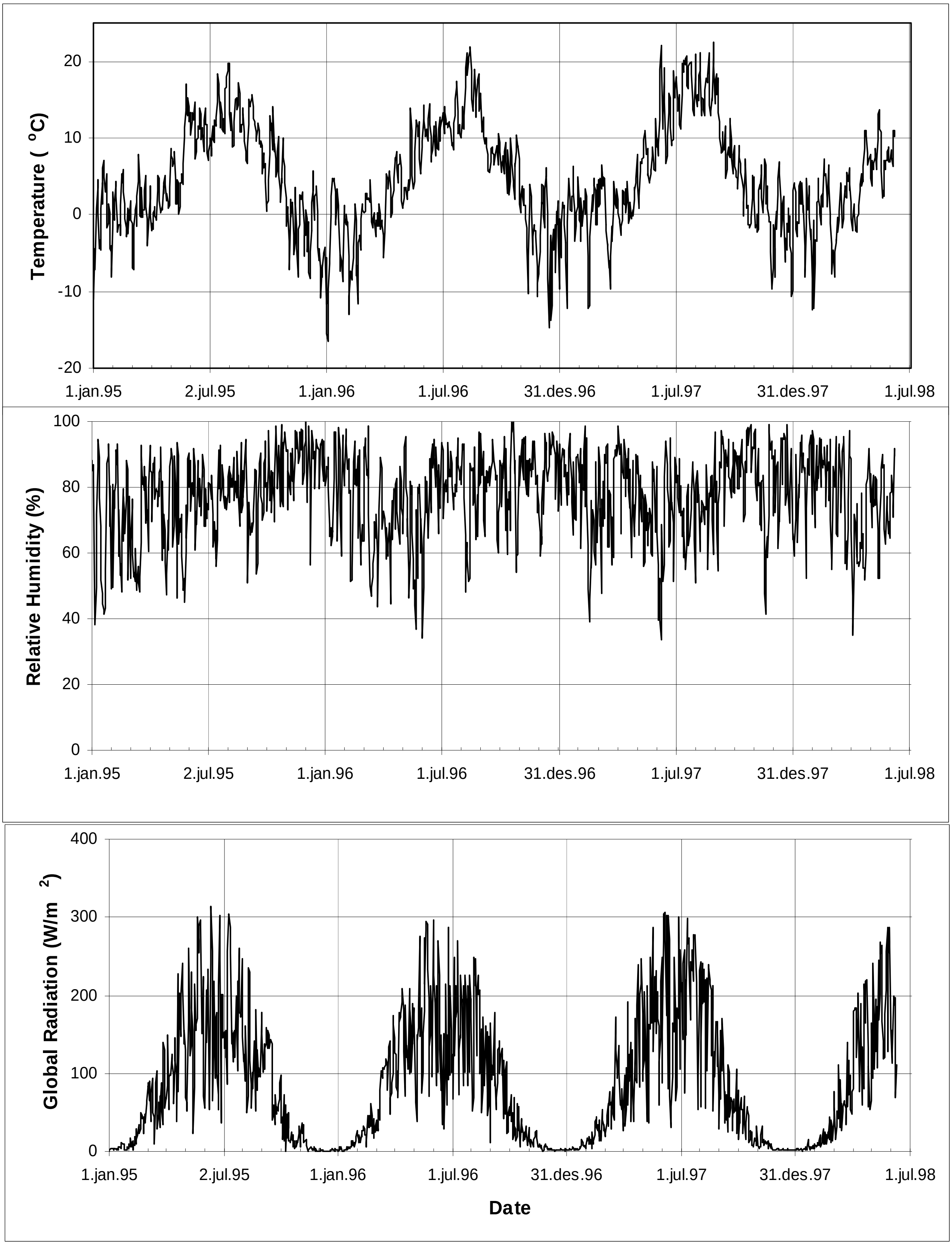


Figure 7 Outdoor climate measured at the automatic weather station (daily averages).

3 DESCRIPTION OF WALL AND ROOF SECTIONS

3.1 Wall sections

The overall dimensions of the wall sections are 1190 mm x 3250 mm, with stud and top/bottom plate dimensions of 48 mm x 148 mm (spruce), except of section E8 with 300 mm wood I-joists (46 mm x 46 mm wood flanges, 10 mm particle board web). To achieve normal conditions for natural convection, the height of the insulated cavities was made normal (2418 mm) by mounting an extra “sill plate” in the wall sections approximately 0.9 m above the floor level as shown in figure 8. The “E” and “W” sections were located on the eastern and western facades respectively. A PE-foil isolated the test wall perimeter from the surrounding constructions in terms of mass transfer, and adiabatic conditions were maintained at the wall perimeter with respect to heat transfer.
The wall sections are described in detail in table 5 and figures 9 -10. All the timber frame walls have 150 mm glass fibre insulation (density ≈ 18 kg/m^3, thermal conductivity = 0,036 W/mK), except section E8 which has 300 mm insulation and a timber frame made of wooden I-joists instead of solid spruce. All the wall sections, except sections W2, W5, E5 and E6, have a 23 mm ventilated air gap and 19 mm shiplap cladding outside of the wind barrier. Section W2 has 19 mm shiplap cladding but no air gap between the wind barrier and the cladding. Section W6 has two noggings with 0.8 m spacing).

Table 5 Description of materials used in the various wall sections. W1 and E1 denote section no. 1 on the western facade and eastern facade respectively.

Sections	Internal lining	Vapour barrier	Wall construction/insulation	Wind barrier
W1	wood fibre board 12 mm	polypropylene foil (wind barrier)	timber frame wall (48x148 mm) / 150 mm glass fibre	wood fibre board 3 mm
W2* + W3	wood fibre board 12 mm	polypropylene foil (wind barrier)	timber frame wall (48x148 mm) / 150 mm glass fibre	gypsum board 9 mm
W4 + E4	wood fibre board 12 mm	-	timber frame wall (48x148 mm) / 150 mm glass fibre	gypsum board 9 mm
W5 + E5	-	-	LECA-block 250 mm/ 80 mm PUR-insulation in the middle	-
W6	gypsum board 9 mm	-	timber frame wall (48x148 mm) with noggings / 150 mm glass fibre	gypsum board 9 mm
W7 + W8	gypsum board 9 mm	-	timber frame wall (48x148 mm) / 150 mm glass fibre	gypsum board 9 mm
E1	wood fibre board 12 mm	polyethylene foil 0.15 mm	timber frame wall (48x148 mm) / 150 mm glass fibre	asphalt impr. wood fibre board, 12 mm
E2 **	wood fibre board 12 mm	polyethylene foil 0.15 mm	timber frame wall (48x148 mm) / 150 mm glass fibre	spunbonded polyethylene foil
E3**	wood fibre board 12 mm	polyethylene foil 0.15 mm	timber frame wall (48x148 mm) / 150 mm glass fibre	polypropylene foil
E6 + E7	-	-	aerated concrete 300 mm	-
E8	wood fibre board 12 mm	-	timber frame wall (300 mm I-joists) / 300 mm glass fibre	gypsum board 9 mm

* No air gap between the wind barrier and the cladding.
** In September 1996 the wall sections E2 and E3 were modified. The wind barrier of section E3 was changed to 9 mm gypsum board. For both sections a horizontal 3 mm wide gap was sawn through the internal lining and vapour barrier near the bottom sill, and a similar gap through the wind barrier near the top sill at the external side.

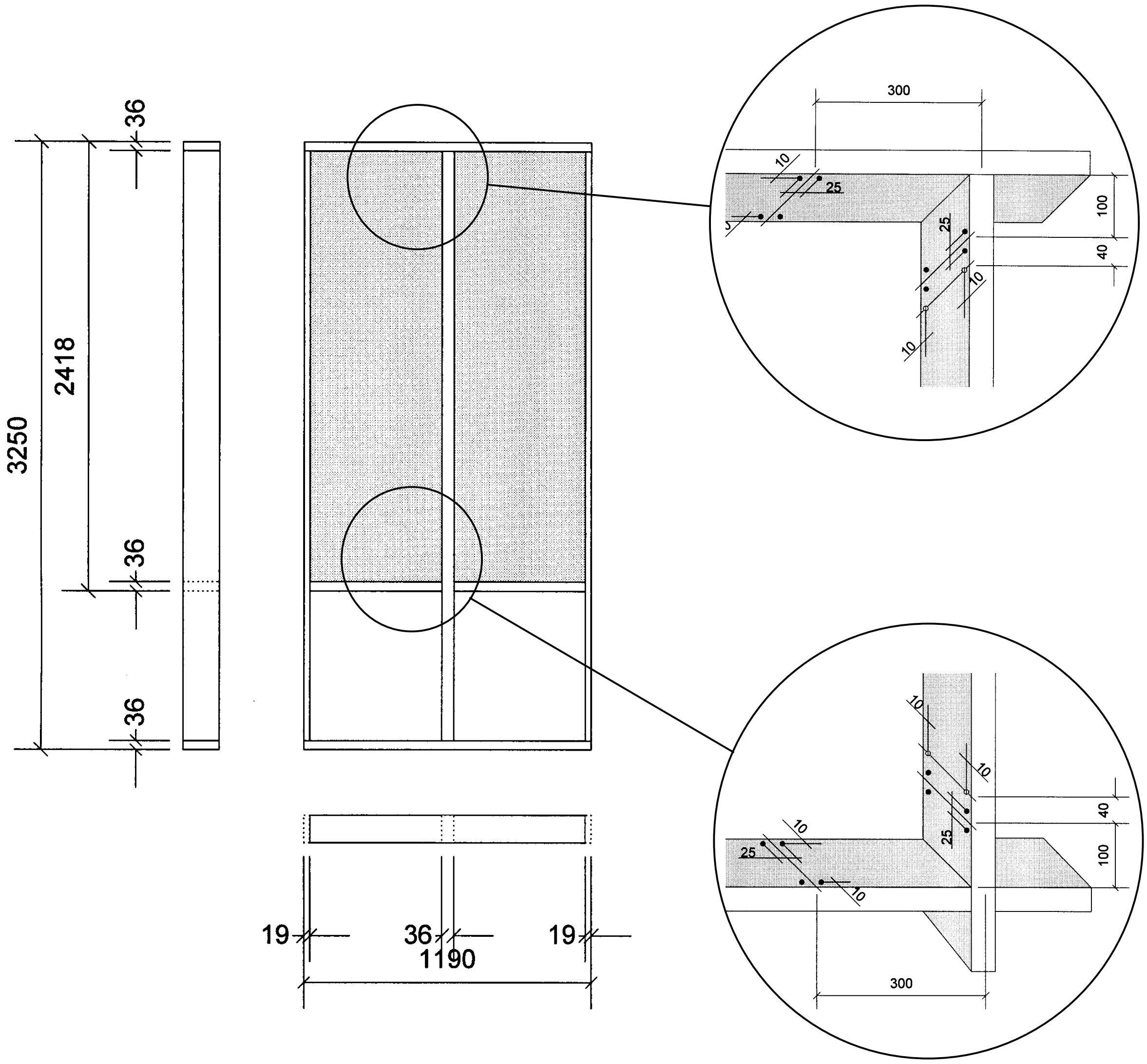


Figure 8 Dimensions of the timber frame wall sections, in mm. The location of the sensors for measuring moisture content (• •), and temperature (◦) to the right.

One of the purposes of the measurements was to investigate how untraditional combinations of indoor and outdoor water vapour resistance influence on the moisture conditions of timber frame walls. In table 6 is therefore shown the water vapour resistance on cold and hot side and the ratio, for the timber frame walls. The water vapour resistances on the cold side were probably somewhat lower during the winter than the values given in table 6. This because the water vapour resistance of a material is dependent on the moisture content, especially for wood based materials. During the winter the RH for the wind barriers were probably higher than 72 %, which is the average RH-level for the cup-measurements of which table 6 is based on.

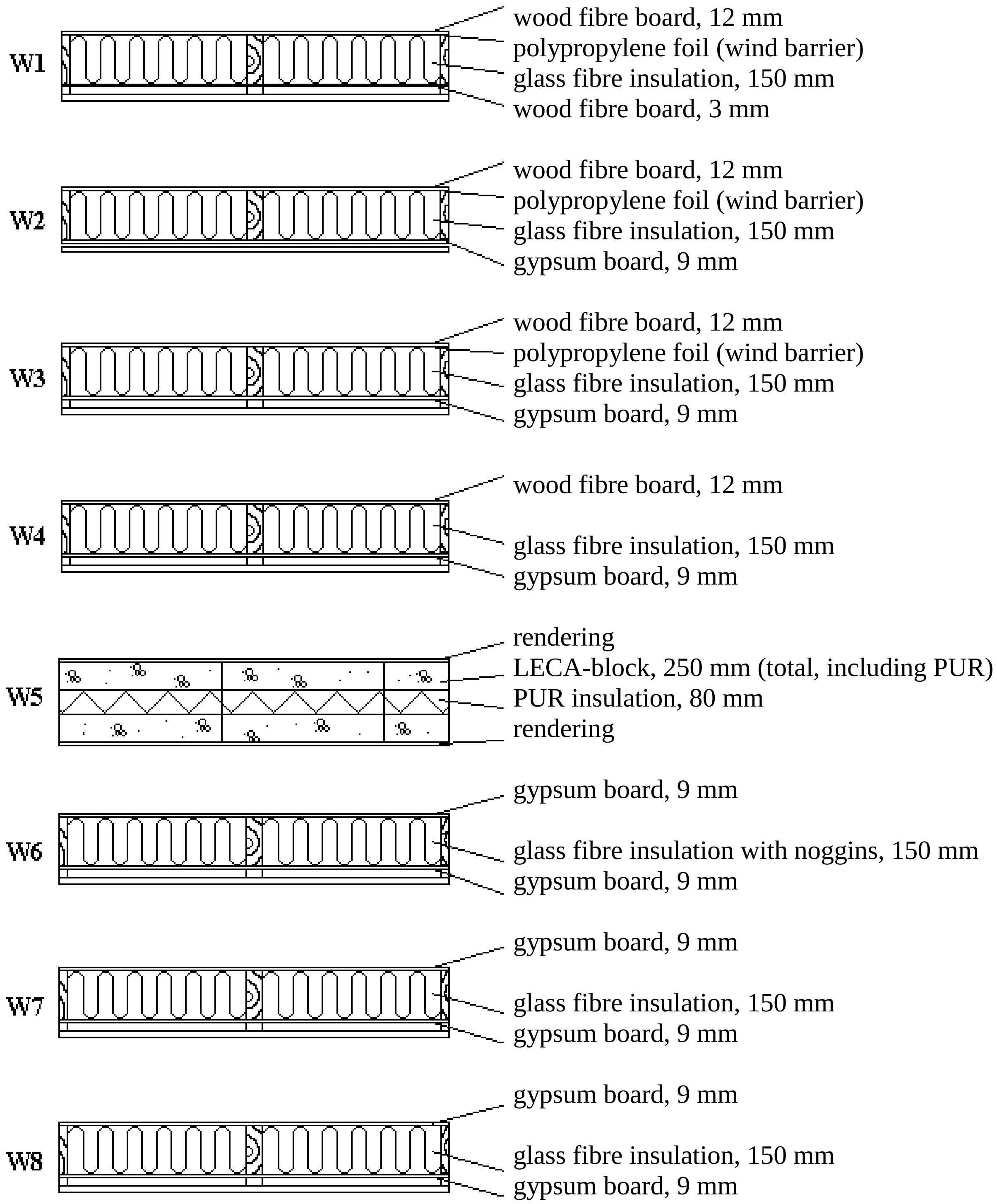


Figure 9 Wall sections of the western facade.

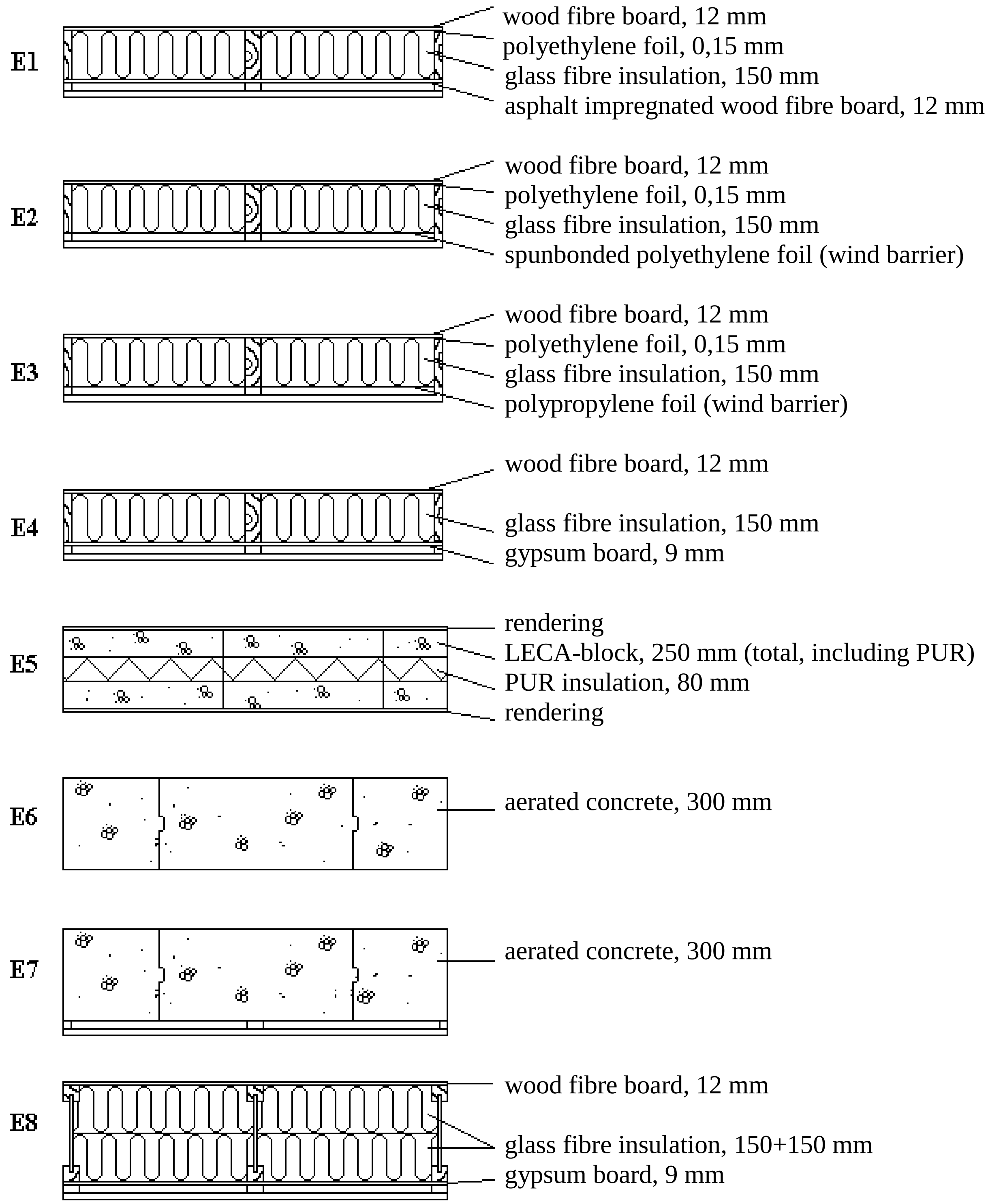


Figure 10 Wall sections of the eastern facade.

