STUDY REPORT

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First Results of a Study of Roof Underlays

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Preface

This is the second of a series of reports prepared during research into the role of roof underlays for moisture management in roof spaces. The report describes the physical properties of a range of roof underlays and other building wraps, the layout and instrumentation of a test house built to test them and some of the experimental results obtained.

Acknowledgments

This work was funded by the Building Research Levy.

Note

This report is intended for other researchers interested in moisture management in roof spaces.

FIRST RESULTS OF A STUDY OF ROOF UNDERLAYS

BRANZ Study Report SR 215 2009 **L Quaglia and M J Cunningham**

Reference

Quaglia L. and Cunningham M. 2009. 'First Results of a Study of Roof Underlays'. BRANZ *Study Report 215* BRANZ Ltd, Judgeford, New Zealand.

Abstract

Roof underlays constitute the second line of defence of the roof envelope and they are an essential element of the interstitial moisture management strategy in roof spaces. This report describes some of the experimental results obtained during a study of roof underlays aimed at investigating which of their physical properties are required to fulfil the task of managing moisture in interstices. After a review of some of the physical properties of a range of building wraps (mainly roof underlays but also wall wraps), a description of the layout and of the instrumentation of an experimental building where most of the tests are conducted is given. Then two phenomena which could give rise to interstitial condensation are investigated: condensation generated by night sky radiative cooling and condensation driven by solar radiation. Some preliminary experimental results about the behaviour of roof underlays are given for both mechanisms.

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1. INTRODUCTION

1.1 Introduction

Roof underlays are an integral part of the building envelope: they provide a second line of defence behind the roof cladding and contribute to the overall moisture management in roof spaces. The properties required by roof underlay to fulfil their functions are covered by the New Zealand standard NZS 2295, the Australian New Zealand standard AS/NZS 4200 and Table 23 of the Compliance Document to the NZ Building Code "External Moisture". These properties fall under several categories: moisture-related properties, mechanical properties, flammability properties, chemical properties and optical properties.

A few years ago, the standards related to underlays underwent scrutiny and the process of revision exposed a lack of experimental data to inform further decisions, especially in the field of moisture-related properties. Until recently, the types of roof underlay mainly used in New Zealand in residential dwellings have been the paper-based ones (i.e. asphalt-impregnated Kraft paper). The current standards advocate properties and test methods which seem well suited for evaluating this class of products. But in the overseas market synthetic roof underlays have appeared as a replacement for paper-based ones. These products usually do not meet some of the moisture-related requirements of the current New Zealand standard.

Several questions come to mind, for example: What really are the functions of roof underlays? What is the role of roof underlays in the moisture management of roof cavities? What are the physical properties required by roof underlays to efficiently achieve their functions? Do synthetic products require different properties from paper-based products?

Due to the lack of experimental data to answer those questions and to inform a revision of the standards, a multi-year experimental project was set up to study roof underlays under New Zealand climatic conditions. This report gives a detailed account of the experimental set-ups and methods used to study the underlays and some of the experimental results.

1.2 Possible functions of roof underlays

Before proceeding with detailed explanations, it is important to consider the possible functions of roof underlays in order to put some of the measurements and experiments into context.

It is usually claimed that roof underlays act as second line of defence of the roof envelope, the first being the roof cladding. If water penetrates behind the roof cladding, due to wind-driven rain or a leak, the roof underlay should be there to shelter and protect the integrity of the timber framing of the roof and insulation. The roof underlay could also act as an air barrier and prevent strong air movements inside the roof cavity and above the insulation. Strong air movements on top of the insulation decrease its R-value due to an effect called "wind wash".

Another important function that a roof underlay should perform is to contribute to the management of interstitial moisture in the roof envelope. During cold nights, the temperature of the roof cladding can fall below the dew point and moisture could condensate on the underside of the cladding. If the liquid droplets of condensate drip, the roof underlay should be able to deal with the situation. It could absorb (or adsorb) the water until the climatic conditions improve and the moisture held in the underlay can evaporate, or it could make the water drain towards the outside of the building envelope.

1.3 Goals of the study

This study aims to gain an understanding of the physics of roof underlay performance under New Zealand climatic conditions, especially in order to inform the revision of standards. This knowledge is gained through experiments conducted in a specially designed test building where underlays can be tested in full-scale roof specimens and through theoretical modelling.

1.4 Outline of the report

This report has five parts. The first part describes the moisture-related properties of roof underlays as tested by the current standards. After an overview of these properties, measured values of these properties for a range of roof underlays are given. These underlays represent a selection of roof underlays or building wraps available in New Zealand or overseas. The second part describes the results obtained by measuring the sorption curves of these underlays. The sorption curve characterises the hygroscopic behaviour of the building wraps. The third part describes the experimental building that is used to investigate the behaviour of roof underlays under real climatic conditions. The fourth part describes some of the typical measurements which are obtained from the experimental building. The fifth part describes some of the results of the study of radiative cooling, solar-driven moisture and artificially generated condensation.

2. PROPERTIES OF A RANGE OF ROOF UNDERLAYS

2.1 Introduction

Several properties of a range of roof underlays were tested. The properties more likely to affect the moisture management behaviour of roof underlays have been selected. These are:

- Area density: measured in g/m^2, it represents the mass of 1 m^2 of dry material.
- Water vapour resistance: measured in MNs/g, it indicates the resistance of the material to the passage of water vapour. According to Table 23 of the Compliance Document to the NZ Building Code "External Moisture", the maximum allowed water vapour resistance is 7 MN·s/g.
- Water absorbency: measured in g/m^2, it quantifies the ability of the material to absorb liquid water. According to the standard NZS 2295, the minimum allowed water absorbency is 150 g/m^2.
- Liquid penetration resistance: measured with a Pass or Fail, it indicates the resistance of the material to the passage of liquid water. According to the standard NZS 2295, the minimum allowed liquid penetration resistance is 100 mm.
- Air resistance: measured in MN·s/m^3, it indicates the resistance of the material to the passage of air. At present, there is no requirement for any level of air resistance.

The properties of 11 building wraps were tested. These building wraps are:

- Wrap A: soft spun-bonded polypropylene non-woven membrane (used for walls).
- Wrap B: spun-bonded polypropylene substrate coated with a polyolefin-copolymer (used for walls and floors).
- Wrap C: microporous water-resistant film sandwiched between two layers of spun-bonded polyolefin (used for roofs).

- Wrap D: spun-bonded high-density polyethylene heat bonded to a polypropylene non-woven sheet (used for roofs).
- Wrap E: diffusion permeable polyolephyne membrane sandwiched between two polypropylene microfiber cover fleeces (used for roofs).
- Wrap F: bituminous Kraft paper (used for roofs).
- Wrap G: coated polyolephyne woven into a sheet form with micropores (used for walls).
- Wrap H: non-woven polypropylene fabric with a water-resistant coating (used for roofs).
- Wrap I: vapour open membrane with metallised low-emissivity surface (for roofs).
- Wrap J: polymer modified with ketone ethylene ester (used for roofs).
- Wrap K: air-tight membrane with metallised low-emissivity surface (used in roofs).

2.2 Area density

Area density was measured gravimetrically. Five 100 mm x 100 m specimens of each type of underlay were dried at 70°C for 24 hours before being weighed. The drying procedure was needed to eliminate the bound moisture in the specimens. To some extent, most of the roof underlays are hygroscopic and they tend towards an equilibrium moisture content depending on the relative humidity (RH) of the environment they are immersed in. Table 1 summarises the results of these measurements.

Table 1 Dry area density of a range of building wraps

Wrap	Area Density (g/m^2)
Wrap A	110
Wrap B	105
Wrap C	265
Wrap D	145
Wrap E	155
Wrap F	370
Wrap G	90
Wrap H	115
Wrap I	135
Wrap J	205
Wrap K	110

2.3 Water vapour resistance

Water vapour resistance was measured using the “wet cup test” described in ASTM E96, Procedure B. A circular specimen of underlay is placed on top of a round container holding distilled water and its edges are sealed with wax. This ensemble is stored in a climate chamber at 20°C and 50% RH for a certain number of days and weighed every 24 hours. The distilled water slowly evaporates and permeates through the specimen of underlay. The rate of mass loss is directly linked with the water vapour resistance of the specimen. Table 2 summarises the results of these measurements.

Table 2. Water vapour resistance of a range of building wraps

Wrap	Water Vapour Resistance (MN·s/g)
Wrap A	0.15
Wrap B	0.25
Wrap C	0.30
Wrap D	0.40
Wrap E	0.45
Wrap F	0.60
Wrap G	4.25
Wrap H	5.40
Wrap I	24.6
Wrap J	1100
Wrap K	3040

Maximum allowed water vapour resistance is 7 MN s/g.

2.4 Water absorbency

Water absorbency was measured according to the method described in the standard AS/NZS 4201.6. Five 200 mm x 200 mm specimens of roof underlay are weighed to obtain their unsoaked weights and then they are immersed in distilled water for 24 hours. After having taken a specimen out of the water, a square 100 mm x 100 mm is cut out of the centre of it. This square is immersed in the water again for a few instants, and then it is hung for a minute in a vertical position to drain excess water. Finally it is weighed to obtain the soaked weight. From the values of the soaked weight and the unsoaked weight, it is possible to calculate the absorbency. Table 3 summarises the results of these measurements.