Table 6 Water vapour resistance (diffusion equivalent air layer thickness) on hot and cold side of the timber frame walls. "Ratio" is water vapour resistance on the hot side divided by the water vapour resistance on the cold side.

Wall section No	Water vapour resistance, diffusion equivalent air layer thickness, s_d [m] Hot side	[m] Cold side	[-] Ratio
W1	5,0	0,14	35
W2	5,0	0,08	62
W3	5,0	0,08	62
W4	0,53	0,08	7
W6	0,08	0,08	1
W7	0,08	0,08	1
W8	0,08	0,08	1
E1	64	0,23	280
E2	64	0,02	3200
E3	64	4,4	14
E4	0,53	0,08	7
E8	0,53	0,08	7

3.2 Roof sections

The overall dimensions of the roof sections were 1190 mm x 4750 mm, as shown in figure 11. The roof sections are described in detail in table 7 and figure 12. A PE-foil isolated the roof section perimeter from the surrounding sections in terms of mass transfer, and adiabatic conditions were maintained at the test section perimeter with respect to heat transfer.
The timber frame roof sections (R1-R6) consists of the following materials from the interior; 12 mm chipboard, 0,15 mm polyethylene foil, 200 mm glass fibre insulation (48x198 mm wooden rafters), 22 mm plywood and 1,3 mm PVC roofing membrane. In two of the timber frame roof sections (R5 and R6) the rafter spacing is 1.2 m to achieve 1-dimensional conditions in the middle of the section, while the other four timber frame roofs (R1-R4) have a more normal 0.6 m rafter spacing. In sections R5 and R6 the wooden rafters are separated from the rest of the section with a polyethylene foil (see Figure 12 and 18). The sections R7 and R8 consist of 300 mm and 200 mm aerated concrete respectively. R8 has a 100 mm layer of rockwool fibre insulation on the top.

Table 7 Description of materials used in the various roof sections.

Sections	Internal lining	Vapour barrier	Roof construction/ insulation	Roofing
R1	chipboard 12 mm	polyethylene foil, 0.15 mm	timber frame (48x198 mm) / 200 mm glass fibre	22 mm plywood/ 1.3 mm PVC roofing membrane (dark side upwards)
R2 + R3 + R4	chipboard 12 mm	polyethylene foil, 0.15 mm	timber frame (48x198 mm) / 200 mm glass fibre	22 mm plywood/ 1.3 mm PVC roofing membrane (light side upwards)
R5	chipboard 12 mm	polyethylene foil, 0.15 mm	timber frame* / 200 mm glass fibre	22 mm plywood/ 1.3 mm PVC roofing membrane (light side upwards)
R6	chipboard 12 mm	polyethylene foil, 0.15 mm	timber frame* / 200 mm glass fibre	22 mm plywood/ 1.3 mm PVC roofing membrane (dark side upwards)
R7	-	-	aerated concrete 300 mm	1.3 mm PVC roofing membrane (dark side upwards)
R8	-	-	aerated concrete 200 mm, 100 mm rockwool	1.3 mm PVC roofing membrane (dark side upwards)

* Spacing between rafters is 1.2 m. The thermal insulation is isolated from the two rafters regarding mass transfer by use of PE-foil, see figure 12 and 18.

Four elements (R1, R6-R8) have a dark coloured roofing membrane (emissivity ≈ 0.9), while the other four have the same roofing membrane, but the light side facing upwards (emissivity ≈ 0.65).

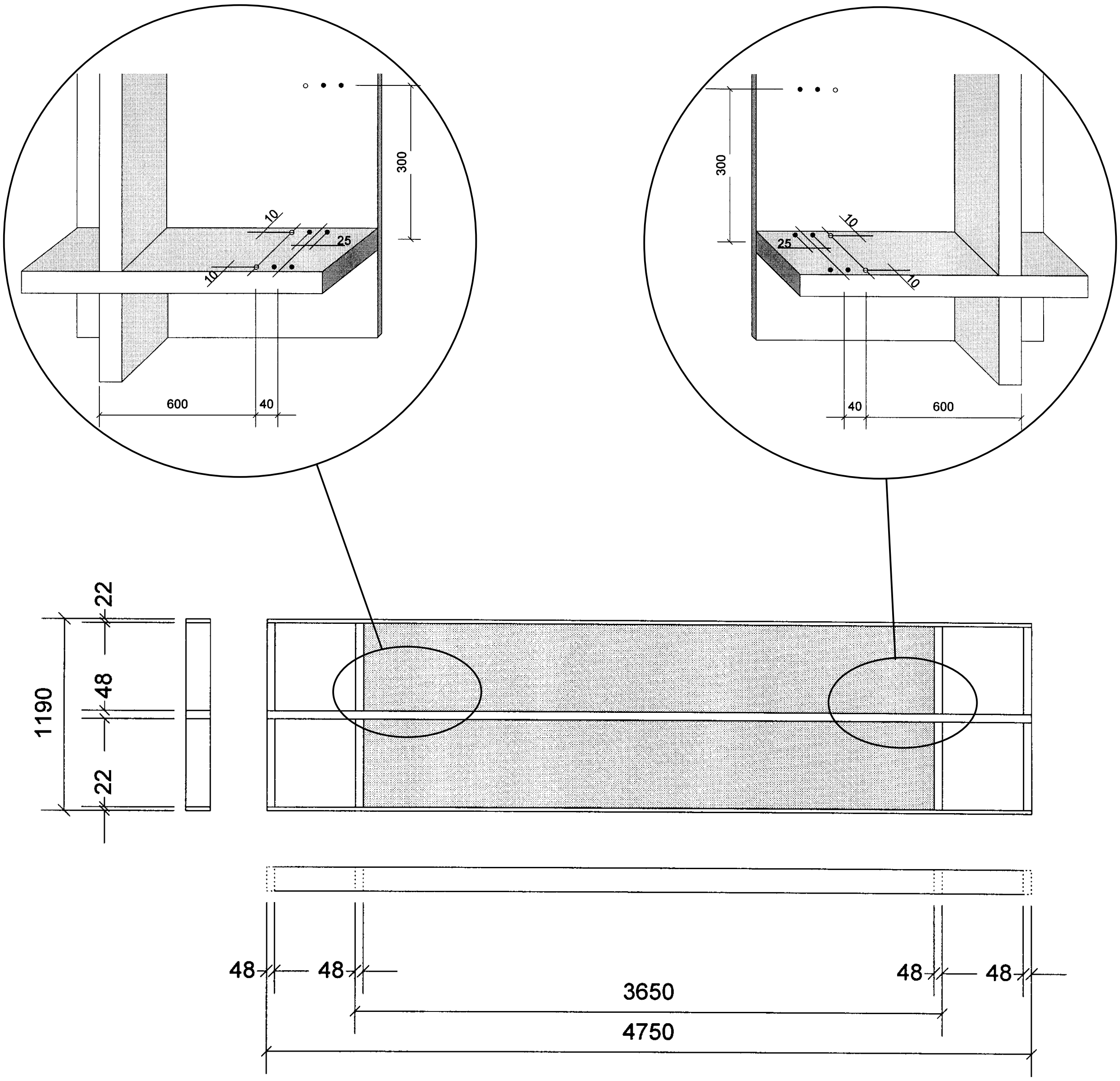


Figure 11 Dimensions of the timber frame roof sections R1-R6, in mm. The location of the sensors for measuring moisture content (• •), and temperature (◦) at the top.

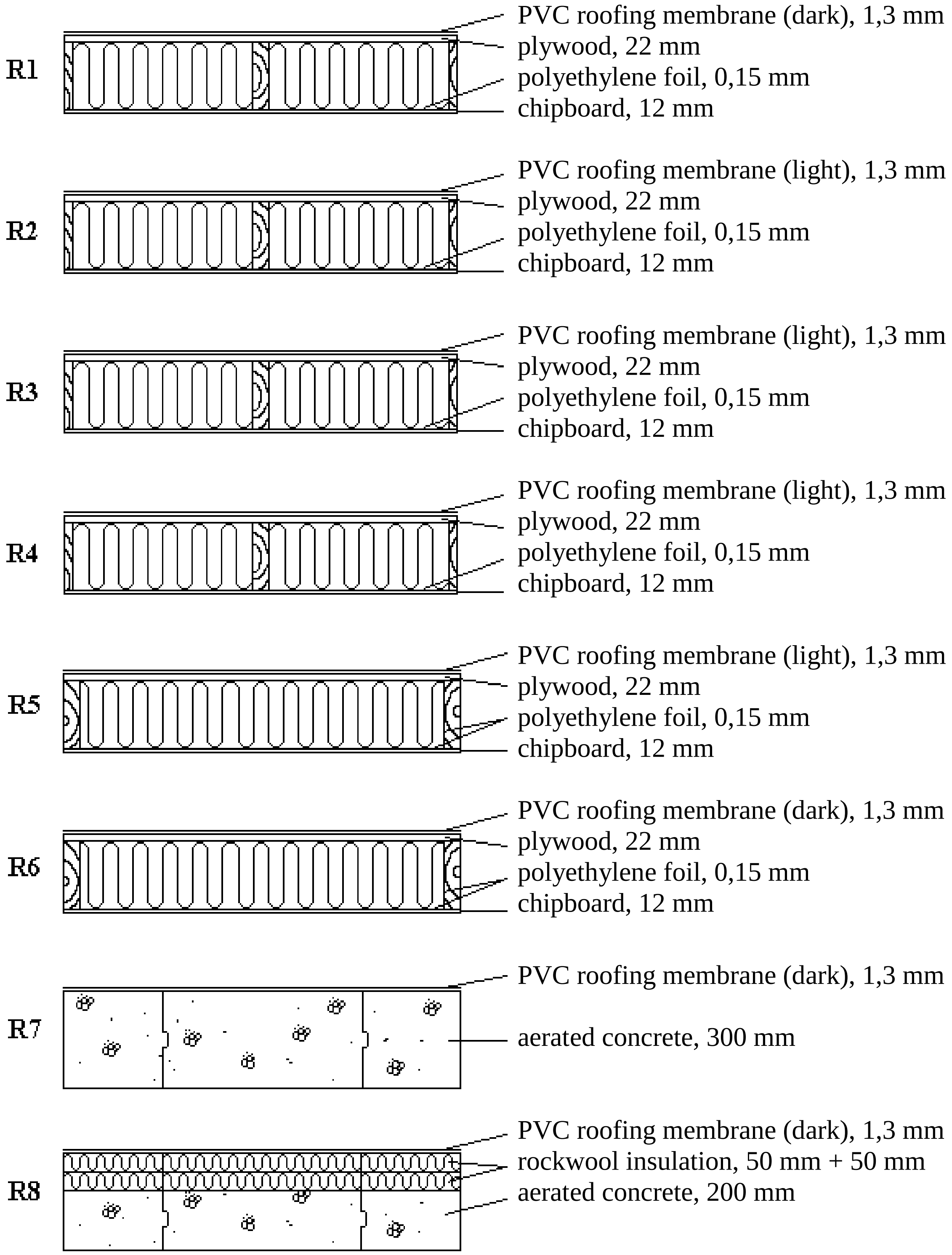


Figure 12 Roof sections. The timber frame sections are insulated with 200 mm glass fiber insulation.

3.3 Materials used in wall and roof sections

The trade name, manufacturer in Norway, thickness and density of the materials used in the test sections are given in Table 8. All the wall and roof sections (except E5 and W5) were all prefabricated indoors in a partly heated environment. This means that all the materials that were used were relatively dry at installation. It is assessed that the various materials were at moisture equilibrium at approximately 60% RH, which can be used as initial moisture conditions. At installation of the elements the moisture content of the wooden parts (studs, top/bottom sills) were measured to be approximately 11 weight%.

Table 8 Specification of materials used in the test house

Material	Trade name in Norway / manufacturer *	Thickness [mm]	Density [kg/m^3]
Aerated concrete	"Siporex vegg/tak element" / Siporex A/S, Norway	-	474
Asphalt impregnated wood fibre board, porous	"Asfalt vindtett" / Hunton Fiber A/S, Norway	12	251
Glass fibre insulation	"Glava matte A 36"/ Glava A/S, Norway	100/150	18
Gypsum board, exterior grade	"GU, Utvendig gipsplate" / Norgips A/S, Norway	9	757
LECA-block	"LECA-isoblokk" / as Norsk Leca	250	
Plywood **	"WBP P-30, Vänerply takplater" / Vänerply AB, Sweden	22	411
Polyethylene foil, 0.15mm (PE-building membrane)	"Tenotett" / Rosenlew AB, Sweden	0.15	
Spunbonded polypropylene foil, wind barrier	"Rockwool airbarrier" / Reemay Inc., USA	0.27	
PVC roofing membrane	"Sarnafil SE 3" / Protan A/S, Norway	1.3	
Rockwool insulation	"Rockwool" / a/s Rockwool, Norway	50 + 50	~ 150 + ~ 90
Norway spruce (Picea abies)			350-465
Spunbonded polyethylene foil, wind barrier	"Isola vindsperre (Tyvek)" / Du Pont de Nemours, Luxemb.	0.14	
Wood chipboard	"Sponplate" / Norske skogindustrier A/S	12	554
Wood fibre board (hardboard)	"Huntonit bygningsplate" / Hunton Fiber A/S, Norway	3 / 11	803

* The reader is cautioned that manufacturers may change products over time while retaining the same brand name.
** Material of spruce or pine, number of layers = 7.

3.4 Hygroscopic material properties

To be able to simulate the hygrothermal conditions of the various constructions the material properties have to be known. The most important material properties in this context are probably the water vapour permeability and the hygroscopic sorption curves. These two properties have been measured for most of the materials used in the constructions in the test house, and the results are presented in table 9-11. A more detailed presentation of these measurements and results are given in (Bergheim et.al, 1998) and (Geving, Time and Hovde, 1999). Air permeability of the glass fibre insulation has also been measured (Økland, 1998).

Table 9 Water vapour permeability for spruce measured in the transverse direction, i.e. a combined radial/tangential direction, for various RH-levels (with standard deviation σ). The values represent a mean value for thickness ranging from 2.4 mm to 10 mm.

Material	Density $kg \cdot m^{-3}$	Water vapour permeability ± σ ($10^{-12} \cdot kg \cdot m^{-1} \cdot Pa^{-1} \cdot s^{-1}$)		
		$\overline{RH}$: 31%	63%	72%
Spruce *	350-380	1.75 ± 0.34	6.01 ± 0.51	
Spruce *	440-465		3.94 ± 0.09	7.23 ± 0.26

* The measurements of the vapour permeability of spruce are more thoroughly reported in [Time, 1998].

Table 10 Measured water vapour permeance (with standard deviation σ) and corresponding equivalent air layer thickness. Average RH-level during measurements was 72 % (50%/94%).

Material	Thickn. mm	Density (kg/m^3)	Water vapour permeance ± σ ($10^{-12} \cdot kg \cdot m^{-2} \cdot Pa^{-1} \cdot s^{-1}$)	Equivalent air layer thickness ± σ (m)
Aerated concrete	21	474	1180 ± 70	0.165 ± 0.01
Asphalt impregnated wood fibre board, porous	12	251	845 ± 264	0.231 ± 0.10
Gypsum board, exterior grade	9	757	2430 ± 80	0.080 ± 0.003
Plywood	22	411	145 ± 10	1.34 ± 0.10
Polyethylene foil, vapour barrier	0.15		3.09 ± 0.57	63.0 ± 14
Polypropylene foil, wind barrier	0.27		44.1 ± 3.3	4.4 ± 0.4
PVC roofing membrane	1.3		15.0 ± 1.1	13.0 ± 1.0
Spunbonded polyethylene foil, wind barrier	0.14		9720 ± 760	0.020 ± 0.002
Wood fibre board, high density	11	803	371 ± 25	0.525 ± 0.04

Table 11 Measured equilibrium moisture contents (weight-%) for adsorption and desorption curves.

	Wood chipboard		Wood fibre board (hardboard)		Plywood		Aerated concrete		Spruce	
RH (%)	Ads.	Des.	Ads.	Des.	Ads.	Des.	Ads.	Des.	Ads.	Des.
11.3	-	-	-	3.4	-	3.8	-	1.01	-	3.1
32.9	5.7	-	5.1	7.2	6.8	8.3	0.23	1.40	7.2	7.8
53.5	7.7	-	7.0	8.8	8.9	10.3	0.44	1.59	9.6	10.0
75.4	10.6	-	9.6	12.1	12.2	14.8	0.93	1.89	13.2	14.7
81.2	11.5	-	10.5	-	13.2	-	1.21	-	14.1	-
94	15.6	-	13.7	-	17.8	-	1.88	-	18.6	-
97.4	-	-	16.0	16.0	18.9	18.9	2.43	2.43	21.0	21.0

3.5 Air tightness measurements

The air tightness of the various wall sections was measured on site by blowing air through a tube, via an air-flow meter (type Rotameter), into the two insulation cavities of each section. By simultaneously controlling the indoor pressure of the test house, by use of an adjustable fan installed in the test house door, three types of air leakages were measured at several pressure differences in the range 5 to 50 Pa. The pressure differences between the wall cavity and indoor air (ΔP_{si}) and between indoor and outdoor air (ΔP_{ie}) were measured with micro-manometers. The air flow through the interior surface (Q_{si}), through the exterior surface (Q_{se}) and the sum of these two (Q_{se+si}) were measured. The sum Q_{se+si} was found by adjusting to zero the pressure difference between indoor and outdoor air, and vary ΔP_{si} between 5 and 50 Pa. Q_{se} was found by adjusting to zero the pressure difference between the wall cavity and indoor air, and vary ΔP_{ie} between 5 and 50 Pa. Q_{si} was found by adjusting to zero the pressure difference between the wall cavity and outdoor air, and vary ΔP_{si} between 5 and 50 Pa. The measurement setup is shown in figure 13.