Table 3 Surface absorbency of a range of building wraps

Wrap	Surface Absorbency (g/m2)
Wrap A	140
Wrap B	95
Wrap C	295
Wrap D	80
Wrap E	225
Wrap F	210
Wrap G	0
Wrap H	230
Wrap I	90
Wrap J	50
Wrap K	90

Minimum allowed water absorbency is 150 g/m^2.

2.5 Liquid penetration resistance

Liquid penetration resistance has been estimated using the method described in the standard AS/NZS 4201.4. A circular specimen of underlay (of an area of at least 25 cm^2) is clamped at the bottom of an open cylinder and the edges sealed. The cylinder is kept in upright position with the specimen at the bottom and is put onto a piece of filter paper. The cylinder is then filled with 100 mm of an aqueous solution of distilled water with a dye such as methylene blue. After 24 hours the filter paper is inspected for traces of dye which would signal the passage of liquid water. If no traces of dye are found, the result is Pass otherwise it is Fail. Beyond the requirements of the test, the state of the paper filter was noted: specifically if it appeared damp or if its surface had wrinkled. Table 4 summarises the results of these measurements.

Table 4 Liquid penetration resistance of a range of building wraps

Wrap	Liquid Penetration Resistance	Dampness	Ripples
Wrap A	PASS	Yes	Yes
Wrap B	PASS	No	No
Wrap C	PASS	Yes	Yes
Wrap D	PASS	No	No
Wrap E	PASS	Yes	Yes
Wrap F	PASS	Yes	Yes
Wrap G	FAIL	Yes	Yes
Wrap H	PASS	No	No
Wrap I	PASS	No	No
Wrap J	PASS	No	No
Wrap K	PASS	No	No

2.6 Air resistance

Air resistance was measured according to the methods described in the standard BS 6538.3 (based on the standard ISO 6536.5). Some wraps have a labelled side which is quite different from the unlabelled side so two air resistances are measured, with one or the other face on the high pressure side. Table 5 summarises the result of these measurements.

Table 5 Air resistance of a range of building wraps.

Wrap	Air Resistance (MN·s/m3)	Air Resistance (MN·s/m3)
	Labelled Side	Unlabelled Side
Wrap A	too porous	too porous
Wrap B	impermeable	0.059
Wrap C	0.041	0.032
Wrap D	leaked	8.43
Wrap E	0.121	3.58
Wrap F	0.567	0.69
Wrap G	0.237	0.243
Wrap H	impermeable	0.046
Wrap I	0.065	3.2
Wrap J	impermeable	impermeable
Wrap K	impermeable	leaked

Air resistance is measured with a Gurley apparatus. The description “impermeable” indicates that the air resistance is higher than the maximum value measurable with a Gurley machine. The description “too porous” indicates that the air resistance was lower than the minimum value measurable with a Gurley machine. The description “leaked” indicates that the surface of the wrap does not allow clamping of the Gurley machine in order to conduct an accurate measurement.

3. SORPTION CURVES OF A RANGE OF ROOF UNDERLAYS

3.1 Introduction

Like many other building products, roof underlays are able to store water molecules, a property known as hygroscopicity. The hygroscopicity of a building material is characterised by its sorption isotherm which is the relationship between moisture content of the material and RH. The moisture content is defined as the amount of water, in any physical form, bound to the material and expressed as a percentage of the dry weight of the material. The moisture content is referred to the situation when the material has reached equilibrium with an environment at a certain RH. Being expressed in function of the RH, the sorption curve is only weakly dependent on temperature.

Sorption isotherms are usually affected by the phenomenon of hysteresis; the material has a “memory” of the variations of RH. The moisture content of a sample of dry material exposed to increasing RH follows the adsorption curve. The moisture content of a sample initially at 100% RH and exposed to decreasing RH follow the desorption curve. Due to hysteresis, the adsorption and desorption can differ, sometimes noticeably.

Sorption isotherms are an important parameter to characterise the moisture behaviour of roof underlays.

3.2 Experimental procedure

Only a subset of all the wraps available was considered. The sorption curves were measured by means of a climate chamber and of saturated salt solutions. Five 100 mm x 100 mm specimens for each of the wraps considered were put in a climate chamber at set temperature and RH for 24 hours and subsequently weighed. Soon after each weighing, the RH was changed and the procedure repeated again using the same specimens. The temperature in the chamber was kept at 5°C and the RH set in order at: 40%, 70%, 80%, 90%, 95%, 90%, 80%, 70% and 40%. Those values of RH were chosen to probe both the adsorption and the desorption components of the sorption isotherm. Because the climate chamber could not reach and stably maintain very high values of RH, in order to characterise the sorption curve at RH close to 100%, a saturated salt solution was used. When a saturated solution is kept in an air-tight container, the air above the solution reaches an equilibrium RH which depends on the salt used. Using potassium nitrate, the equilibrium RH is around 94%. Using potassium sulphate, it is around 98%. If distilled water is used instead of a saturated salt solution, an equilibrium RH of around 100% can be reached.