On basis of these results, air leakage data for the various sections were estimated. It was assumed that there was no air leakage through the perimeter of the test sections or from the upper wall cavities to the "dummy" wall cavities in the bottom of the wall. The air leakage area used in the calculations of specific air leakage is therefore 2,88 m^2 (2,418m x 1,19 m) for each face of the wall. The specific air leakage through the wall section (q_{ie}), through the interior surface (q_{si}), through the exterior surface (q_{se}) and the sum of these two (q_{se+si}) were calculated. In figure 14 an example of these results are shown for section E1.

The dependance of specific air leakage to the pressure difference was found by curve fitting, using the following equation:

$$q = \alpha \cdot \Delta P^{\beta} \qquad (1)$$

where α and β are coefficients dependent of type of leakage and section. In table 12 these coefficients are given for each air leakage type, together with the specific air leakage at 50 Pa.

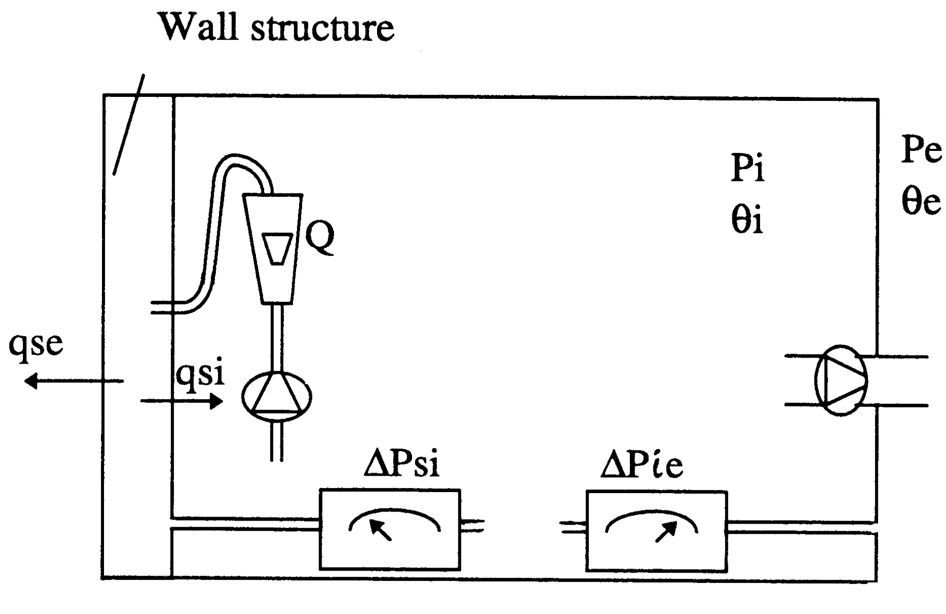


Figure 13 Sketch of air leakage measurements in the test house

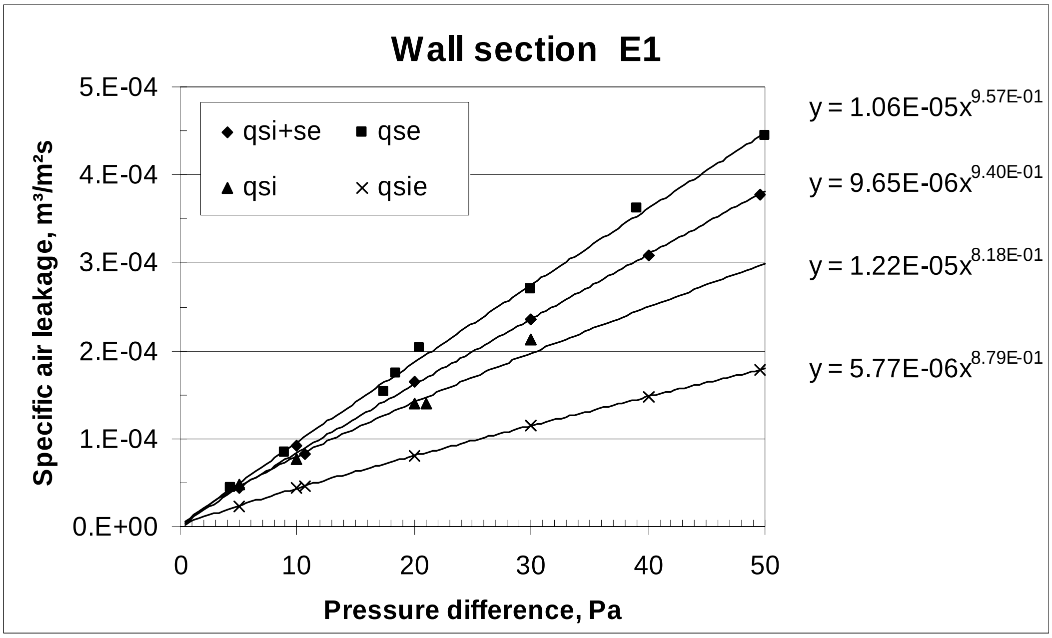


Figure 14 Example of results for specific air leakage for section E1.

Table 12 Specific air leakage of the various sections

Wall section	Coefficients α and β according to eq. (1)					Specific air leakage at 50 Pa [10^{-4} ·m^3/m^2s]			
		q_{si+se}	q_{se}	q_{si}	q_{ie}	q_{si+se}	q_{se}	q_{si}	q_{ie}
W1	β: α [10^{-5}]:	0,884 1,14	0,914 1,15	1,0 0,686	0,963 0,433	3,6	4,1	3,4	1,9
W2	β: α [10^{-5}]:	0,922 0,943	0,98 0,991	0,971 0,564	0,974 0,359	3,5	4,6	2,5	1,6
W4	β: α [10^{-5}]:	0,931 0,847	0,945 0,252	0,946 1,39	0,945 0,213	3,2	1,0	5,6	0,86
W6	β: α [10^{-5}]:	0,935 1,35	0,937 0,2	0,939 2,52	0,937 0,185	5,2	0,78	9,9	0,72
W7	β: α [10^{-5}]:	1.01 0,636	0,863 0,251	1,03 1,01	0,886 0,204	3,3	0,73	5,7	0,65
W8	β: α [10^{-5}]:	0,986 0,632	0,938 0,241	1,04 0,99	0,954 0,195	3,0	0,94	5,8	0,81
E1	β: α [10^{-5}]:	0,94 0,965	0,957 1,06	0,818 1,22	0,879 0,577	3,8	4,5	3,0	1,8
E2*	β: α [10^{-5}]:	0,875 5,71	0,802 7,37	0,723 9,53	0,763 4,18	17	17	16	8,3
E3**	β: α [10^{-5}]:	0,766 6,96	0,735 6,02	0,732 11	0,734 3,89	13,9	10,7	19,3	6,9
E4	β: α [10^{-5}]:	0,889 1,26	0,628 0,351	0,882 2,53	0,644 0,314	4,1	0,41	8,0	0,39
E8	β: α [10^{-5}]:	0,891 0,997	0,614 0,678	0,87 1,94	0,651 0,521	3,25	0,75	5,8	0,67

4 HYGROTHERMAL MEASUREMENTS

4.1 General

The measurements in the wall and roof sections started in October 1994 and lasted till June 1998. The logging system stores hourly mean values. What has been measured in each wall and roof element can be summarized as follows:

- *Timber frame wall sections (12 sections):* 8 moisture contents (bottom/top plate and studs) and 8 temperatures (bottom/top plate, studs and surfaces).
- *Timber frame roof sections (6 sections):* 2-6 moisture contents (beams and plywood) and 10 temperatures (beams, plywood and surfaces).
- *Wall and roof sections of aerated concrete (3 sections):* 3 relative humidities and 3 temperatures in holes in the aerated concrete.
- *Timber frame wall sections-special investigation of forced convection (2 sections).* 8 moisture contents (bottom/top plate and studs), 8 temperatures (bottom/top plate, studs and surfaces), 3 relative humidities/temperatures (insulation cavity).

Moisture content in wood

The moisture content of wood members was measured by traditional pin electrode resistance measurements. The measurement sequence was as follows:

1. The measurement output (voltage) was converted to moisture content using the converter Delmhorst MT(G) 40. The converter employs the following calibration curve:

   $$u_0 = -0{,}5 \cdot U^4 + 3{,}62 \cdot U^3 - 5{,}16 \cdot U^2 - 15{,}5 \cdot U + 40{,}2$$

   where u_0 is moisture content (weight%) not compensated for temperature and wood species and U is the output voltage (V).

2. u_0 is then compensated for temperature with the following formula:

   $$u_1 = \frac{u_0 + 0{,}567 - [0{,}026 \cdot (t + 2{,}8)] + [0{,}000051 \cdot (t + 2{,}8)^2]}{0{,}881 \cdot 1{,}0056^{t+2{,}8}}$$

   where u_1 is moisture content corrected for temperature t (°C).

3. u_1 is then compensated for wood species, i.e. in this case spruce:

   $$u = -1{,}5476 + 1{,}5986 \cdot u_1 - 0{,}01023 \cdot u_1^{\,2} - 0{,}001233 \cdot u_1^{\,3} + 0{,}000045 \cdot u_1^{\,4}$$

   where u is the corrected moisture content.

The diameter of the metal electrodes used was 2 mm and they were covered with 0.5 mm plastic except for 10 mm at the tip. The MC electrodes intruded from the insulation cavity side until a depth so that the unprotected part of the electrode was located 4-14 mm beneath the opposite wood surface (studs, sill plate and bottom plate). The location of the moisture electrodes in a top plate is shown in figure 15. The location of the moisture electrodes in the plywood in the roof sections is shown in figure 16. To avoid that condensed water at the wood surface could be transported into the wood along the moisture electrodes, silicone was used to tighten between the electrode and wood (see figure 15 and 16). The distance between the electrodes in a pair was 25 mm. In the wood MC range 7-25% the accuracy of the MC measurements is estimated to be within ±2 %, while values outside of this range have higher levels of uncertainties.

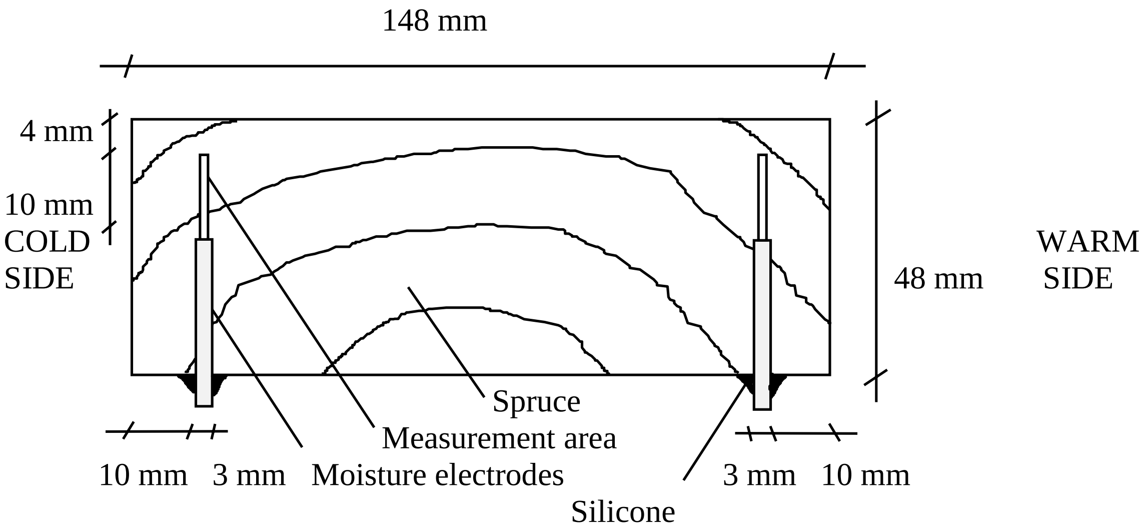


Figure 15 Detail of top plate in a timber frame wall section showing location of two pairs of moisture electrodes.

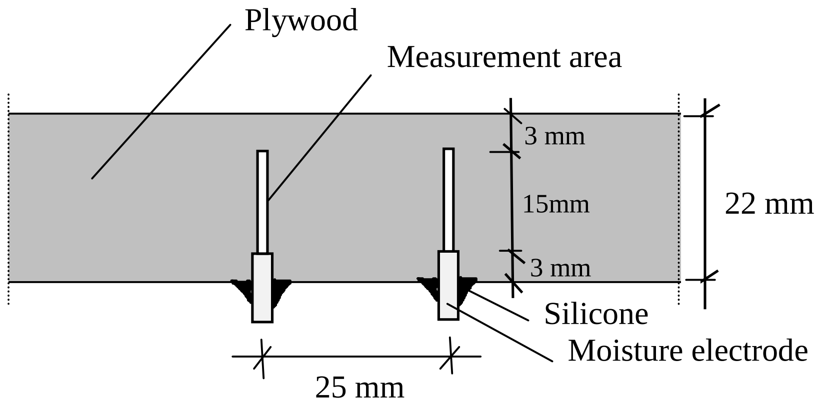


Figure 16 Detail of plywood in timber frame roof section showing location of a pair of moisture electrodes.

Identification system for measurement points

Each measurement point is given a unique alphanumeric 5 sign number which clearly identify the location of the measurement point, se Table 13 and 14. *Example:* E3U22 is a moisture content (U) measurement in the outer part of the top plate (22) in section E3.

Table 13 Identification system for measurement points, 5 sign number.

Position	Description
1.	R = roof section E = eastward wall section W = westward wall section A = measurements in indoor or outdoor air
2.	1 – 8 (number of each section starting from the southern section) I = indoor air O = outdoor air
3.	U = moisture content sensor T = temperature sensor F = relative humidity sensor
4-5.	Location within each section (see Table 14) 0-19 : temperature sensors 20-39: moisture content sensors 40-59: relative humidity sensors

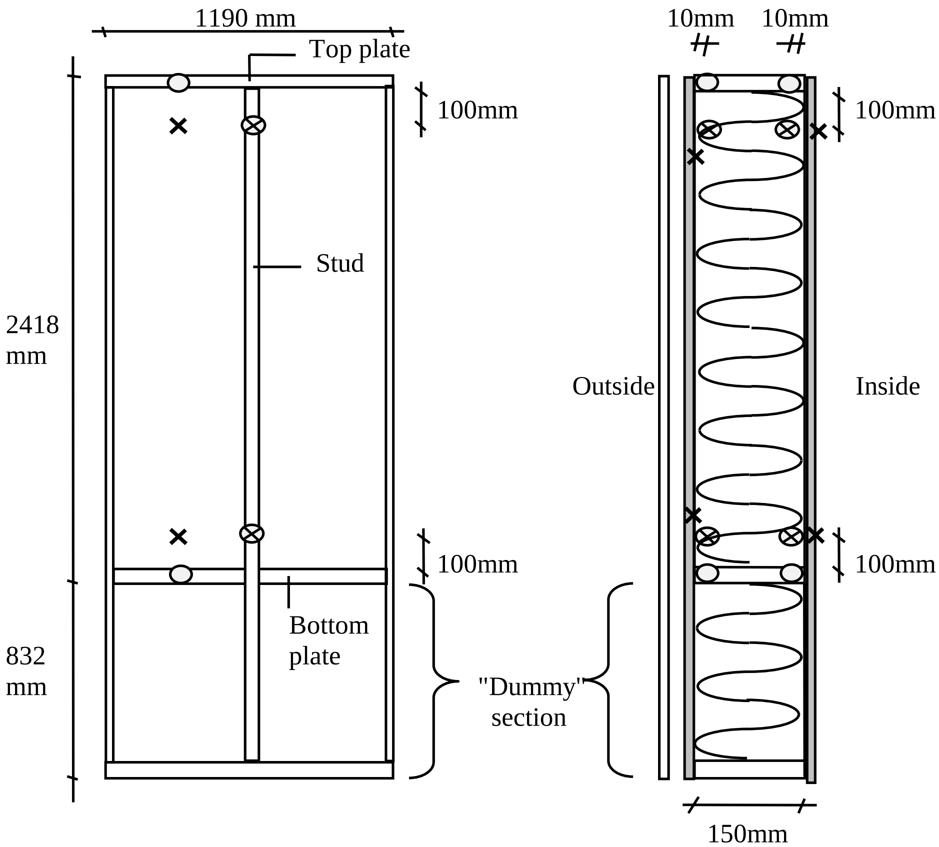
Table 14 Identification system for location of measurement points within each section, 4. and 5. position of the 5 sign number described in Table 14. Se also Figures 8 and 11 for location of the measurement points.

Sections	Location within each section	Number, 4. and 5. position		
		Sensor type		
		Moisture content	Temperature	Relative humidity
Timber frame walls	Sill plate, outer part	20		
	Sill plate, inner part	21		
	Top plate, outer part	22		
	Top plate, inner part	23		
	Stud, bottom, outer part	24	03	
	Stud, bottom, inner part	25	04	
	Stud, top, outer part	26	05	
	Stud, top, inner part	27	06	
	Wind barrier, bottom, inside		01	
	Wind barrier, top, inside		02	
	Indoor surface, bottom		07	
	Indoor surface, top		08	
Timber frame roofs	Roofing membrane, east, inward surface		01	
	Plywood, east, inward surface		02	
	Roofing membrane, west, inward surface		03	
	Plywood, west, inward surface		04	
	Plywood, east	20		
	Plywood, west	21		
	Beam, east, outer part	22	05	
	Beam, east, inner part	23	06	
	Beam, west, outer part	24	07	
	Beam, west, inner part	25	08	
	Indoor surface, east		09	
	Indoor surface, west		10	
Aerated concrete walls	Aerated concrete, top, outer part		04	44
	Aerated concrete, top, middle part		05	45
	Aerated concrete, top, inner part		06	46
	Aerated concrete, bottom, outer part *		07	47
	Aerated concrete, bottom, middle part *		08	48
	Aerated concrete, bottom, inner part *		09	49
Aerated concrete roofs	Aerated concrete, west, outer part		04	44
	Aerated concrete, west, middle part		05	45
	Aerated concrete, west, inner part		06	46
	Aerated concrete, east, outer part *		07	47
	Aerated concrete, east, middle part *		08	48
	Aerated concrete, east, inner part *		09	49

* Measurement locations that has not been used

4.2 Timber frame walls

The measurements in the timber frame wall sections started in October 1994 and lasted till June 1998. The top plates, the bottom plates and the studs were instrumented for moisture measurements on the cold as well as warm side of the constructions. Corresponding temperature measurements were only employed for the studs. In the studs moisture and temperature measurements were employed both in the top and bottom part of the wall. Surface temperatures were measured at the inside of the wind barrier and at the interior surface at the top and bottom section of the wall. The locations of the measuring devices for moisture content (MC) and temperature are shown in Figure 8 and 17. The moisture content of the timber frame members was measured by traditional pin electrode resistance measurements. The MC electrodes intruded from the insulation cavity side until a depth so that the unprotected part of the electrode was located 4-14 mm beneath the opposite wood surface as shown in figure 15. Surface temperatures were measured at the inside of the wind barrier and at the interior surface at the top and bottom part of the wall.



⊗ Location of MC sensors and thermocouples in studs
O Location of MC sensors in top and bottom plate
× Location of thermocouples at surfaces (wind barrier/insulation and interior surface)

Figure 17 The framework of the wall test section, with measuring points. The bottom part of the wall (the "dummy" section) is not included in the measurements. The dimensions of the figure are not in scale. See also figure 8.

4.3 Timber frame roofs

The measurements in the timber frame roof sections started in October 1994 and lasted till June 1998. The locations of the measurement points in the roof sections are shown in figures 11 and 18. Measurements were made in two different sections of the roof section, so every measurement location shown in figure 18 is represented by two parallel measurements.

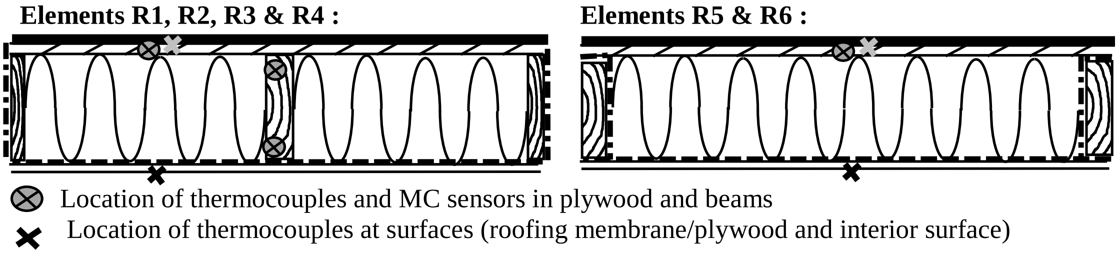


Figure 18 The framework of the timber frame roof sections, with measurement points. The dimensions of the figure are not in scale. See also figure 11.

4.4 Sections of aerated concrete

The measurements in the sections of aerated concrete started in February 1996 and lasted till June 1998. Relative humidity and temperature were measured in three different depths in the roof and wall sections. There were not performed any measurements in section E7. In section E6 the measurements were made in the top part of the wall, 1100 mm from the top. The location of the relative humidity and temperature sensors (type Vaisala) are shown in figure 19. The sensors were inserted into 24 mm drilled holes from a cylindric opening at the side of the element, see figure 20.

4.5 Investigation of forced convection in timber frame walls

In September 1996 the wall sections E2 and E3 were modified to investigate the effect of forced convection. The wind barrier of section E3 was changed to 9 mm gypsum board and both sections were perforated at both faces. A horizontal, 3 mm wide gap was sawn through the internal lining and vapour barrier near the bottom sill, and a similar gap through the wind barrier near the top sill at the external side. Relative humidity and temperature were then in a period measured at three heights in the middle of the insulation layer. Miniature RH- and temperature loggers (TinyTalk-loggers with the size of film boxes) were used for that purpose. In addition the air pressure was measured behind the ventilated cladding and at the interior, near the top and bottom parts of the wall. These measurements are described in more detail in (Økland, 1998).

4.6 Inspection of wall elements

At 16. December 1997 the shiplap cladding and the wind barrier on the timber frame walls were temporarily dismounted. Imperfections regarding air gaps between the mineralwool and the wood members/board materials were systematically photographed and recorded.

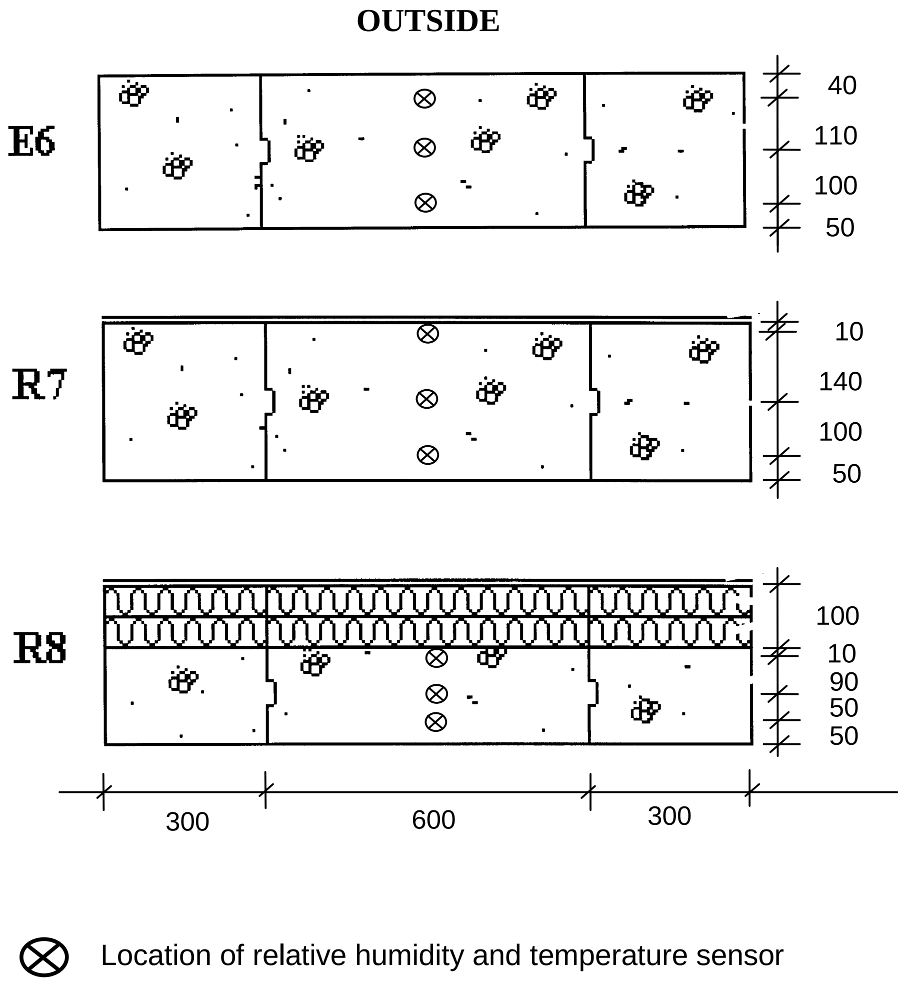


Figure 19 Location of relative humidity and temperature sensors in section E6, R7 and R8.

4.7 Control of the method for measuring moisture content

In addition to to all the moisture content measurements in the timber frame members by use of electrodes, the "moisture content" of five electric resistances used as reference units were logged. This was done in order to detect any failures in the logging and processing systems and to increase the reliability of the measurements.

Four pieces, close to the MC metering points, of the stud in section W8 were sawn out at 16. December 1997 while the sections were open for inspection (see chapter 4.6). This was done in order to compare moisture content measurements made by the logging system using the two pin electric resistance method with moisture content measured gravimetrically. The four pieces, with same cross section as the stud, 35 mm x 146 mm, and heights between 36 and 41 mm, were split into approximately 5 mm thick pieces and weighted immediately. After drying and new weighting the moisture distribution across the stud at four levels were calculated. The results are shown in figures 21 and 22 together with the corresponding logged values. The positions of the centres of the wood pieces and the electrodes relative to the ends of the stud are given in the figure caption.

The figures show a very good agreement between the two methods of measuring moisture content. The deviation between the logged value and the gravimetric value at the cold side of the stud in figure 21 is probably caused by different moisture content at the two levels near the top of the wall section. The moisture content of the corresponding position of the top plate was 28 % at the same time.

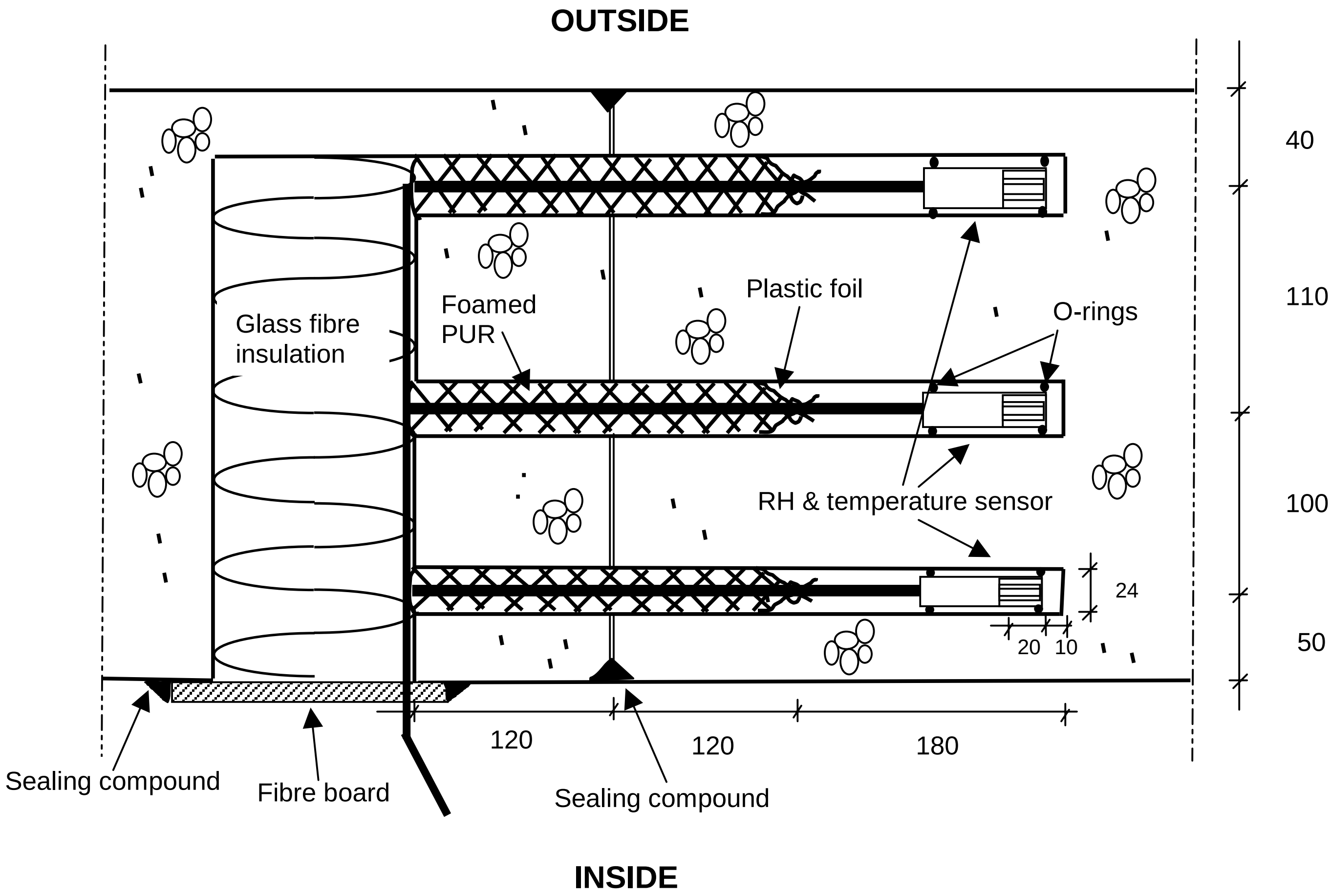


Figure 20 Detailed location of sensors in drilled holes and sealing details in section E6. The dimensions of the figure are not in scale.

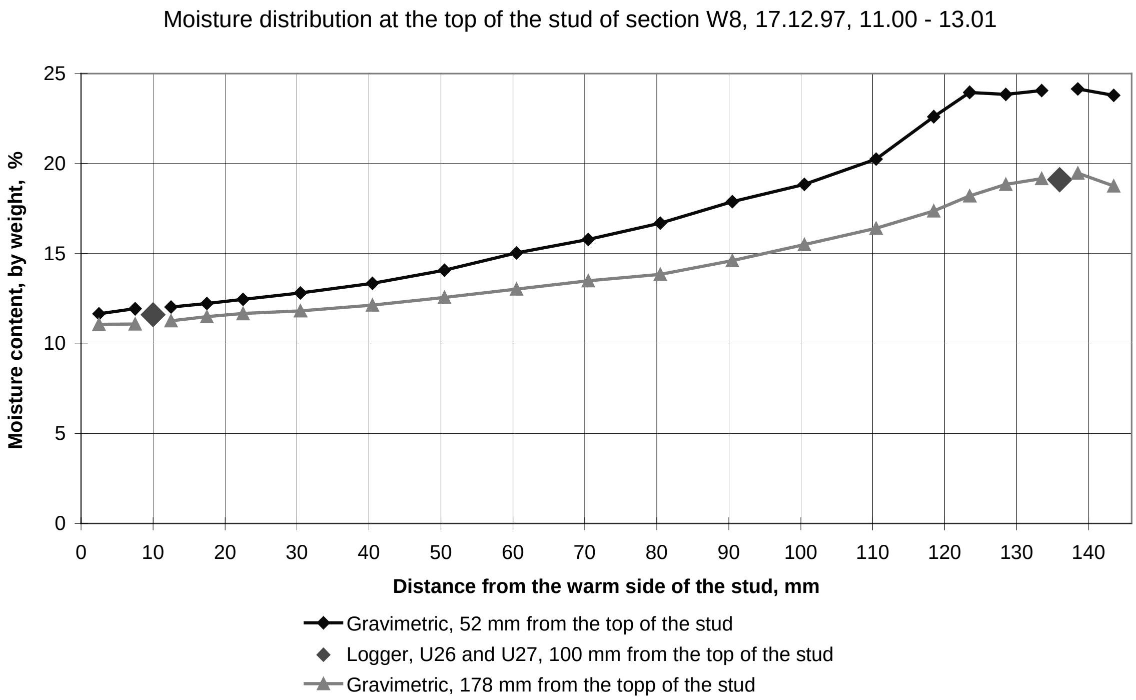


Figure 21 Moisture distribution at the top of the stud in E8.

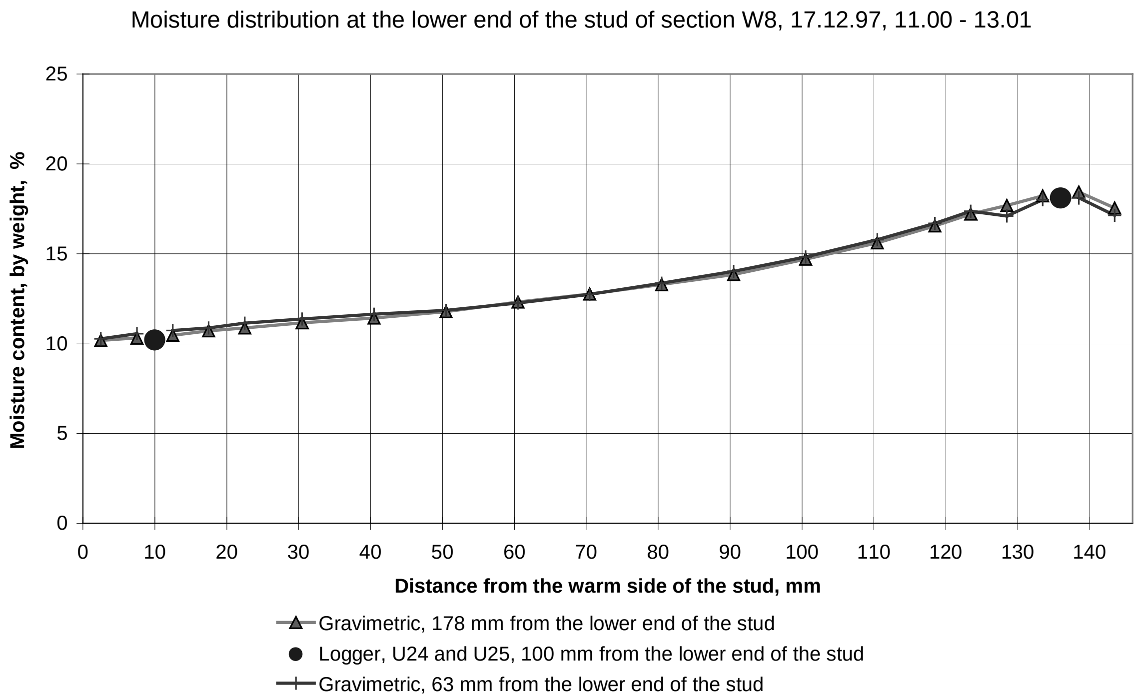


Figure 22 Moisture distribution at the bottom of the stud in E8.

4.8 Indoor climate

Indoor air temperature and RH were controlled at a constant level of approximately 23°C and 45 % RH, and were automatically logged every hour. The measured average RH and temperature is shown in figure 23. For the period July 1995 to February 1996 there were some errors in the ordinary measurements of the RH, and these are therefore not shown in Figure 23. The indoor air temperature have been measured in 8 points, respectively 4 points 1,0 m above the floor and 4 points 2,8 m above the floor. They were located 3,0 m from the closest end wall and approx. 0,1 m from the closest long wall. RH of the indoor air have been measured at two points, approximately 1,4 m above floor level.

The indoor air pressure was negative compared with outdoor pressure until April 1997, when it was turned to be positive by adjusting the ventilation system. The first three heating seasons, until 6th of April 1997, the ventilating system gave a reduction in the indoor air pressure of approximately 2 Pa. The 6th of April the exhaust fan was turned off and blocked. From that date the ventilation system gave an increase in indoor air pressure of approximately 0.5 Pa.