3.3 Sorption curves

3.3.1 Wrap C

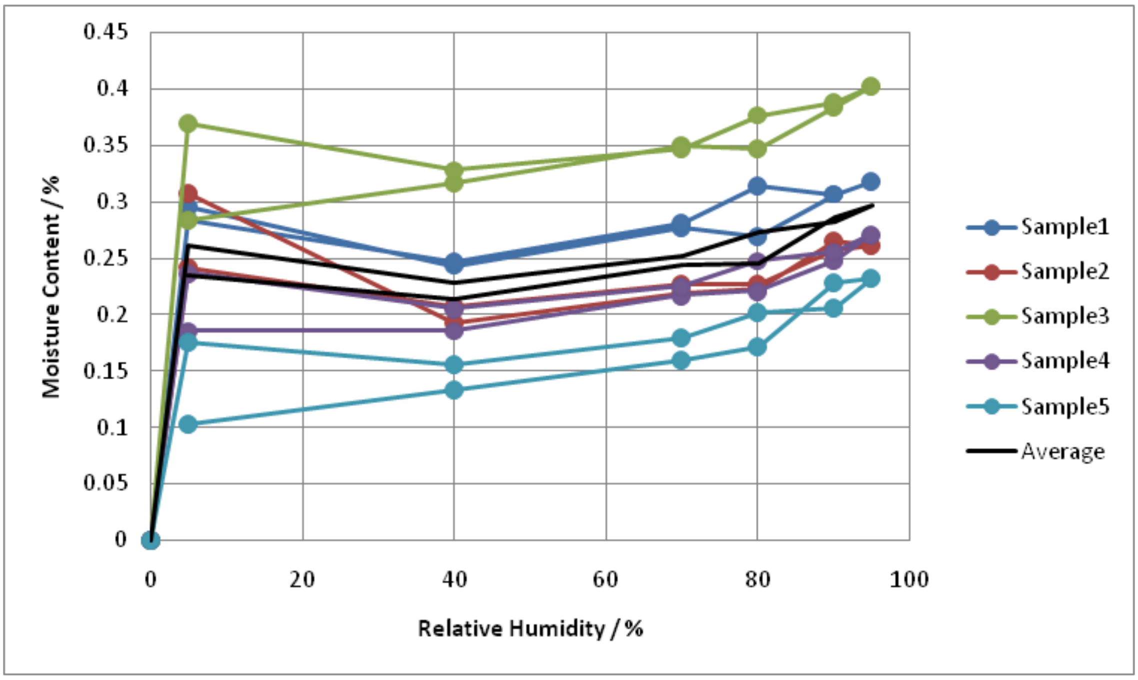

Figure 1. Sorption curve for Wrap C

3.3.2 Wrap D

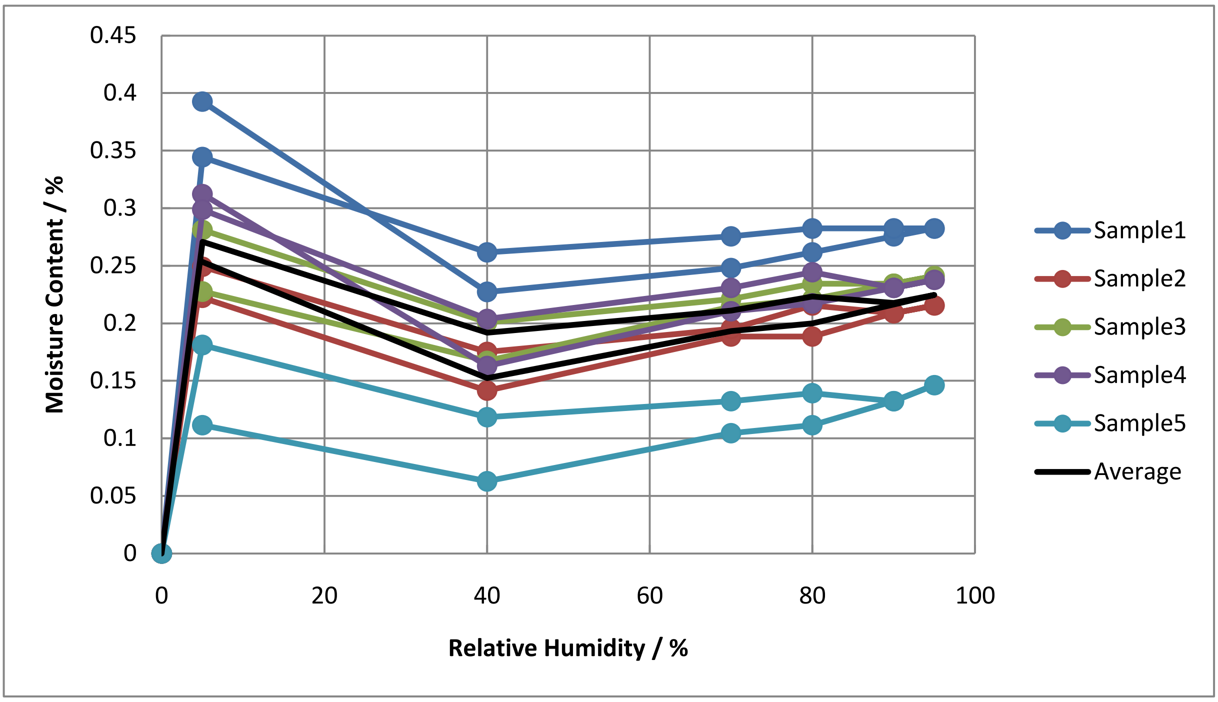

Figure 2. Sorption curve for Wrap D

3.3.3 Wrap E

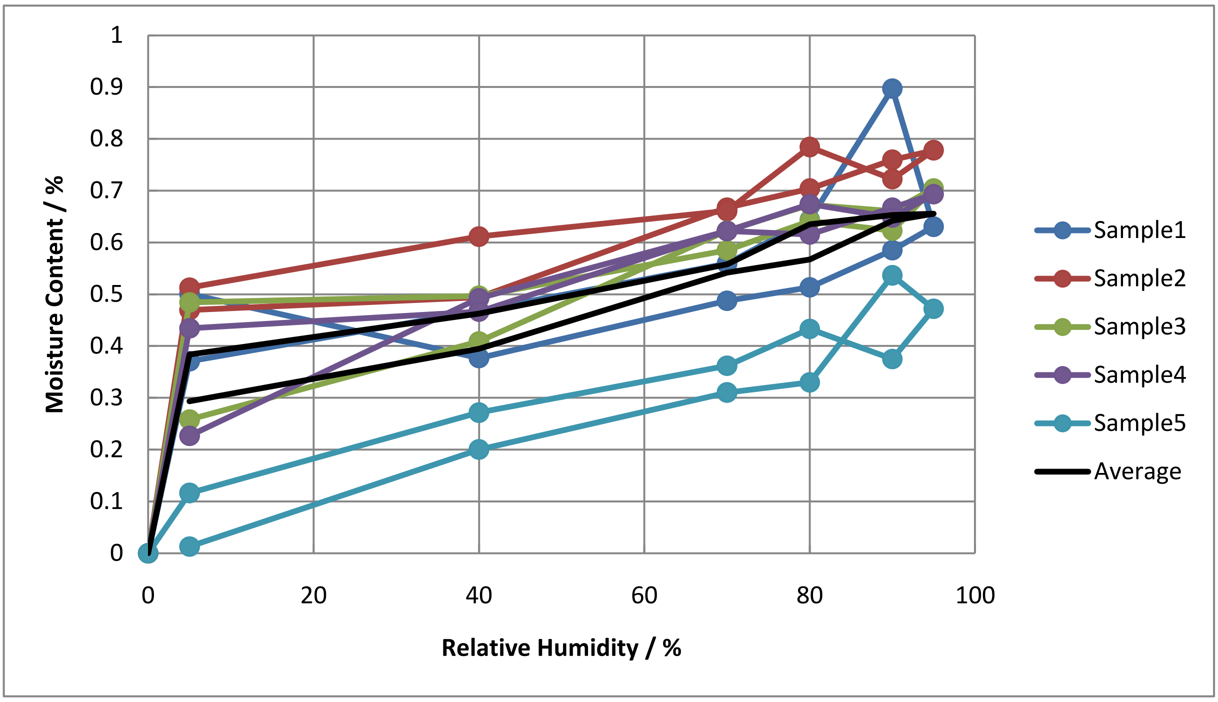

Figure 3. Sorption curve for Wrap E

3.3.4 Wrap F

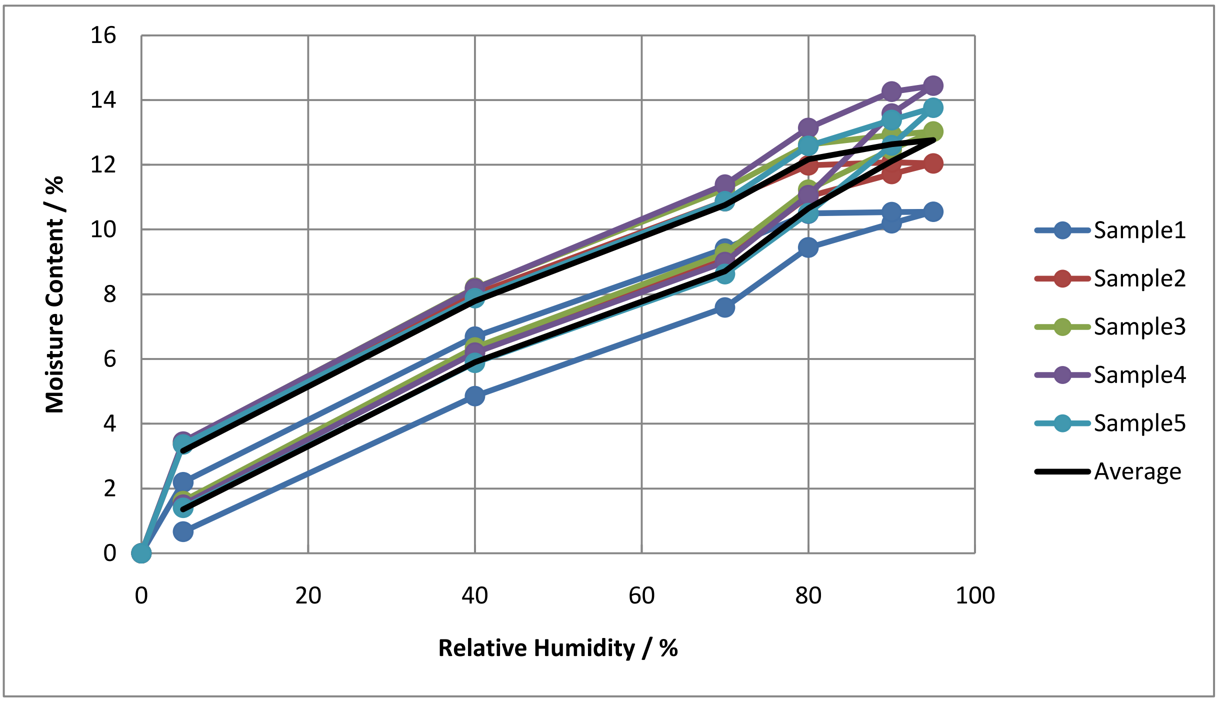

Figure 4. Sorption curve for Wrap F

3.3.5 Wrap J

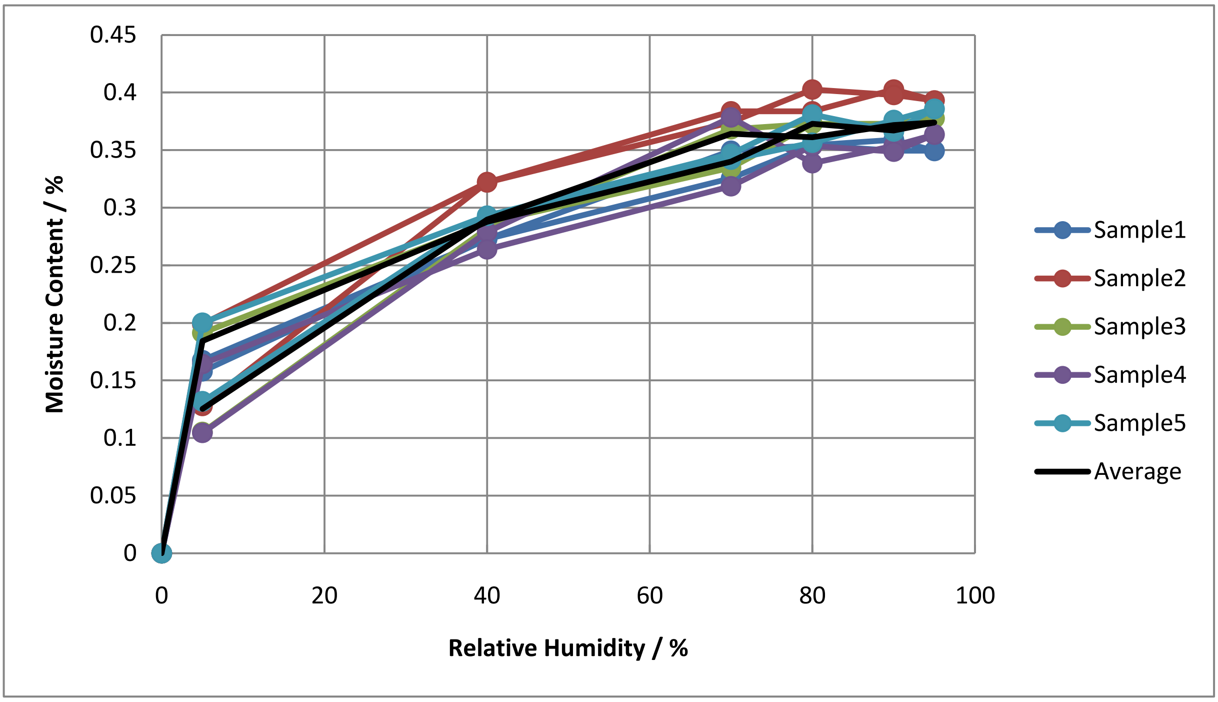

Figure 5. Sorption curve for Wrap J

3.3.6 Comparison of synthetic wraps

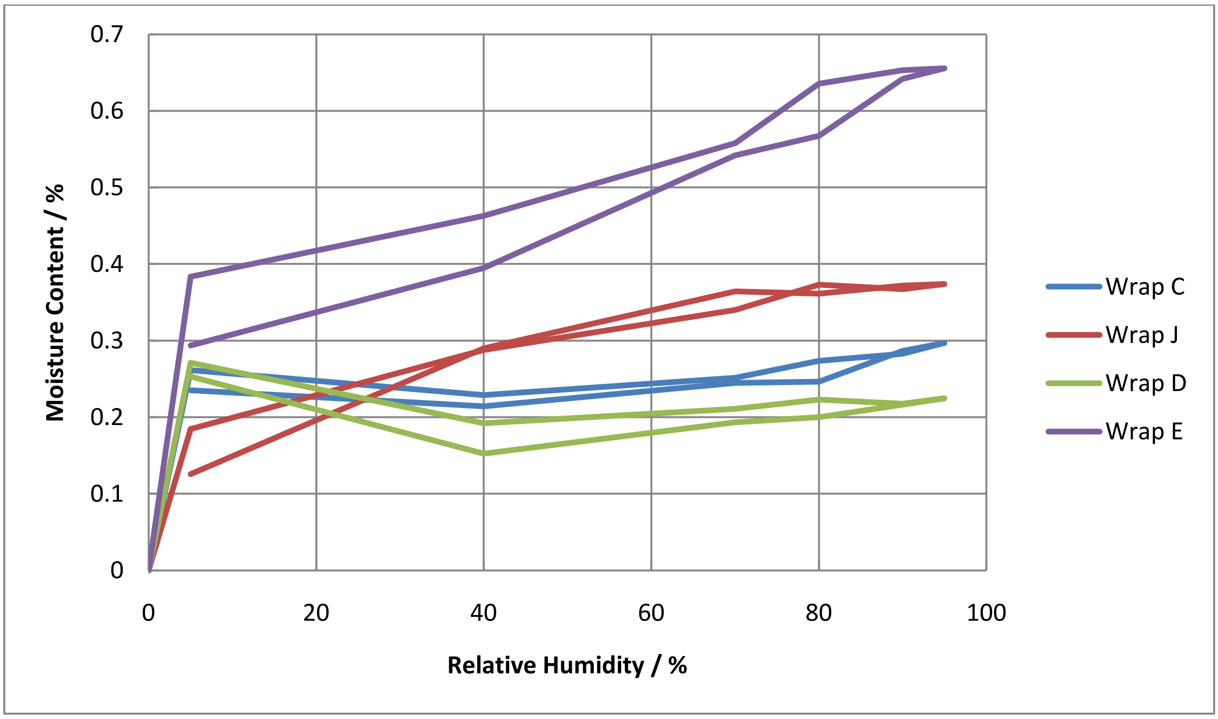

Figure 6. Comparison of sorption curves of synthetic wraps

3.3.7 Wrap C and Wrap F at high relative humidity

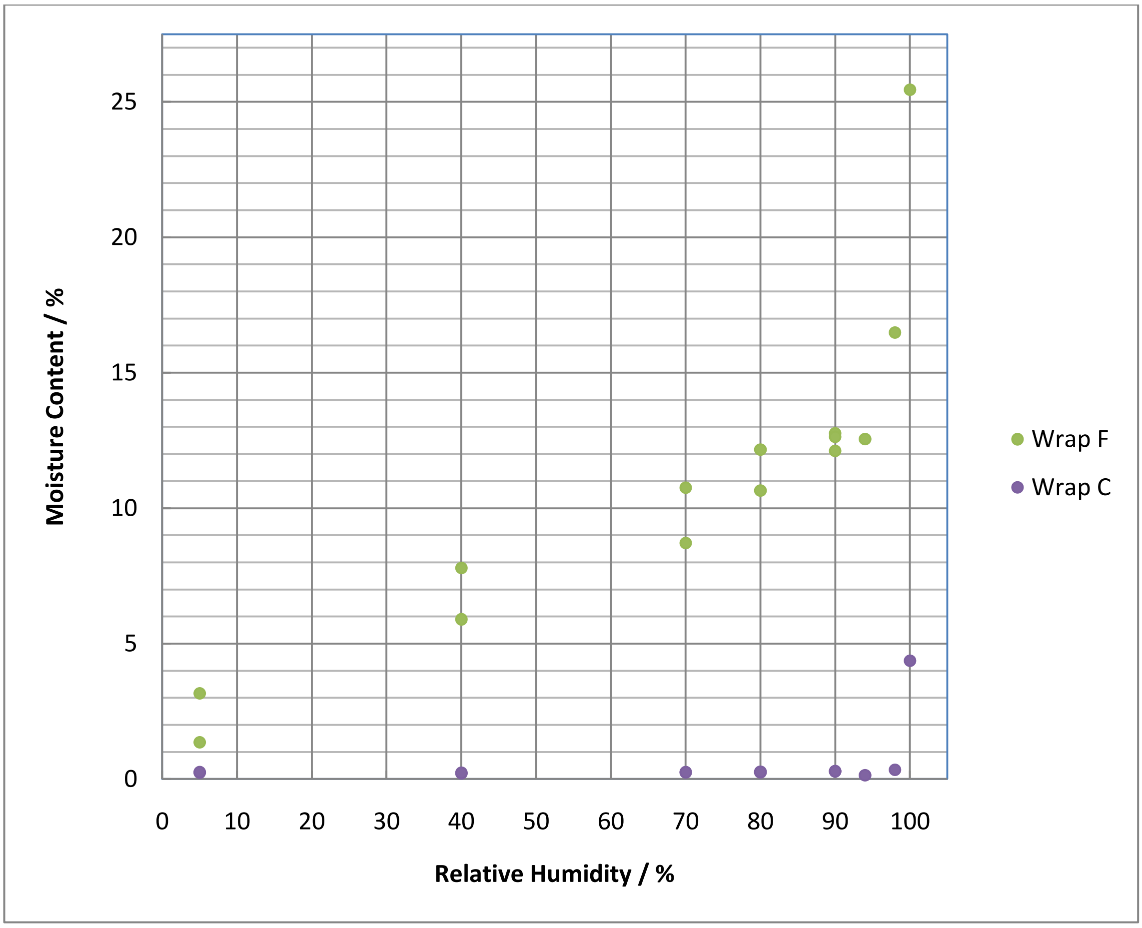

Figure 7. Comparison between a synthetic wrap (Wrap C) and a paper-based wrap (Wrap F)

4. DESCRIPTION OF THE ROOF TEST HOUSE

4.1 Introduction

An experimental building was specifically built for this project in order to provide a series of roof specimens exposed to the elements in which to examine the behaviour of roof underlays. The building is rectangular, 15 m long, 7 m wide, has a roof pitch of 15°, sits on a concrete slab and is without internal partitions. The long side of the building is oriented east-west. Five of the roofs are skillion and five are pitched. Each roof specimen has a north-facing slope and a south-facing slope which share a common section of roof ridge and the same type of cladding. Roof specimens can have either of two types of roof claddings: corrugated galvanised steel sheets or concrete tiles. These claddings have been chosen because they represent the majority of roof claddings of domestic dwellings in New Zealand.

Of the five roof specimens with a flat ceiling and roof space three have corrugated galvanised steel sheets and two have concrete tiles. Similarly of the five roof specimens with sloping ceiling and of skillion type three have corrugated galvanised steel sheets and two concrete tiles. The corrugated galvanised steel sheets are unpainted and the concrete tiles deliberately old. Old concrete tiles have lost most of their coating and they are much more absorbent than new ones. They can absorb considerable amounts of moisture (in comparison to their weight) which should enhance the phenomenon of solar driven moisture.

4.2 Gravimetric condensation apparatus

There is no easy way of measuring the amount of condensation taken in or released by a roof underlay through time but a knowledge of the variation of the moisture content of the roof underlay in function of time and of the changing boundary conditions it is submitted to, is indispensable. A direct way of estimating the moisture content of the roof underlay is simply to weigh a sample of it, but when a roof underlay is installed in a roof exposed to the elements, the underlay becomes “inaccessible” because covered by the cladding.