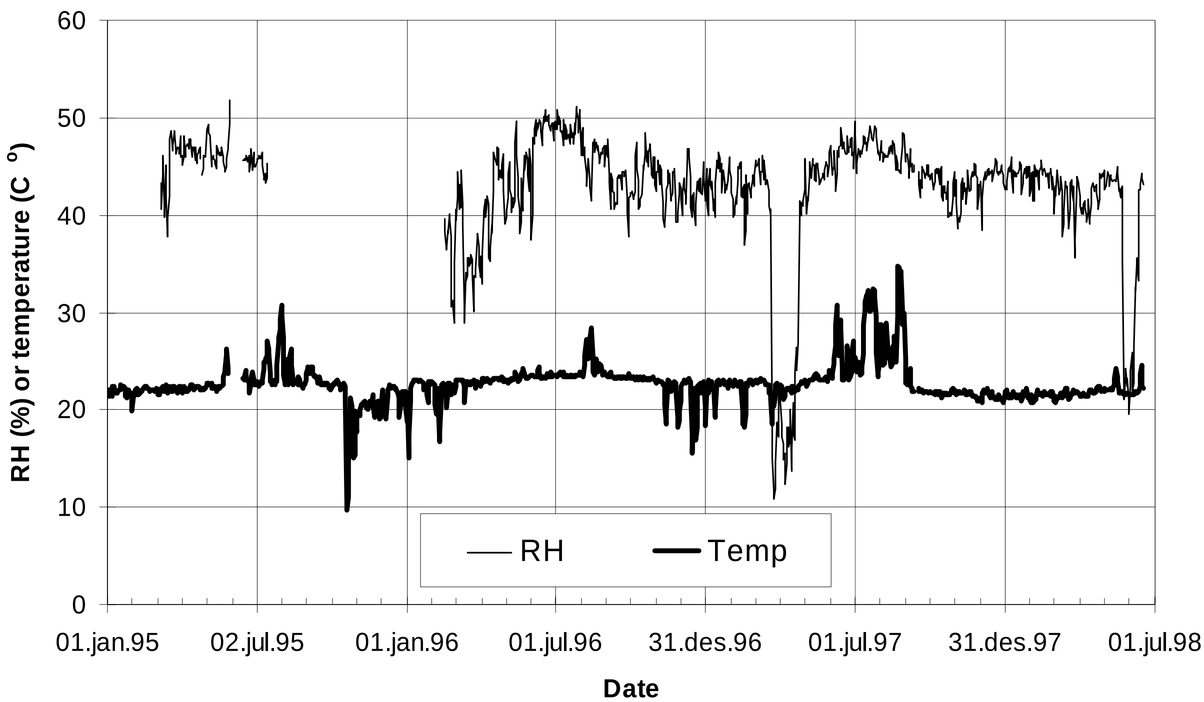


Figure 23 Indoor air temperature and relative humidity during the measurement period.

4.9 Publications where the wall and roof measurements have been presented

(Geving and Thue, 1996):
In this paper measurements for one year of the six timber frame roof sections were compared with simulations using four different one-dimensional heat and moisture transfer models.

(Geving, 1997):
See publication # 7 in part II of this thesis. Measurements from four of the timber frame walls (E1, W1, W7/8, E8) were compared with simulations with the LATENITE two-dimensional hygrothermal model. Simulations and measurements were compared and general good agreement was observed.

(Thue, Uvsløkk et. al., 1998):
In this report results from the strategic research programme "Moisture in Building Materials and Constructions" are presented. As a part of this the test house and some of the measurement results for the wall constructions are presented.

(Økland, 1998):
In this thesis measurements of the modified elements E2 and E3 are presented. The elements were modified to investigate the effect of forced convection, see chapter 4.5.

(Uvsløkk, Geving and Thue, 1999):
In this paper the measurement results for the 12 timber frame walls are presented. A discussion of the factors influencing the moisture distribution in the walls is given.

(Geving, Thue and Uvsløkk, 1999):
This paper gives a short description of the data that are available for verification purposes from the test house. This includes a description of the test house, the wall and roof elements investigated, the instrumentation of the elements, boundary conditions, outdoor climatic parameters and material properties.

5 RESULTS

5.1 General

Measured moisture conditions in the wall sections are shown in chapter 5.2 – 5.3. The highest moisture contents were measured in the outer parts of the sill- or top plate. Yearly maximum measured moisture content of the plates for four heating seasons is given in table 15. Measurements in the roof sections are shown in chapter 5.4.

For the purpose of verification of computer models all the data documented in this report are available on digital format (CD-ROM). Most of the data are easily accessible in EXCEL-files. Some of the data given on the CD-ROM are:

- Hourly and daily measurement results from wall and roof elements
- Hourly measurement results of indoor climate
- Hourly measurement results of outdoor climate
- Air tightness measurement results
- Measurement results of investigation of forced convection
- Various pictures

Table 15 Yearly maximum measured moisture content of top- and bottom sill of the timber frame wall sections. Values exceeding 20 weight % are marked.

Wall section	Yearly maximum measured moisture content, top sill bottom sill [weight %]			
No	1995	1996	1997*	1998
W1	13,8	13,9	14,2	24,0
	13,4	13,9	13,7	15,0
W2	14,8	15,0	15,0	24,4
	13,0	13,0	14,7	15,7
W3	13,0	13,2	12,9	16,7
	12,7	13,0	12,4	12,8
W4	14,0	14,9	14,4	17,2
	12,9	13,8	13,4	13,4
W6	16,3	22,0	17,3	26,0
	15,7	17,8	19,4	26,0
W7	16,4	18,2	18,2	36,2
	15,7	19,7	18,6	23,8
W8	15,9	17,2	18,3	
	16,5	19,9	17,4	
E1	23,8	20,8	19,2	33,8
	12,8	13,0	12,4	13,8
E2**	25,2	22,2	21,1	22,6
	11,6	12,0	13,3	48,0
E3**	19,4	18,5	14,8	18,5
	25,2	22,4	12,3	20,5
E4	46,0	35,5	32,0	53,0
	12,0	12,5	11,0	14,0
E8	15,5	16,5	14,4	16,4
	14,9	16,4	14,4	17,2

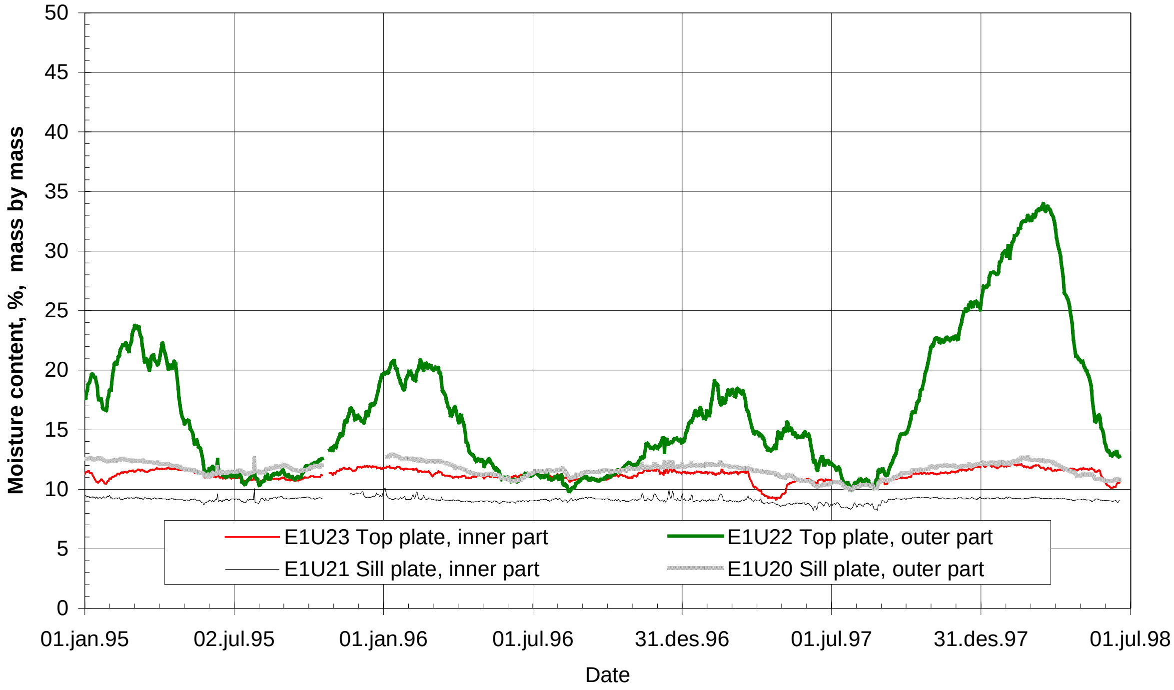
*In April 1997 the indoor air pressure of the test house was turned from negative to positive, compared with outdoor air pressure, by adjusting the ventilation system.

**In September 1996 the wall sections E2 and E3 were modified. The wind barrier of section E3 was changed to 9 mm gypsum board and both sections were perforated at both faces. A horizontal, 3 mm wide gap was sawn through the internal lining and vapour barrier near the bottom sill, and a similar gap through the wind barrier near the top sill at the external side.

5.2 Diagrams – eastern wall sections

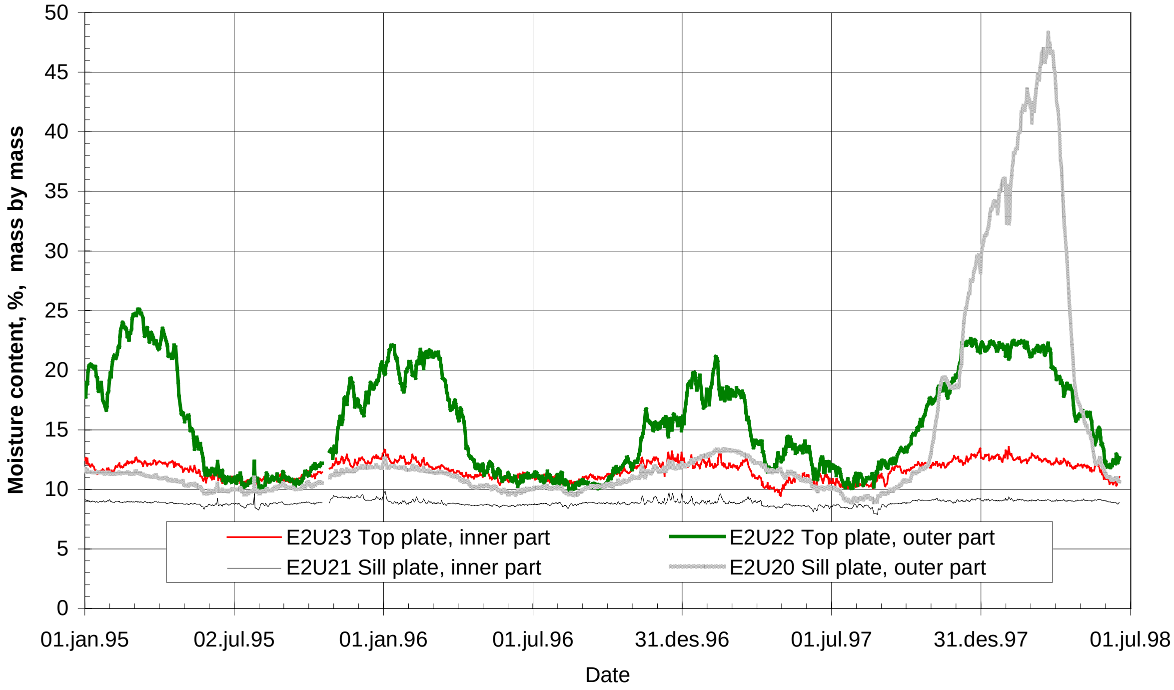
Moisture content, Eastern Wall Section E1

Description: Lining of 12 mm hardboard, vapour barrier of 0.15 mm PE-foil, 150 mm glass-wool/36 mm x 148 mm timber framing members, 12 mm wood fibre board soft, 23 mm ventilated air layer, 19 mm shiplap



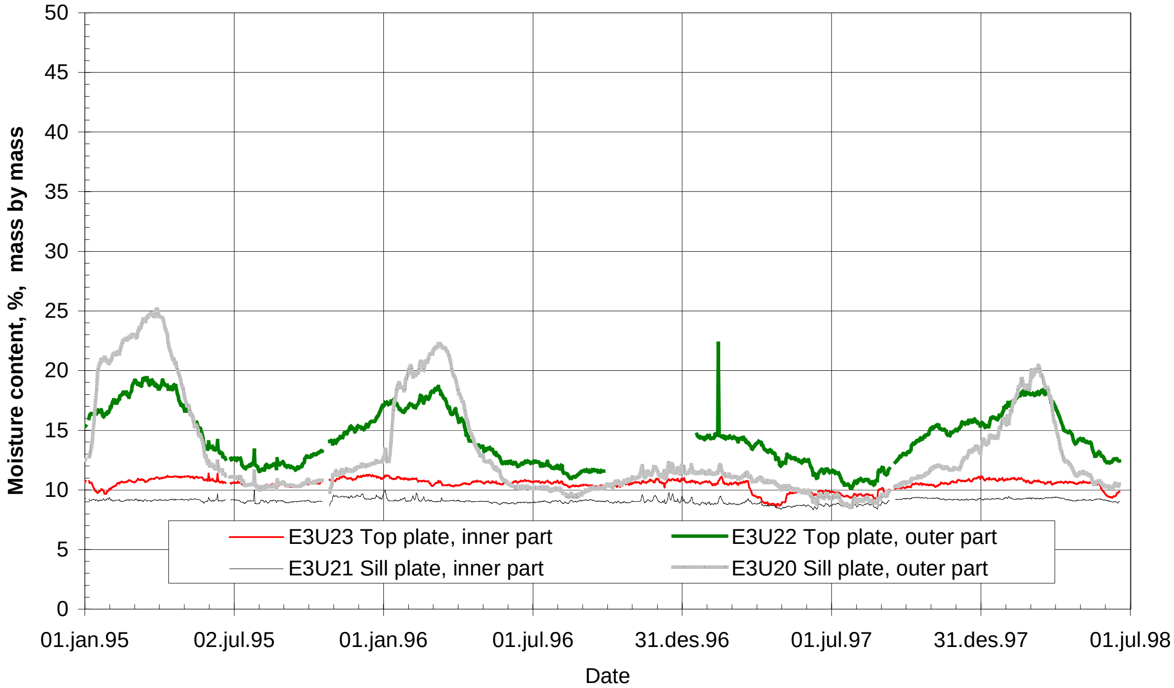
Moisture content, Eastern Wall Section E2

Description: Lining of 12 mm hardboard, vapour barrier of 0.15 mm PE-foil, 150 mm glass-wool/36 mm x 148 mm timber framing members, wind barrier of spun bonded polyetylene fibre, 23 mm ventilated air layer, 19 mm shiplap



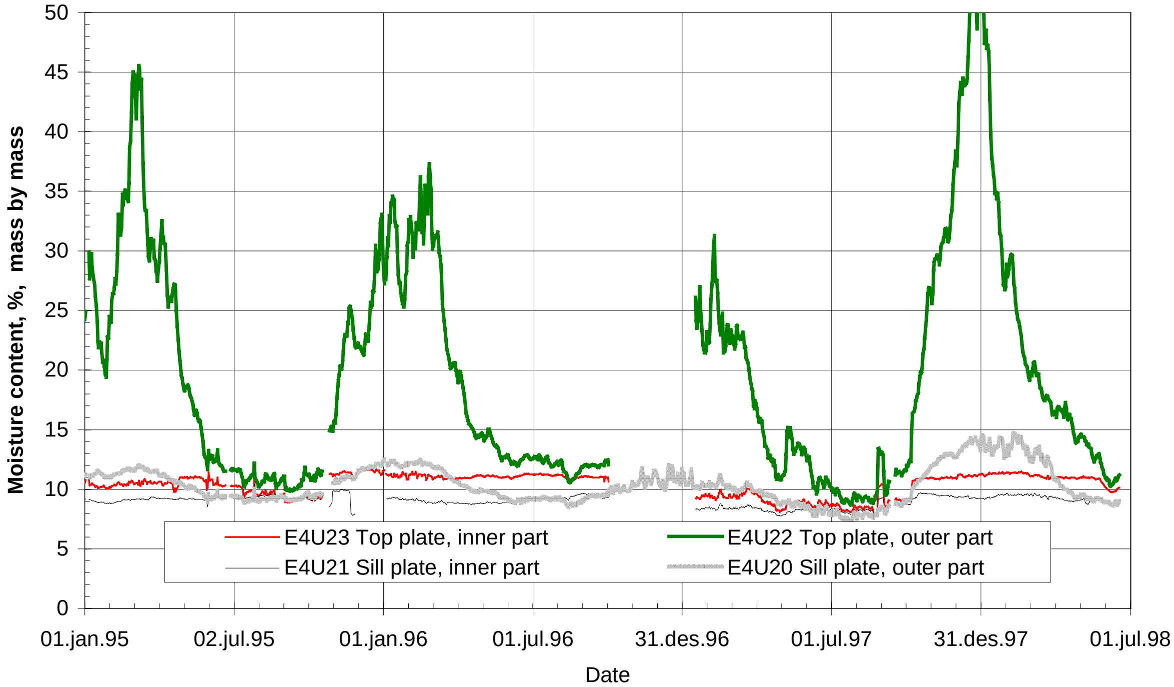
Moisture content, Eastern Wall Section E3

Description: Lining of 12 mm hardboard, vapour barrier of 0.15 mm PE-foil, 150 mm glass-wool/36 mm x 148 mm timber framing members, wind barrier of spun bonded polypropylene fibre, 23 mm ventilated air layer, 19 mm shiplap