To overcome this difficulty, each slope of each roof specimen is equipped with a so-called “gravimetric condensation apparatus”. Roof specimens with metal cladding have a square 140 mm x 140 mm square cut through the metal at a suitable location exposing the roof underlay. Rivets are installed all around the edges of this hole to be able to accommodate screws. The hole is than covered by a cover made of the same material and screwed into the rivets. This removable cover allows access to the underlay and, when in place, ensures the continuity of the cladding. In the case of roof specimens with concrete tiles, removing a tile allows access to the underlay. In order to make the process easier, the upstand that anchors this tile to the batten is ground off. This makes it quite easy to slide the tile off or back without significantly disturbing the neighbouring tiles.

Under the metallic cover or the modified tile, the underlay undergoes a few modifications to complete the gravimetric condensation apparatus. First, a square 140 mm x 140 mm hole is cut through the installed underlay. Around the edges of this hole, four magnetic strips are glued to the remaining underlay. All this constitutes the support for a square piece of underlay with four magnetic strips around its edges. This piece clips onto the hole and completely covers it, again preserving the integrity of the roof underlay.

The condensation apparatus allows “opening” the cladding and “taking” a small section of roof underlay. The “gravimetric” part simply refers to the fact that after doing that it becomes easy to weigh the underlay. After the weighing the small section is put back in place together with the metallic cover or the modified tile. Doing this operation at regular intervals makes it possible to follow the increase or decrease in the weight of the underlay due to wetting or drying and to correlate that with the changing environmental conditions.

4.3 Instrumentation

Each roof specimen is instrumented with temperature sensors, RH probes and moisture content meters. Type T thermocouples measure temperatures, capacitance sensors (Honeywell HIH-4001) measure RH and moisture pins measure moisture contents. All the probes are wired back to a central data acquisition unit (Agilent 34980A) controlled by a software written in LabView. Figure 10 shows the location of these probes in the roof specimen for the case of pitch roof. The arrangement of sensors is similar in the case of skillion roof.

Temperature and RHs are monitored in the large unpartitioned indoor space, as they are outdoors of the experimental building. A weather station nearby provides data on wind speed and wind direction and on the level of global and diffuse solar radiation.

Figure 8. Picture of the condensation apparatus for roof specimens with metal cladding

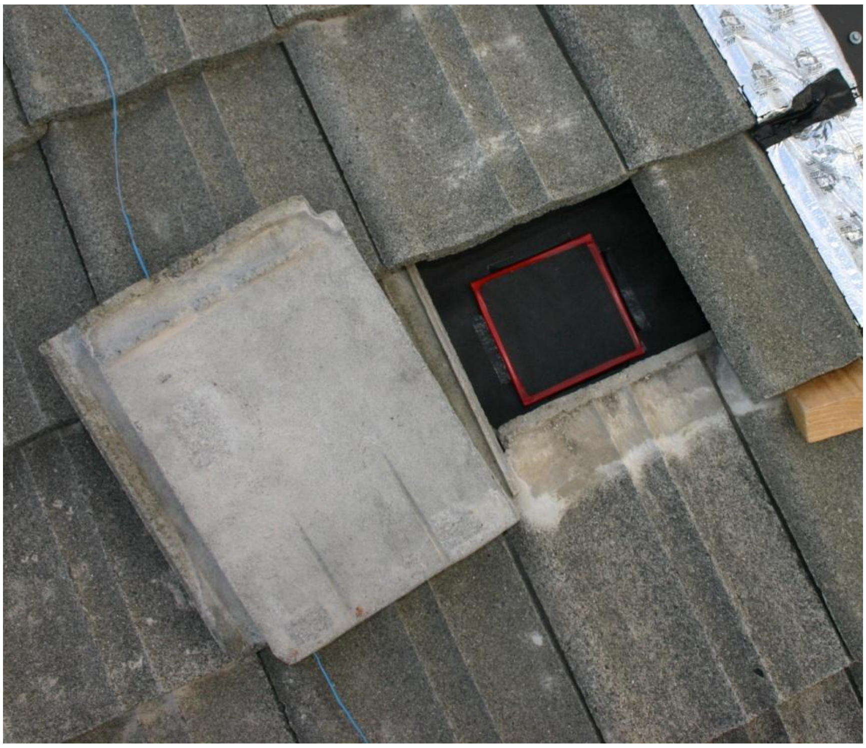

Figure 9. Picture of the condensation apparatus for roof specimens with concrete tiles

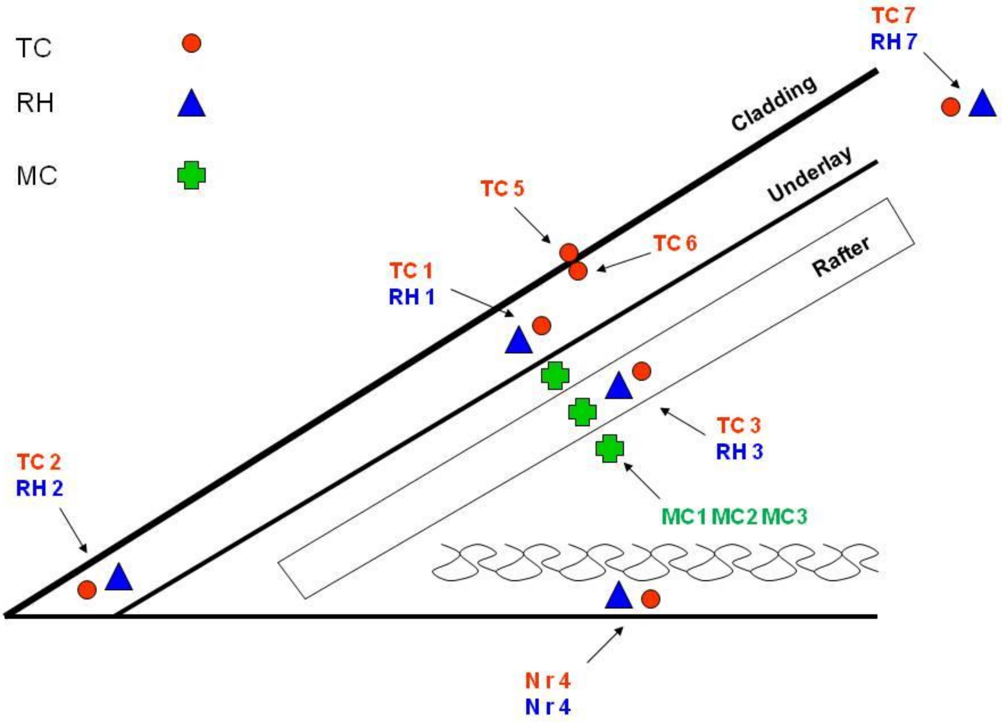

Figure 10. Instrumentation of a slope of a pitch roof specimen. Thermocouples are indicated by red dots, relative humidity sensor by blue triangles and moisture content meters by green crosses

4.4 Conditioning of indoors space

The temperature and the RH of the indoor space of the experimental building are partially controlled by means of two electric heaters and a humidifier. This allows recreating some extreme conditions inside the building, typical of some very humid New Zealand houses. The target profile of temperature is 15°C at 7am, linearly rising to 20°C at 10pm and then linearly decreasing to 15°C at 7am. The RH target profile is 90% at 7pm, linearly decreasing to 50% at 10pm, and then linearly increasing again to 90% at 7am. The power cables of both the heaters and the humidifier are connected to relay boxes controlled by the same software which controls the data acquisition unit. Every minute the conditions inside the house are measured and a decision is taken about switching on or off the humidifier or the heaters.

5. SOME EXPERIMENTAL RESULTS

5.1 Indoor conditions

An example of the indoor climate conditions is presented in Figure 11. The temperature oscillates from 15°C to 20°C and the RH from 60% to 90% in a 24 hours cycle. A temperature of 15°C and an RH of 90% are reached around 7 am and a temperature of 20°C and an RH of 60% are reached around 10 pm. These conditions have been chosen to represent the night cooling and the day warming due to the presence of a heating system and the moisture load due to human presence and activities in the house. The temperature and RH so generated represent the boundary conditions for the roof specimens on the ceiling side. These conditions are typical for a New Zealand house that is slightly damper than average.

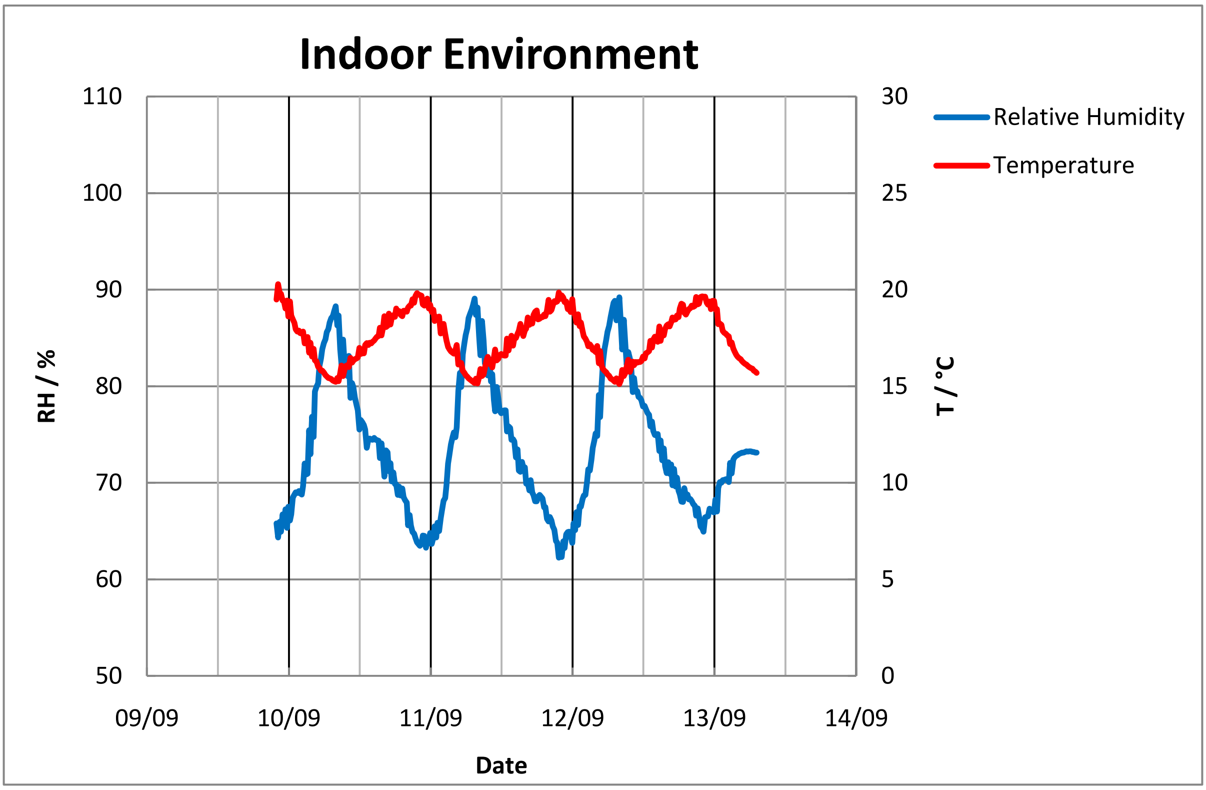

Figure 11. Example of indoor conditions in the experimental building

5.2 Outdoor condition

An example of the outdoor climate condition is presented in Figure 12 (for the same time period as Figure 11). These temperatures and RHs represent the boundary conditions for the roof specimens on the cladding side. Some of the RH values slightly exceed 100%, which is physically impossible. This is due to the difficulty of obtaining an accurate calibration of the sensor for RH values close to saturation and the inherent inaccuracy of the sensor in a condensing environment.

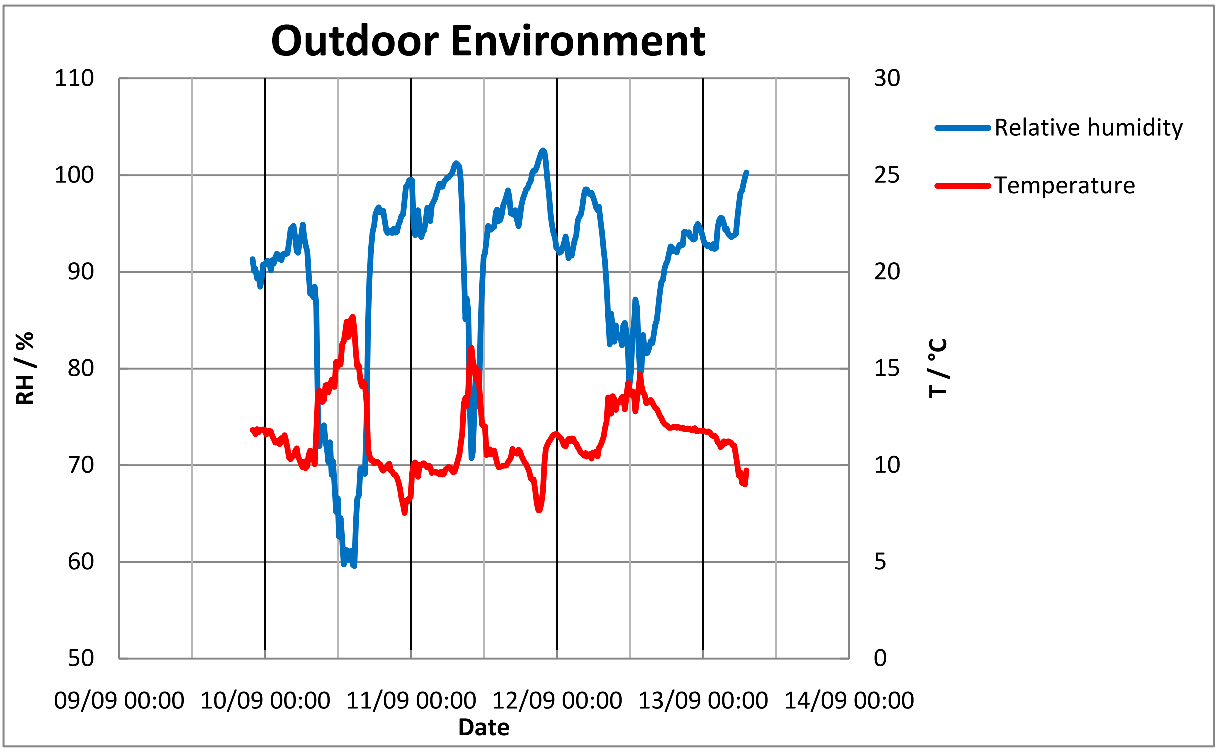

Figure 12. Example of outdoors conditions

5.3 Variations of temperature, relative humidity and moisture content

An example of the variation of temperature at several locations within a roof specimen is shown in Figure 13. The roof specimen is of skillion type and has unpainted corrugated galvanised steel as its cladding. The timeframe is the same as in Figure 11 and Figure 12 which represent the boundary conditions at the ceiling and at the cladding. The thermocouple which is located just above the ceiling and below the insulation records a temperature similar to the temperature of the indoor environment and it oscillates accordingly from 15°C to 18°C. The three thermocouples located near the rafter and below the underlay, on top of the underlay and in contact with it and on top of the cladding and in contact with it display a similar behaviour: during the day the temperature rises above or well above the outdoor air temperature and during the night it descends to the level of temperature of the outdoor air and sometimes below.

The thermocouple recording the more extreme behaviour is the one measuring the temperature of the cladding, followed by the one measuring the temperature of the underlay and the one measuring the temperature below the underlay. During the day the absorption of solar radiation by the cladding heats it up considerably. In turn the warm cladding heats up the air in the cavity above the underlay and under the underlay. The thermal resistance of the underlay makes the temperature of the air near the rafter and below the underlay rise less considerably than in the cavity above it. During the night the opposite happens: the cladding cools down more than the air above the underlay and around the rafter. A comparison of the temperature of the cladding during the night (around 4°C) and the temperature of outside air (around 7°C) shows the rather interesting effect that the metal cladding cools below the temperature of the outside air. This phenomenon is called “radiative cooling” and it is explored in-depth in section 6.

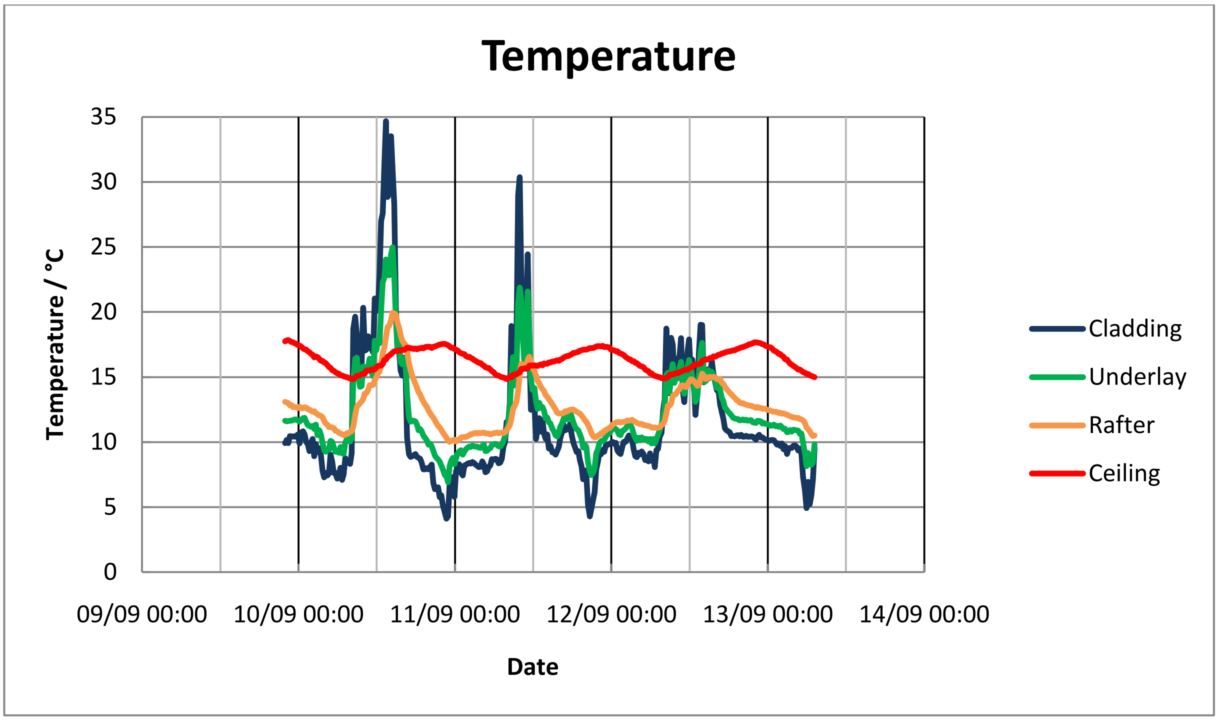

Figure 13. Example of temperature profiles in different "layers" of the roof specimen