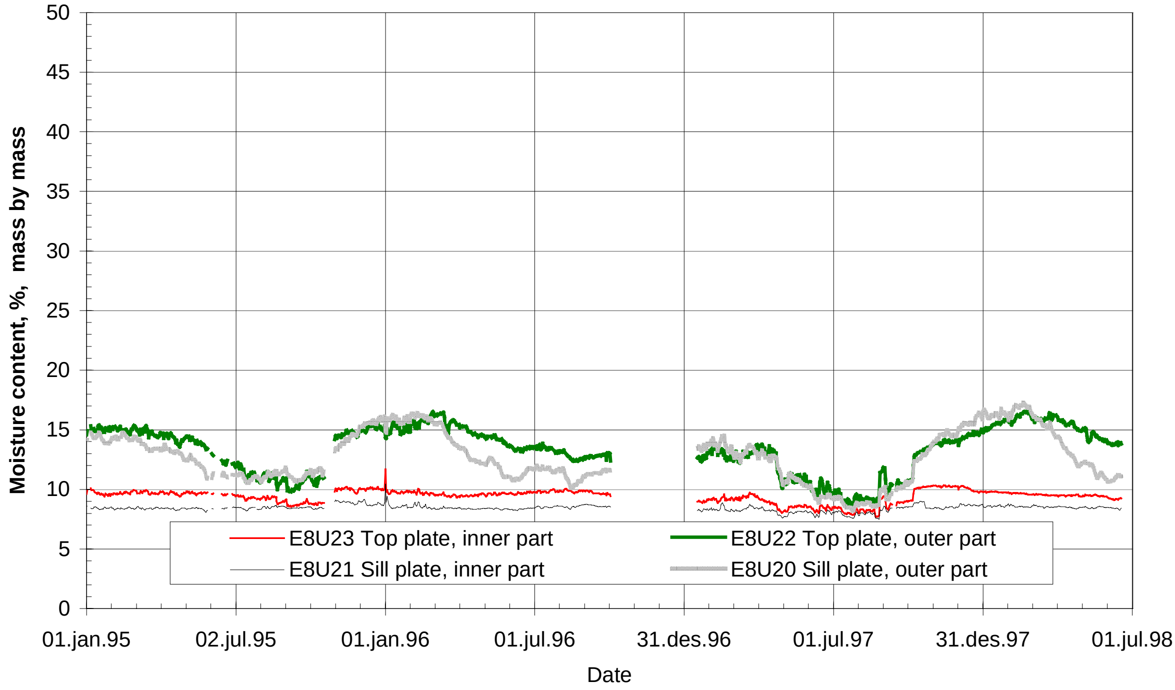
Moisture content, Eastern Wall Section E4

Description: Lining of 12 mm hardboard, no vapour barrier, 150 mm glass-wool/36 mm x 148 mm timber framing members, 9 mm gypsum board, 23 mm ventilated air layer, 19 mm shiplap



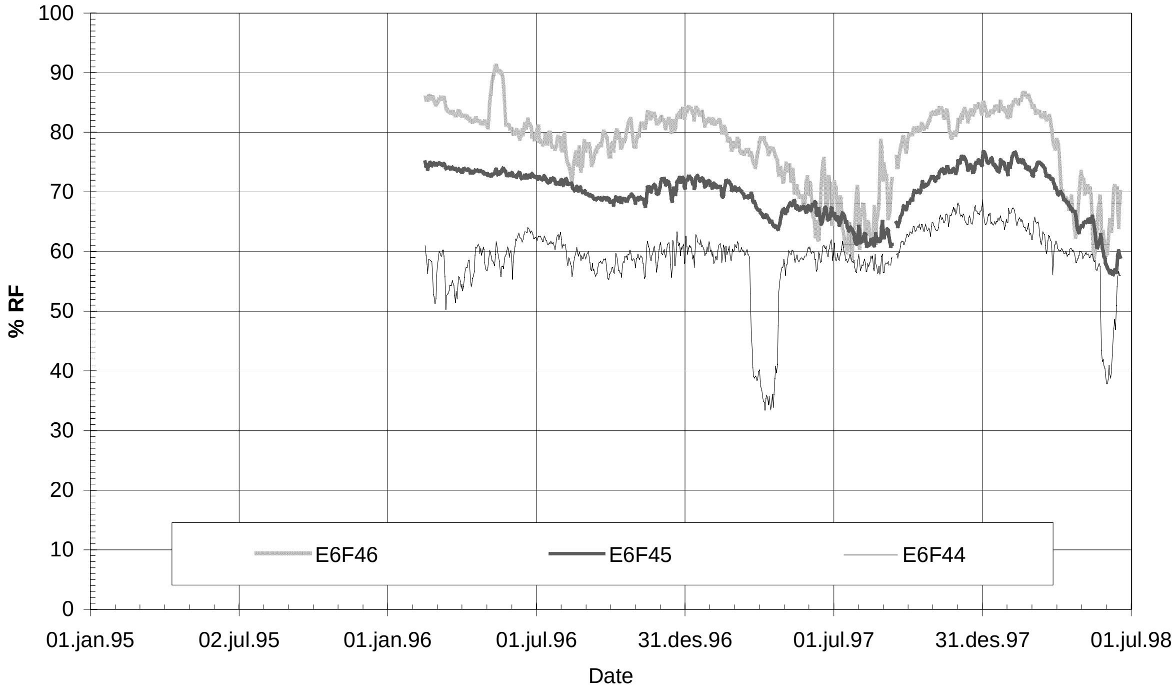
Eastern Wall, Section E8

Description: Lining of 12 mm hardboard, no vapour barrier, 150 mm + 150 mm glass-wool/timber framing members of I-profiles, 9 mm gypsum board, 23 mm ventilated air layer, 19 mm shiplap

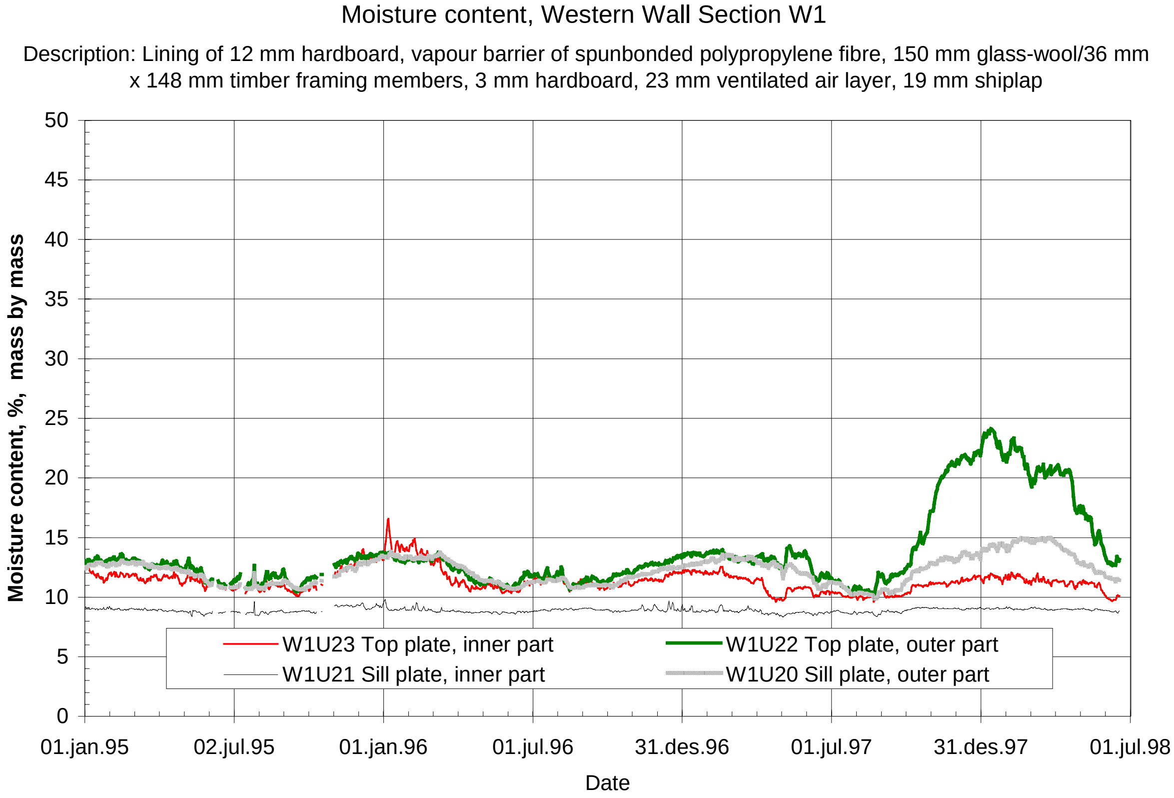


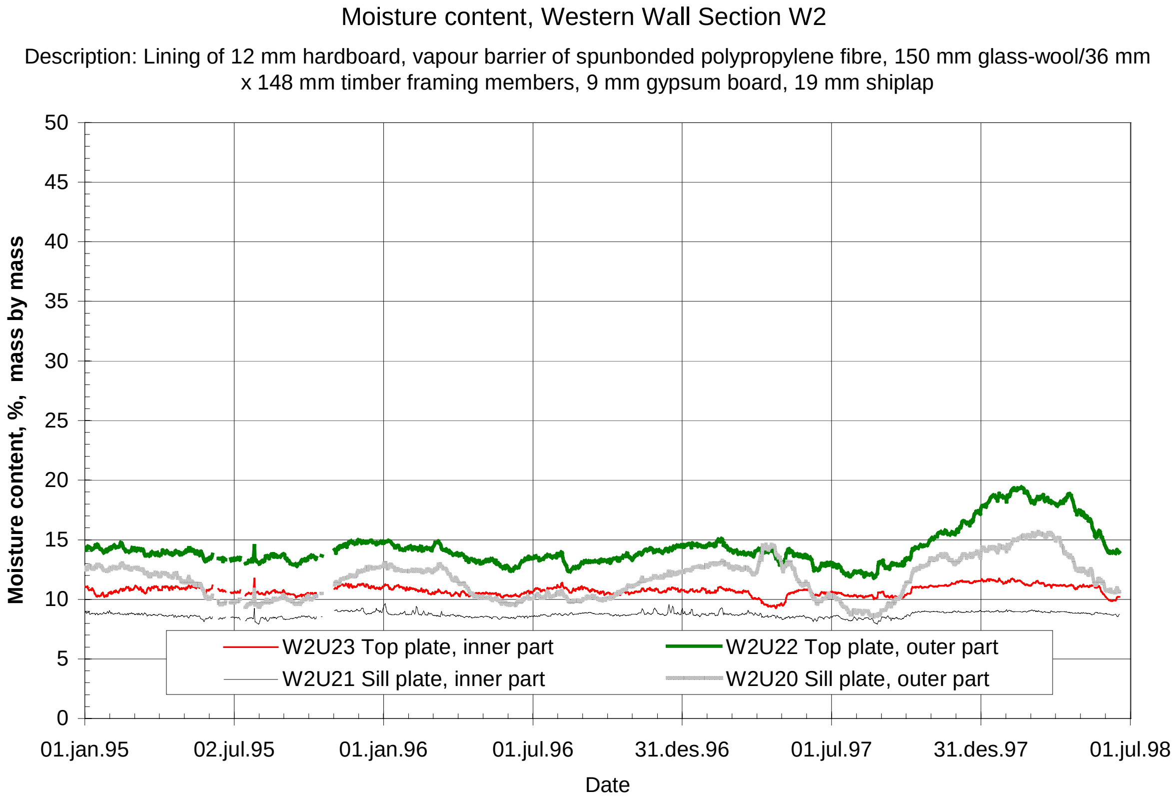
Eastern Wall, Section E6

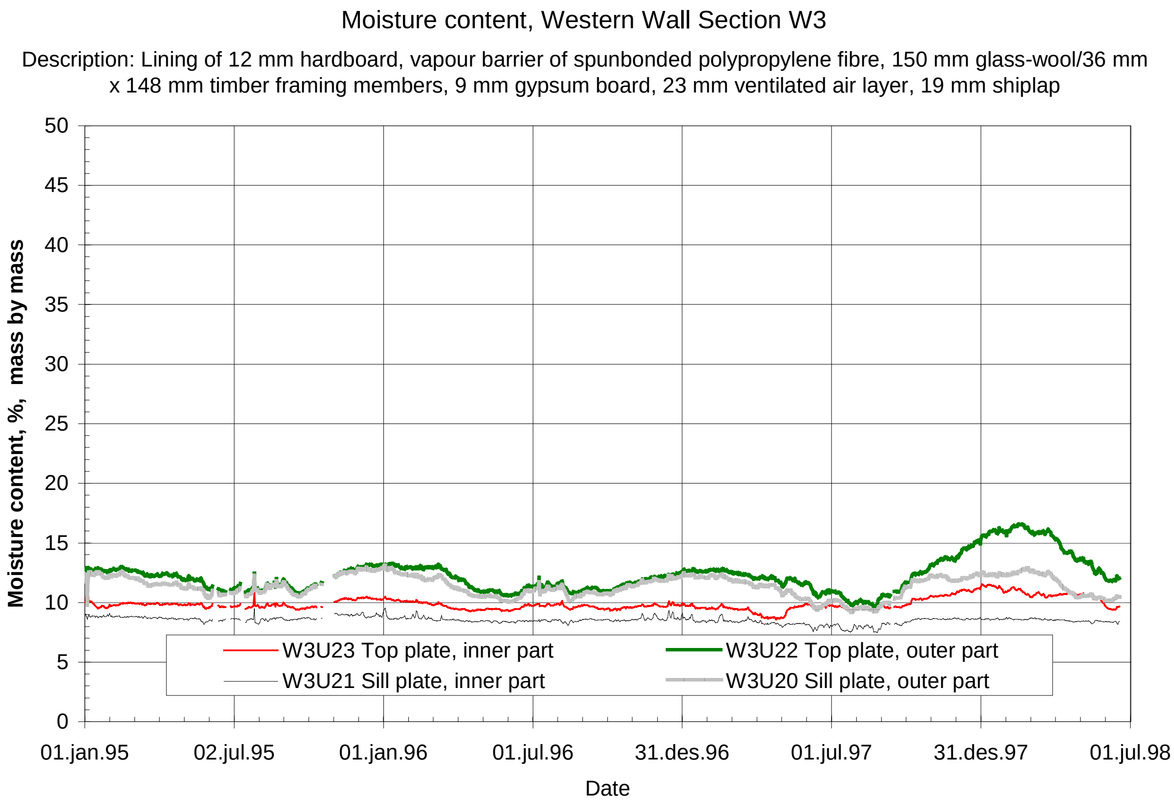
Description: 300 mm Autoclaved aerarated concrete

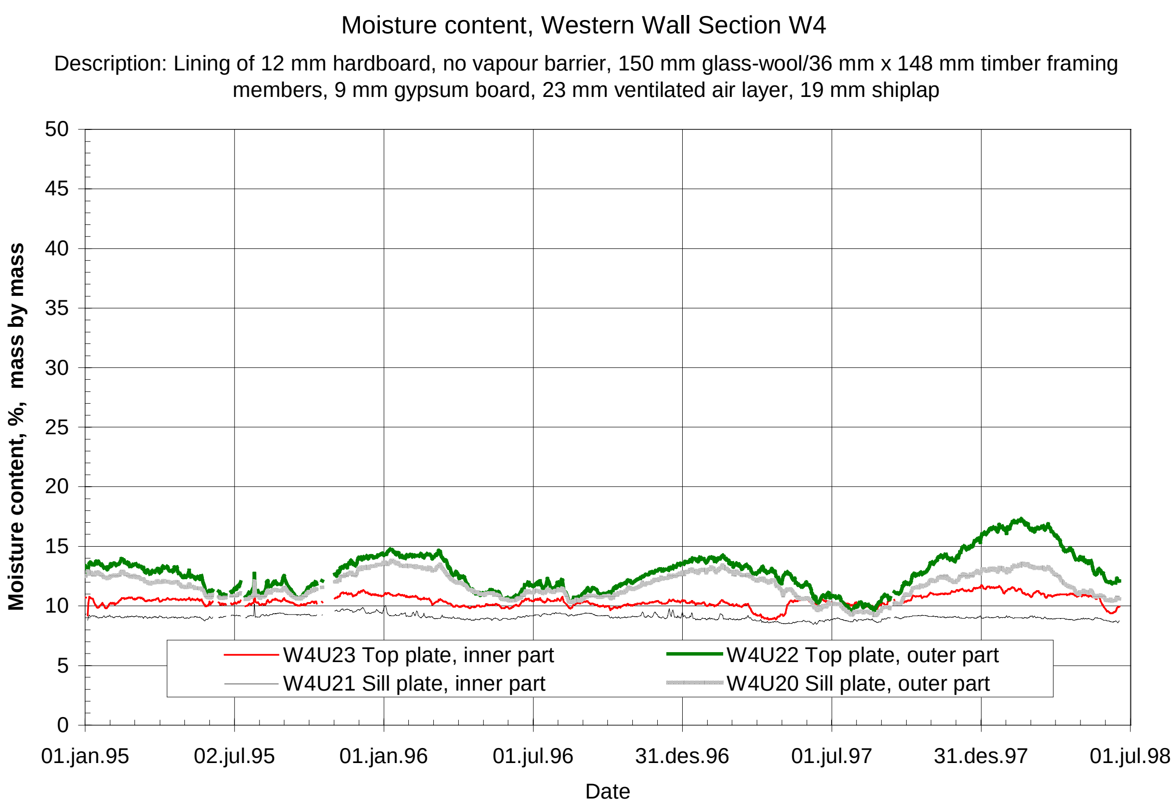


5.3 Diagrams – western wall sections



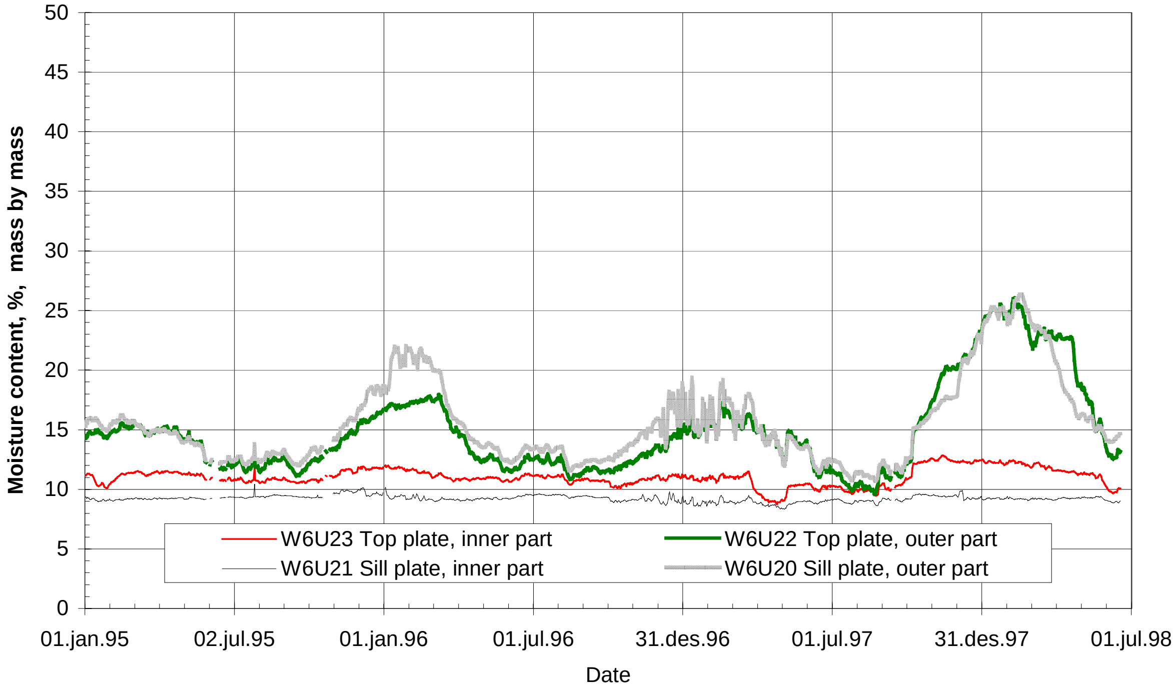



Moisture content, Western Wall Section W3
Description: Lining of 12 mm hardboard, vapour barrier of spunbonded polypropylene fibre, 150 mm glass-wool/36 mm x 148 mm timber framing members, 9 mm gypsum board, 23 mm ventilated air layer, 19 mm shiplap
Moisture content, %, mass by mass
50
45
40
35
30
25
20
15
10
5
0
W3U23 Top plate, inner part
W3U22 Top plate, outer part
W3U21 Sill plate, inner part
W3U20 Sill plate, outer part
01.jan.95
02.jul.95
01.jan.96
01.jul.96
31.des.96
01.jul.97
31.des.97
01.jul.98
Date