The behaviour of RH in several locations of a roof specimen is shown in Figure 14. The roof specimen and the timeframe are the same as in Figure 13. Some of the RH values slightly exceed 100%, which is physically impossible. This is due to the difficulty of obtaining an accurate calibration of the sensor for RH values close to saturation and to the inherent inaccuracy of the sensor in a condensing environment. The RH sensor located between the gypsum board of the ceiling and the insulation oscillates between 70% and 80%, in phase with the daily variation of RH in the conditioned indoor space but of smaller amplitude. The RH sensor located above the underlay exhibits the most extreme behaviour. It mimics the variation of RH of the outside air. However during the daytime, since the temperature in the underlay-cladding cavity is often much higher than the outside temperature, the air in that cavity often becomes quite dry, while during night-time, since the temperature in the underlay-cladding cavity is often much lower than the outside temperature, the air in that cavity often becomes saturated for longer periods of time. The RH sensor located near the rafter shows an intermediate behaviour.

The behaviour of the wood moisture content of the rafter is presented in Figure 15 over a period of eight months. Usually the variation of wood moisture content can only be appreciated over long periods of time. The moisture content was measured at the surface of the wood near the top of the rafter and near its bottom and also deep in its core. The surface measurements are more sensitive to short-term fluctuations in the hygrothermal environment around the rafter, while the measurements in the core of the wood are more representative of the behaviour of the bulk of the wood. The surface measurements fluctuate rapidly because the surface of the wood quickly adsorbs and desorbs moisture in response to changing conditions. The moisture content of the top surface of the rafter is marginally higher than the one at the bottom. This is probably due to the fact that the top of the rafter is closer to the roof underlay which absorbs and releases moisture. The moisture content value of the interior of the rafter exhibits slower variations and of smaller amplitude, but all the moisture content values show a trend demonstrating the drying of the wood during the spring and summer months.

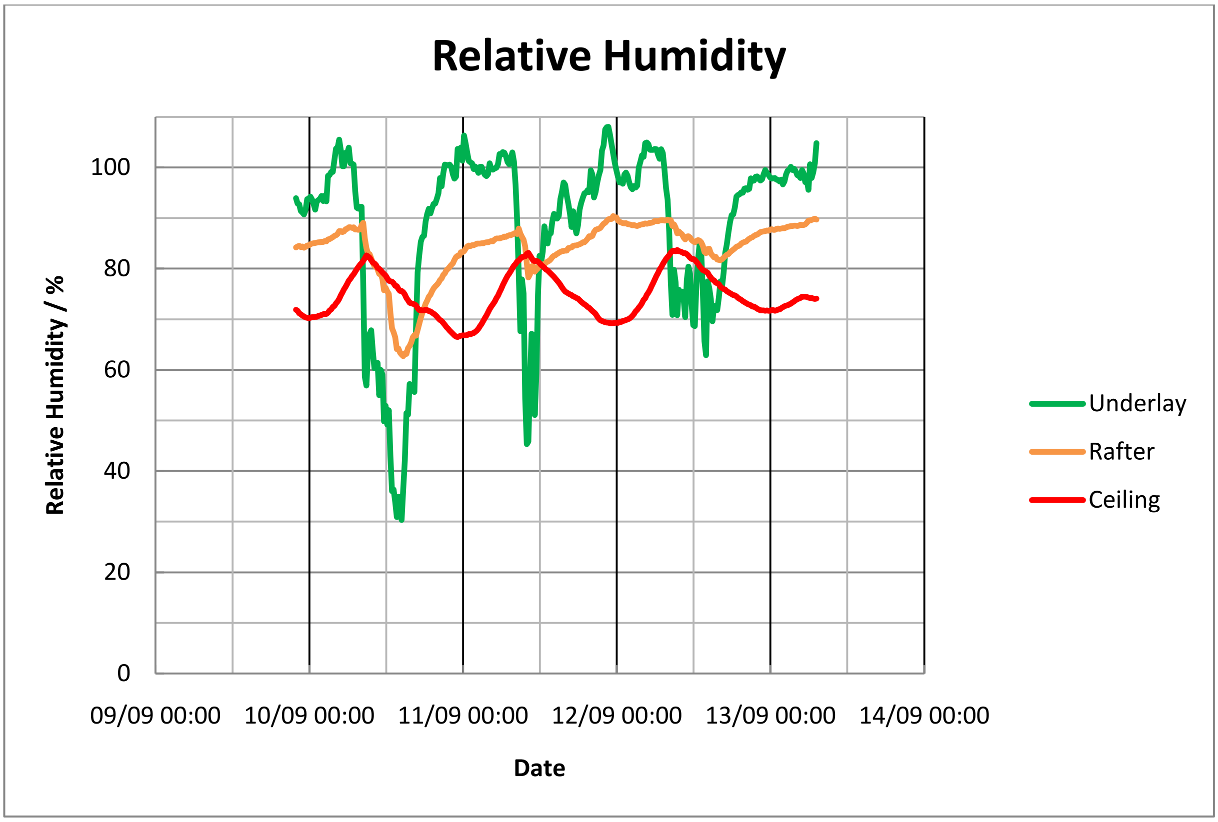

Figure 14. Example of relative humidity profiles in different "layers" of the roof specimen

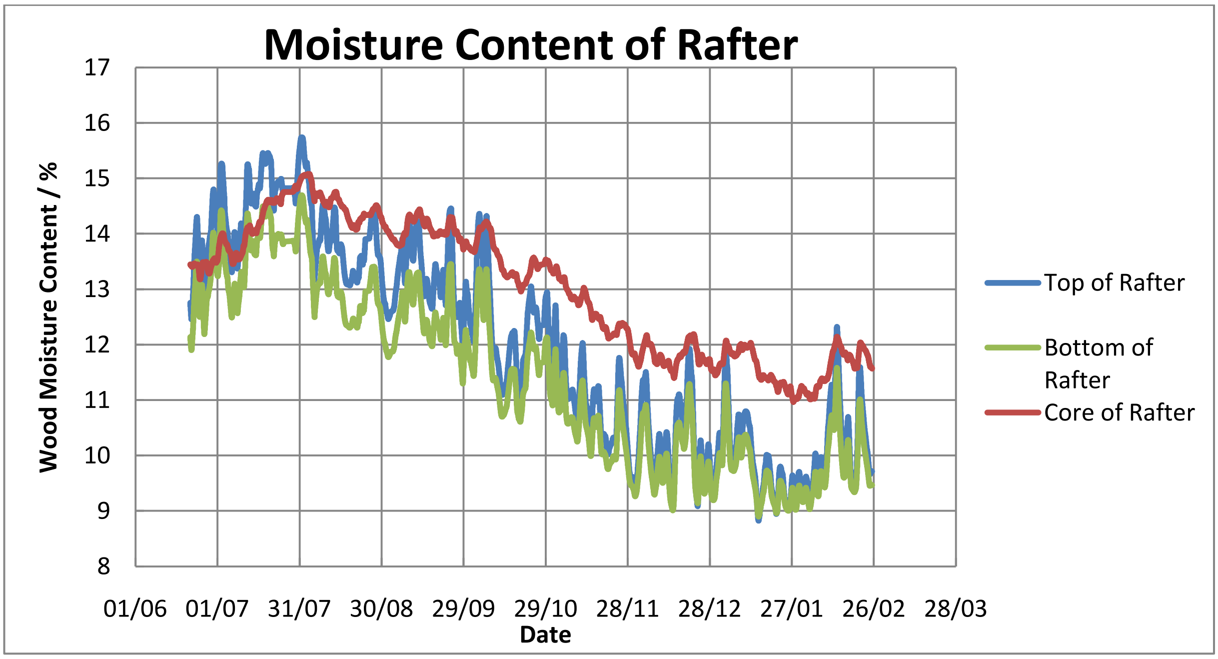

Figure 15. Example of moisture content in wood in different locations of the rafter

6. SOME OBSERVED PHENOMENA

6.1 Evidence of night sky radiative cooling

Night sky radiative cooling is the phenomenon by which horizontal or sloping surfaces facing the sky during the night can cool below the temperature of the outside air. Especially during cloudless and still nights the sky behaves as a black body at a temperature well below the outside air temperature. Empirical relationships (Hagentoft, 2001) show, for example, that when the outside air temperature is 5°C the night sky behaves as a black body at around minus 8°C, when it is 0°C as a black body at around minus 14°C. As a consequence surfaces facing the sky radiate heat away. If there is no or little wind, the surface may quite easily cool several degrees below the ambient temperature. If there is even a moderate air movement, convective heat transfer quickly dominates over radiative cooling and the temperature of the surface equilibrates with the temperature of the outdoor air.