Moisture content, Western Wall Section W4
Description: Lining of 12 mm hardboard, no vapour barrier, 150 mm glass-wool/36 mm x 148 mm timber framing members, 9 mm gypsum board, 23 mm ventilated air layer, 19 mm shiplap
Moisture content, %, mass by mass
50
45
40
35
30
25
20
15
10
5
0
W4U23 Top plate, inner part
W4U22 Top plate, outer part
W4U21 Sill plate, inner part
W4U20 Sill plate, outer part
01.jan.95
02.jul.95
01.jan.96
01.jul.96
31.des.96
01.jul.97
31.des.97
01.jul.98
Date

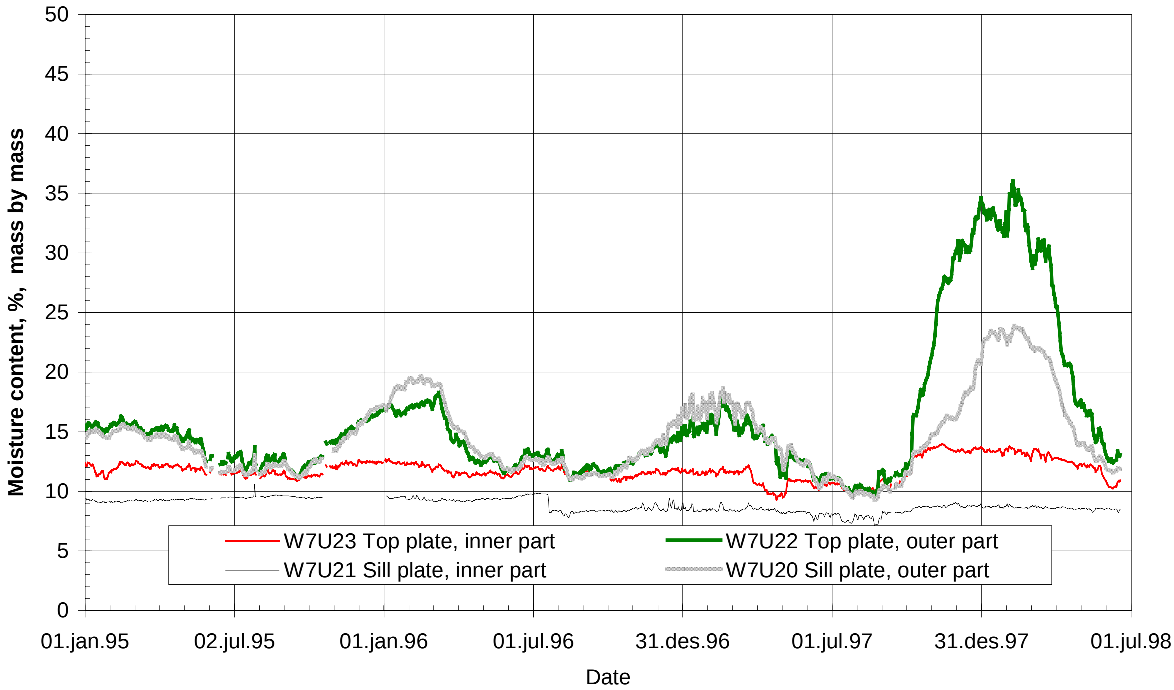
Moisture content, Western Wall Section W6

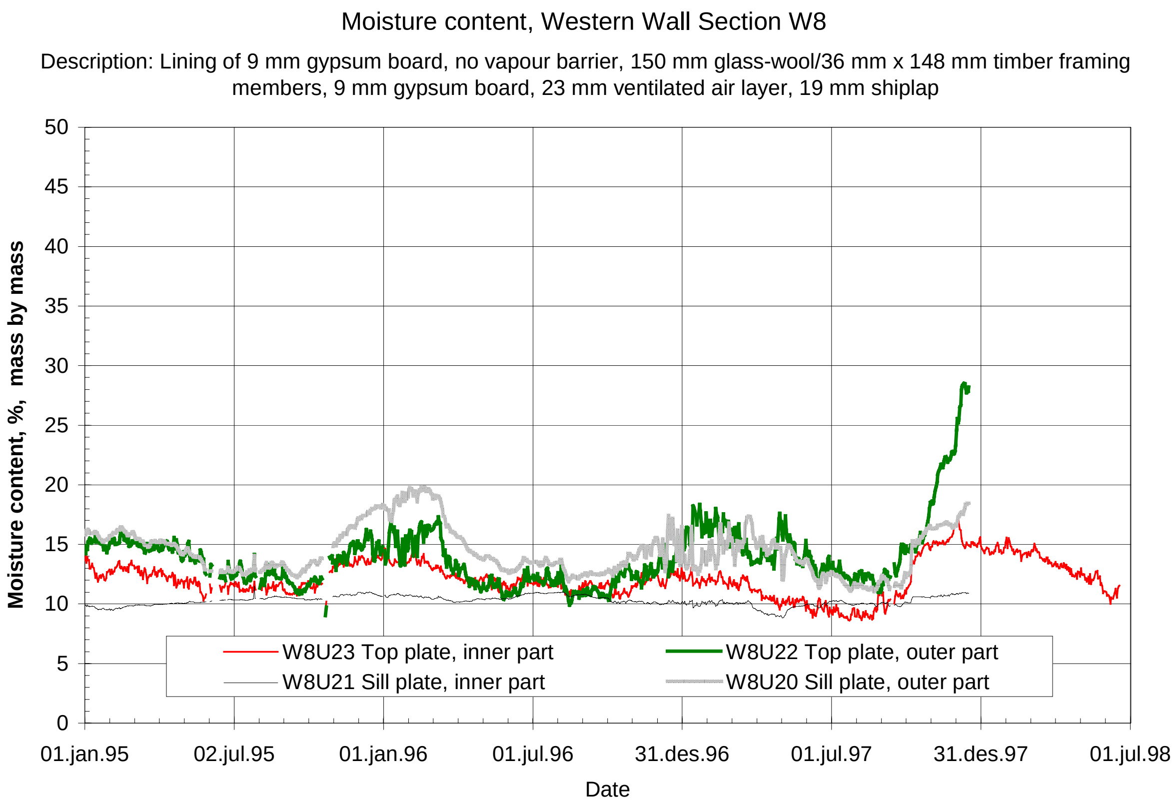
Description: Lining of 9 mm gypsum board, no vapour barrier, 150 mm glass-wool/36 mm x 148 mm timber framing members, with noggins, 9 mm gypsum board, 23 mm ventilated air layer, 19 mm shiplap



Moisture content, Western Wall Section W7

Description: Lining of 9 mm gypsum board, no vapour barrier, 150 mm glass-wool/36 mm x 148 mm timber framing members, 9 mm gypsum board, 23 mm ventilated air layer, 19 mm shiplap

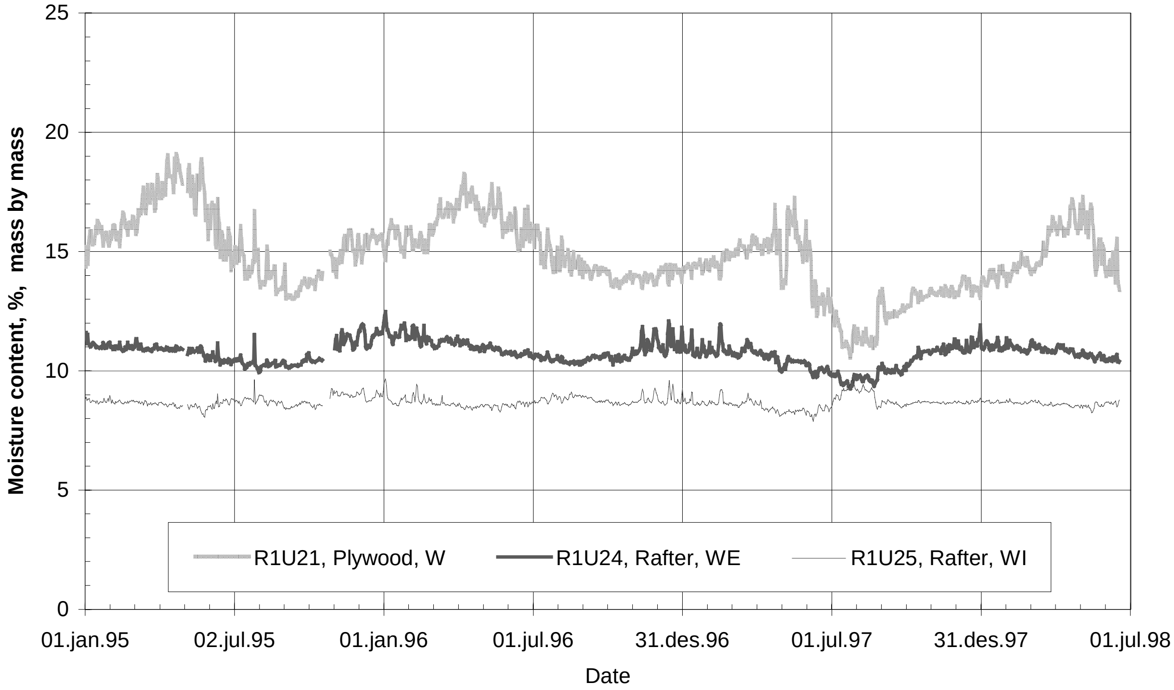



Moisture content, Western Wall Section W8
Description: Lining of 9 mm gypsum board, no vapour barrier, 150 mm glass-wool/36 mm x 148 mm timber framing members, 9 mm gypsum board, 23 mm ventilated air layer, 19 mm shiplap
Moisture content, %, mass by mass
50
45
40
35
30
25
20
15
10
5
0
W8U23 Top plate, inner part
W8U22 Top plate, outer part
W8U21 Sill plate, inner part
W8U20 Sill plate, outer part
01.jan.95
02.jul.95
01.jan.96
01.jul.96
31.des.96
01.jul.97
31.des.97
01.jul.98
Date

5.4 Diagrams – roof sections

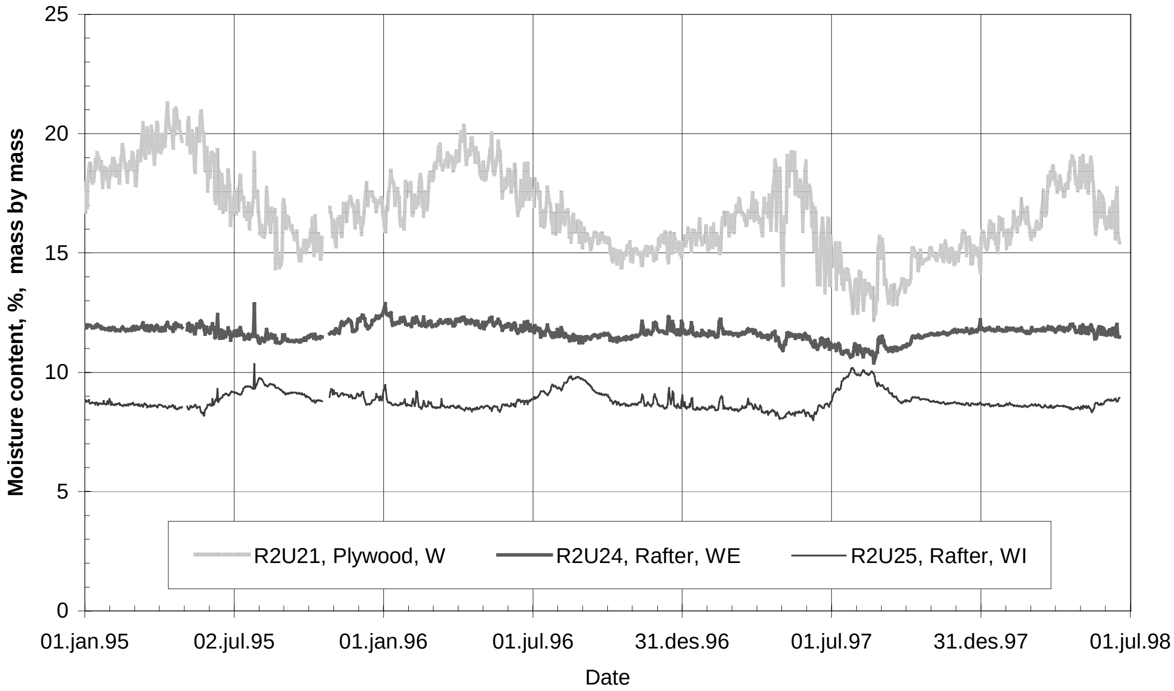
Moisture content, Roof Section R1

Description: Ceiling of 12 mm wood chipboard, vapour barrier of 0.15 mm PE-foil, 200 mm glass-wool/198 mm x 48 mm rafters c/c 600 mm, 22 mm plywood, dark roofing membrane of 1 mm PVC



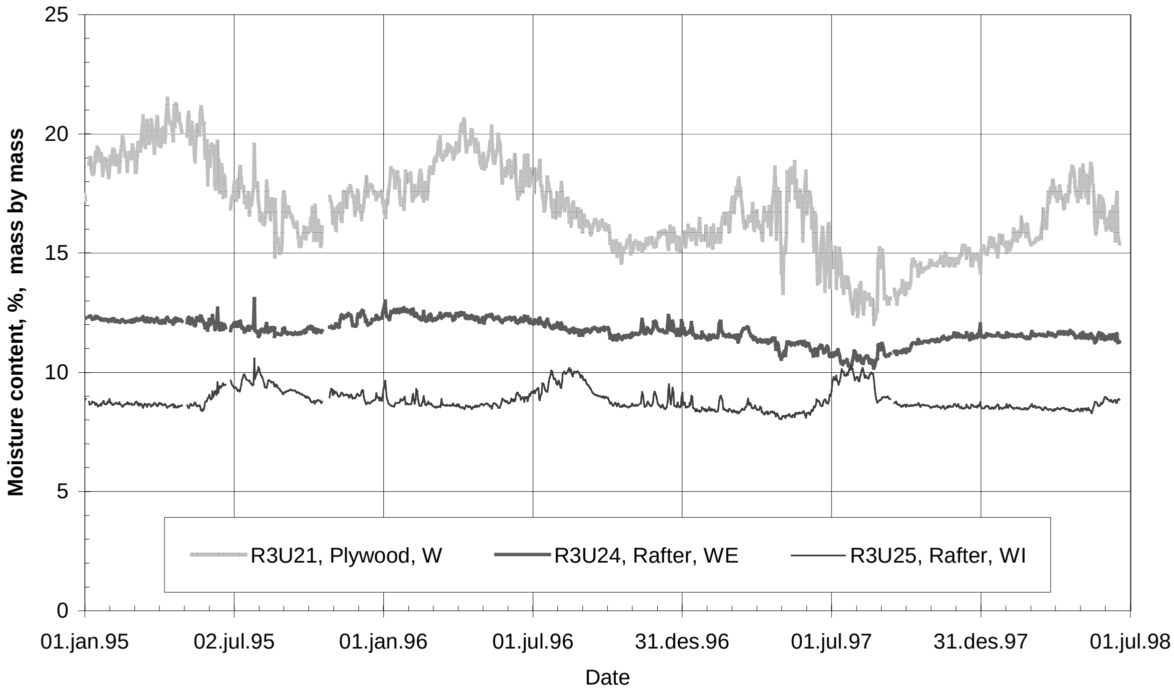
Moisture content, Roof Section R2

Description: Ceiling of 12 mm wood chipboard, vapour barrier of 0.15 mm PE-foil, 200 mm glass-wool/198 mm x 48 mm rafters c/c 600 mm, 22 mm plywood, light roofing membrane of 1 mm PVC



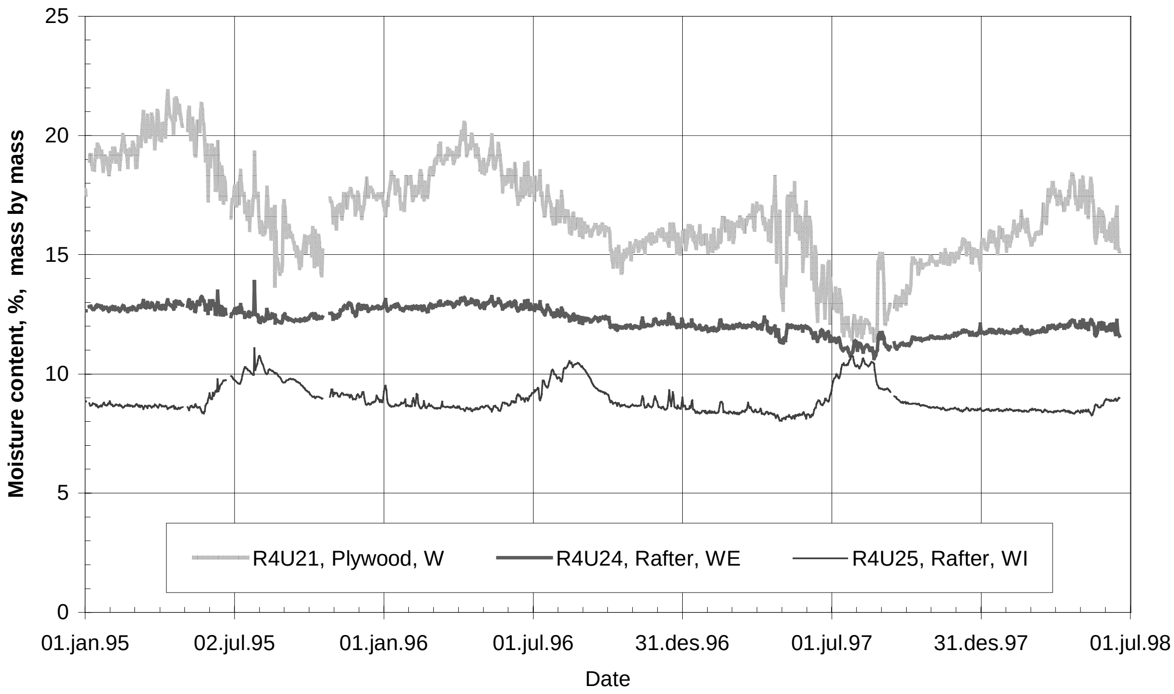
Moisture content, Roof Section R3

Description: Ceiling of 12 mm wood chipboard, vapour barrier of 0.15 mm PE-foil, 200 mm glass-wool/198 mm x 48 mm rafters c/c 600 mm, 22 mm plywood, light roofing membrane of 1 mm PVC



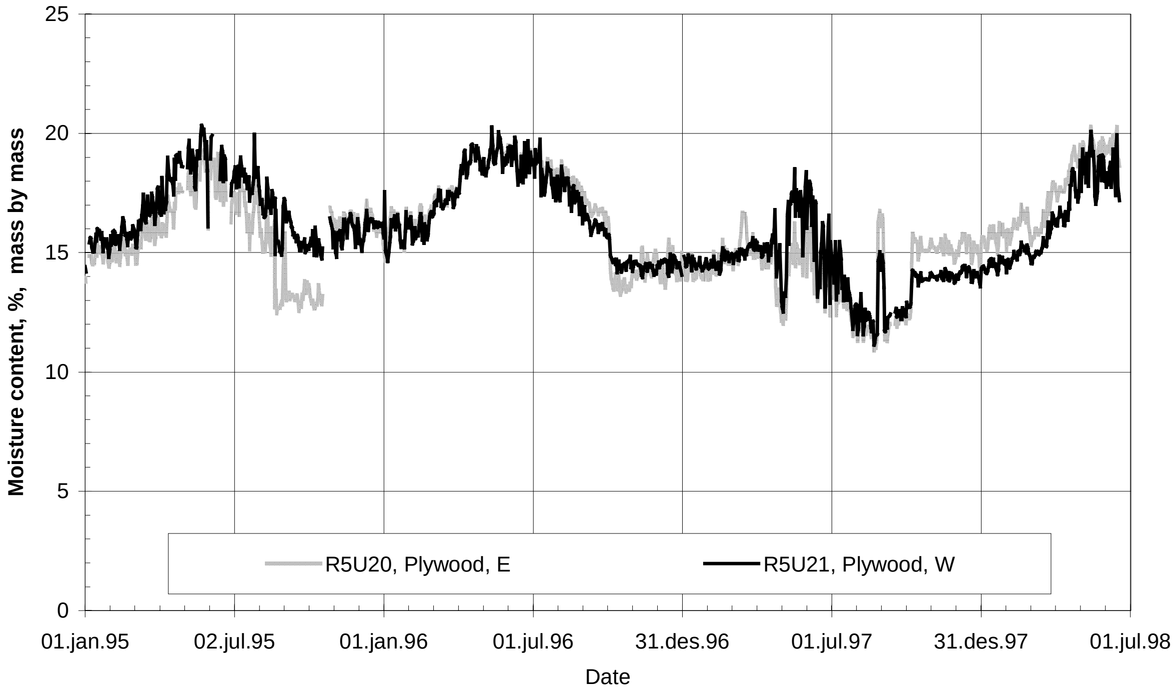
Moisture content, Roof Section R4

Description: Ceiling of 12 mm wood chipboard, vapour barrier of 0.15 mm PE-foil, 200 mm glass-wool/198 mm x 48 mm rafters c/c 600 mm, 22 mm plywood, light roofing membrane of 1 mm PVC



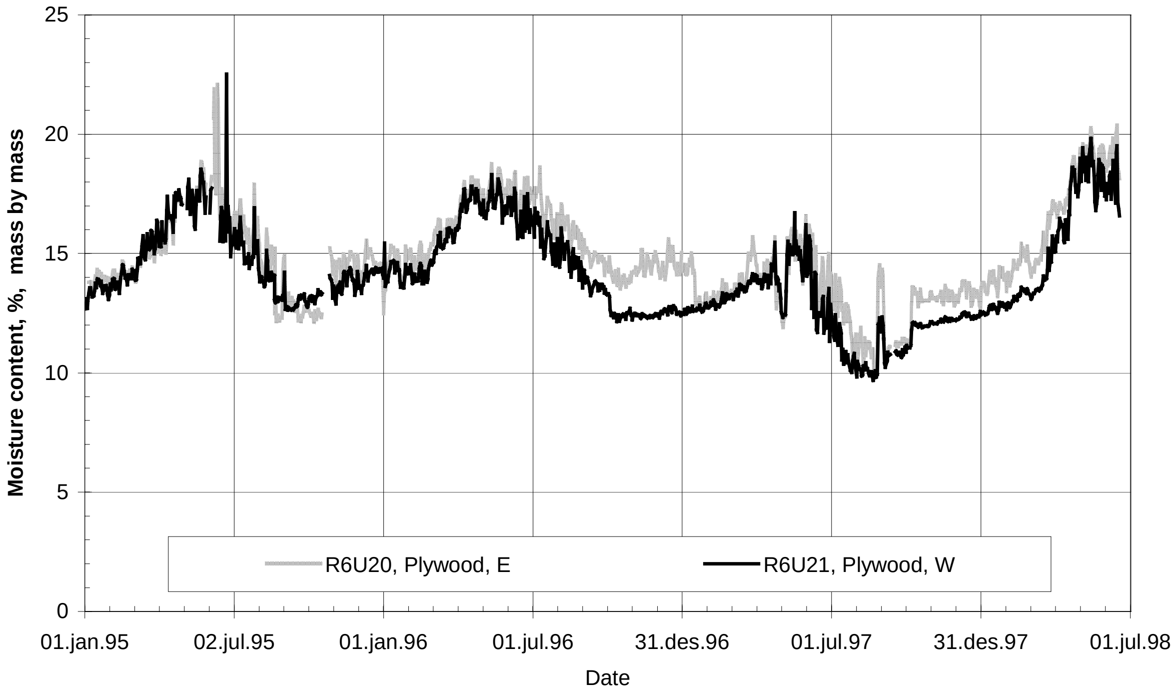
Roof, Section R5

Description: Ceiling of 12 mm wood chipboard, vapour barrier of 0.15 mm PE-foil, 200 mm glass-wool, 22 mm plywood, light roofing membrane of 1 mm PVC



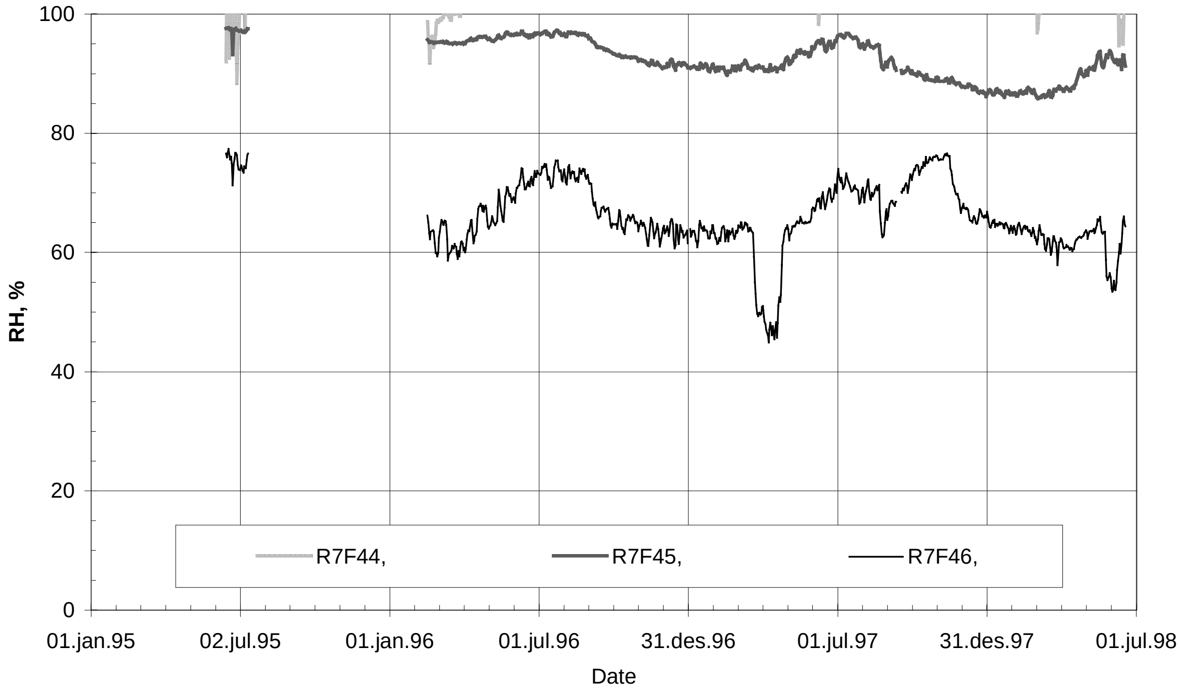
Roof, Section R6

Description: Ceiling of 12 mm wood chipboard, vapour barrier of 0.15 mm PE-foil, 200 mm glass-wool, 22 mm plywood, dark roofing membrane of 1 mm PVC



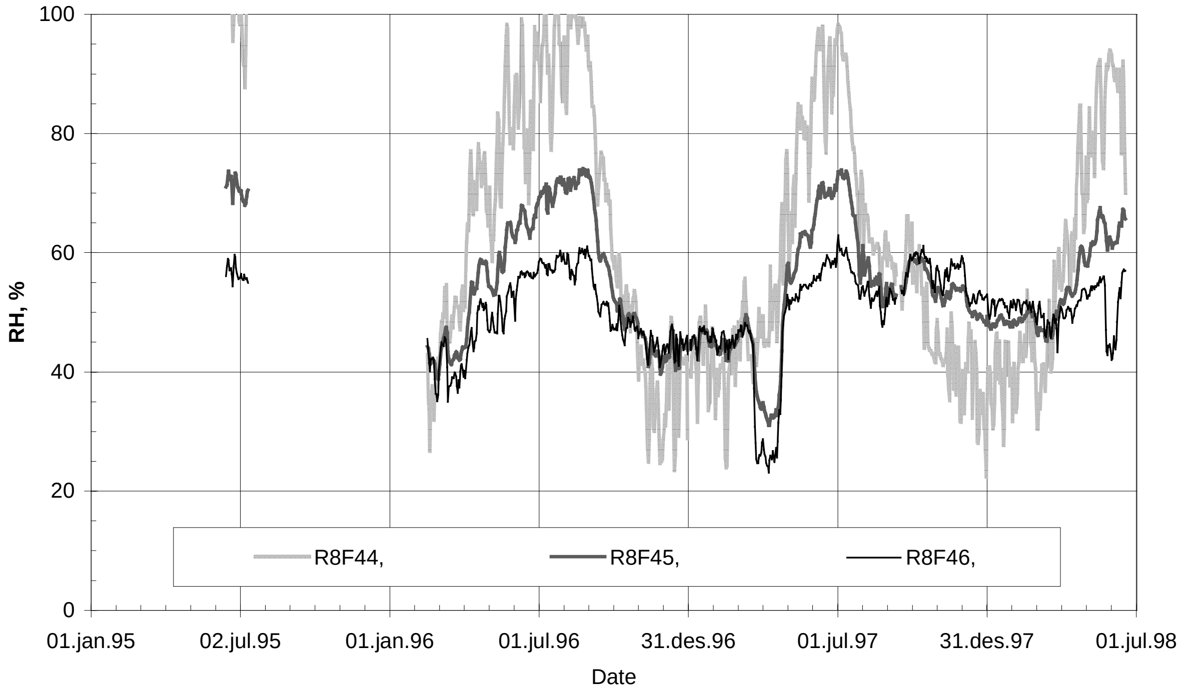
Roof, Section R7

Description: Autoclaved aerated concrete 300 mm, dark roofing membrane of 1 mm PVC



Roof, Section R8

Description: Autoclaved aerated concrete 200 mm, 50 mm + 50 mm glass-wool, 22 mm plywood, dark roofing membrane of 1 mm PVC



6 DISCUSSION

6.1 Wall sections

Moisture redistribution
The measurements show, for most wall sections, a clear tendency of moisture redistribution in wintertime, from the inner and lower parts of the timber-framing members to the upper and outer parts. This moisture redistribution is partly caused by the horizontal temperature- and corresponding RH-gradient and partly by the natural convection in the insulation layer, as shown earlier in laboratory experiments (Uvsløkk 1996, Økland 1998). In permeable insulation layers like mineral wool in wall cavities, natural convection will take place, even with good workmanship. This convection may not cause significant increase of heat loss, but is sufficient to strongly influence the RH and moisture content distribution in the insulated cavity and in the timber frame members.

Air gaps in the insulation layer
In some of the sections, E1, E2 and E4, the outer part of the top plate got unexpected high moisture content, se figure 3. When removing the external cladding and wind barrier for inspection, a small gap, approximately 10 mm, was observed between the insulation and the top plate in section E1. Such imperfections in the insulation layer may have caused a concentration of the air flow, from hot to cold side, at the top plate giving extra high RH at the outer part as the air is cooled.

Condensation on wind barrier with high water vapour resistance
In section E3 measured moisture content is highest in the outer part of the sill plate, se figure 4. The water vapour resistance of the “wind barrier” in this wall section is high, s_{de} = 4.4 m, and moisture redistribution by natural convection may have led to condensation on the wind barrier. Condensed water has probably run down along the wind barrier to the outer part of the sill plate and caused the rapid increase in moisture content in the beginning of January both in 1995 and 1996.

Walls with low internal vapour resistance
Several of the wall sections had no traditional vapour barrier and therefore relative low water vapour resistance on the hot side of the insulation layer. This fact has however not led to dramatic high moisture contents. In the sections W4and E8, both with a ratio between the internal and external resistances of 7, the measured moisture contents are approximately on the same low level as in the sections W1, W2, W3 with ratios between the internal and external resistances of 35 to 62. In the sections W6, W7 and W8 however, which have equal materials and very low resistances at both sides, the moisture content is higher and close to 20 weight% in wintertime both in the top and sill plates. Due to the difference in RH at the two faces, the ratio between the internal and external vapour resistances has probably been higher that 1, also for these wall sections.

Air leakage may give high moisture content
In most buildings air leakage from indoor through walls and roofs represents a far higher risk for moisture damage than pure diffusion. That seems to be true also for the test wall sections when the air pressure is higher indoor than outdoor, which was the situation during the last heating season. All the sections got the highest measured moisture content this last year, and in several of the sections the moisture content was very high.

6.2 Roof sections

All the timber frame roof sections are vapour tight at both faces and are therefore not to be recommended for use in real buildings. Because of their inability of drying out for instance built-in-moisture, the risk of moisture damage is too high.

Moisture content
Due to indoor production of the roof sections the built-in-moisture of the timber frame members and the plywood was low in all sections, between 10 % and 15 % by weight at start. Therefore the moisture content of the plywood has exceeded 20 % only for relatively short periods in spring and early summer. The maximum moisture content of the plywood has decreased slightly during the first three heating seasons. The forth heating season the drying seems to have stopped in the sections R1, R2, R3 and R4 as the maximum moisture content is unchanged. In the sections R5 and R6 the moisture content development has turned from decreasing to increasing. The only change in the test condition before the forth heating season was the change in the ventilation system setting. The first three heating seasons, until 6th of April 1997, the ventilating system gave a reduction in the indoor air pressure of approximately 2 Pa. The 6th of April the exhaust fan was turned off and blocked. From that date the ventilation system gave an increase in indoor pressure of approximately 0.5 Pa. This change of indoor pressure seems to have turned the main air leakage direction through the roof sections giving a moisture supply instead of a drying out effect.

Moisture redistribution
The maximum moisture content and the following moisture redistribution occurs later in the plywood in the roof sections than in the rafters and in the timber frame members of the wall sections. So far we have no obvious explanation of this observation.

Light versus dark roofing membrane
The two roof sections R1 and R6 on which the dark side of the roofing membrane faced upwards, had a lower moisture content than sections R2, R3, R4 and R5 with the light side facing upwards. When exposed to sun radiation the roofing temperature was up to 10 °C higher than on the light sections. This temperature difference has given section R1 and R6 a higher drying out potential both regarding diffusion and air leakages from outside to inside and is probably the main reason for the lower moisture content.

7 CONCLUSION

Hygrothermal measurements have been performed on different building envelope constructions at a test house in Trondheim, Norway. The measurement data from this test house are made available for researchers who want to verify computer models for heat, air and moisture transfer through building structures. The measurement data are well documented and available on various data formats. The data are suited for verification purposes of one- (roof sections), two- and three-dimensional computer programs, modelling moisture transfer by water vapour diffusion, capillary suction and air convection. This report gives a description of the data that are available for verification purposes from the test house.

These test house measurements, during four heating seasons, show that moisture redistribution in insulated timber frame walls may lead to high local moisture content in the outer and upper part of the timber framing members. This is the case even for normally “moisture safe” structures with high ratio between internal and external vapour resistances and low build-inn moisture content. Air gaps in the insulation layer will increase the risk of high local moisture content.

The measurements indicates that water vapour diffusion do not represent any high risk for moisture damage, even for walls with relative low internal water vapour resistance, as long as the external vapour resistance is far lower. In these experiments the walls with low internal vapour resistance and a ratio between the internal and external resistances of seven or higher, had the same low moisture content as “normal” walls with high internal water vapour resistance.

The results from the last heating season of the test period, when the air pressure was higher indoor than outdoor, confirm the well known experience from practice that air leakage normally represents far higher risk for moisture damage than pure water vapour diffusion from indoor air.

More information

For more information in order to get access to the data, take contact with one of the following contact persons:

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