Figure 16 shows an example of night sky radiative cooling. During the night between 24 June and 25 June 2008, the sky was cloudless and the outside temperature got to around 0°C for part of the night. At the same time the wind was nearly absent. The right conditions for night sky radiative cooling were all present and indeed the temperature of the cladding plummeted to around minus 5°C!

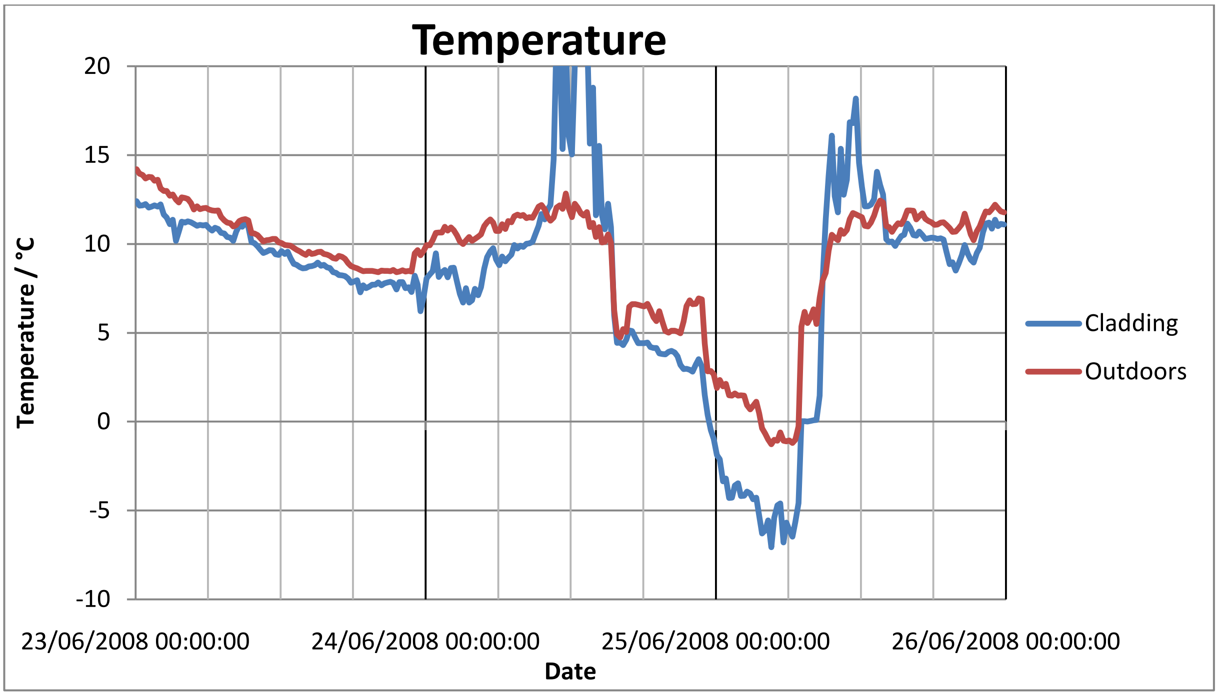

Figure 16. Example of night sky radiative cooling, during cloudless and still nights, the temperature of the cladding can sensibly drop below ambient temperature

Gravimetric measurements during night sky radiative cooling are very instructive to monitor the wetting and drying of the roof underlay during an episode of night sky radiative cooling. The monitoring of the underlay is done by means of the condensation apparatus: at regular time intervals, the removable part of the cladding is taken off and the removable part of the roof underlay is weighed.

Figure 17 shows the temperature of the outdoor air and the temperature of a metallic cladding surface. The night between 6 September and 7 September 2008 was marked by an episode of night sky radiative cooling lasting more than 12 hours and bringing the temperature of the cladding to sub-zero values for most of the night. The wind speed was initially small and then it became moderate. This only marginally reduced the effectiveness of the radiative cooling during the second half of the night. As a consequence of the sub-zero temperature of both the metallic cladding and of the concrete tiles, all exposed surfaces were covered by a thin layer of ice from around 8pm through to around 6am of the following day. The layer of ice grew thicker during the night.

During the regular weighing of the underlay, a visual inspection of the underside of the cladding was carried over in order to observe if droplets of condensate were forming. Quite surprisingly, no evident condensation was observed.

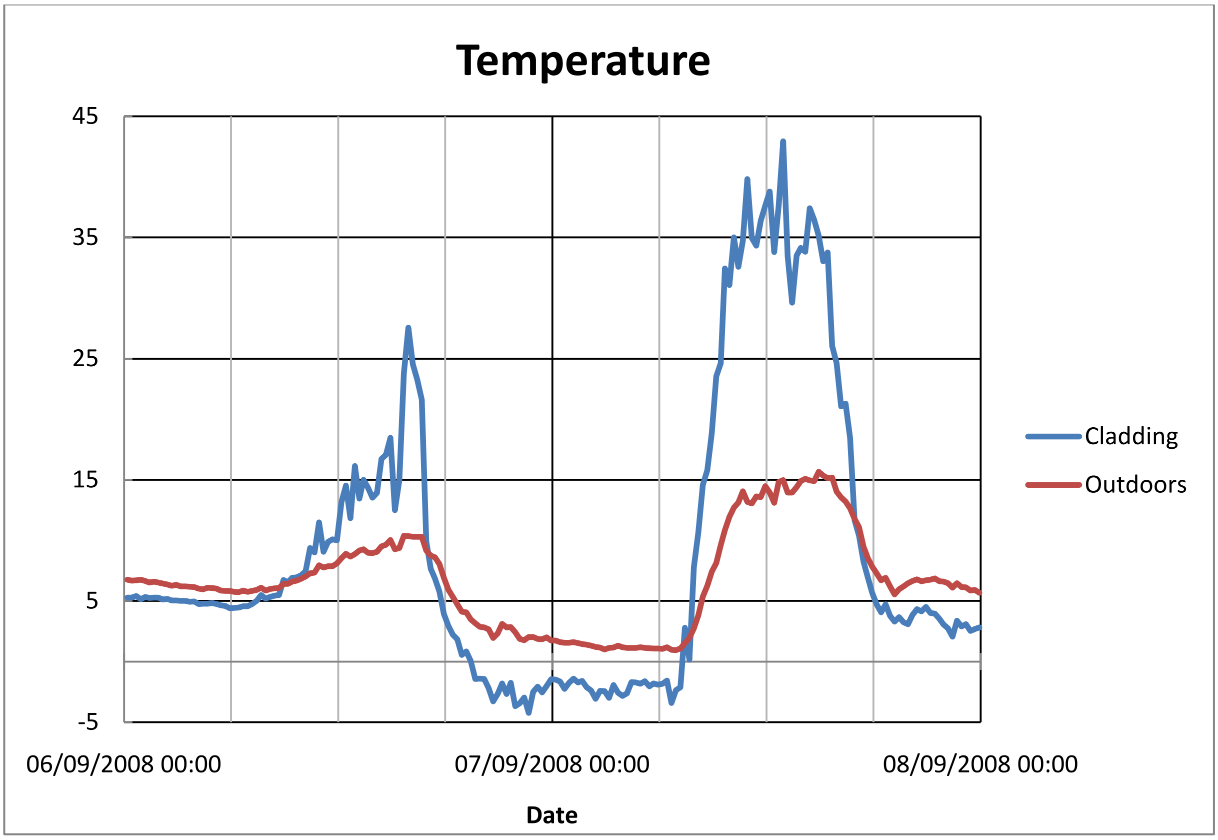

Figure 17. Another example of night sky radiative cooling, the corresponding gravimetric measurements are presented in Figure 18

Figure 18 presents the results of the weighing of the roof underlay. Weight increases and decreases are interpreted as absorption and desorption of moisture by the square sample of underlay forming the condensation apparatus. Instead of reporting the weights, the graph shows values of moisture content: the mass of water bound to the specimen or sitting at its surface is expressed as a fraction of the dry weight of the specimen itself.

Two types of roof underlays were taken into consideration: a traditional paper-based product (Wrap F) and a trilaminate synthetic product (Wrap C). These roof underlays were installed both in skillion and pitched roof specimens and with both metallic cladding and concrete tiles. Due to the different hygroscopic characteristics of the two membranes, their moisture content levels are quite different. Wrap F is very hygroscopic while Wrap C is only moderately hygroscopic.

The behaviour of the paper-based underlay seems to depend on the type of roof (skillion or pitch), but much less on the type of cladding of the roof (metallic cladding or concrete tiles). In the case of the skillion roof, the moisture content rises quite considerably, from around 10% to over 20%, while in the case of the pitch roof the increase is much smaller, from around 10% to around 13%. Having a metallic cladding or concrete tiles does not seem to have a major effect except a slightly greater rise in moisture content in the case of metallic cladding.

The behaviour of the trilaminate synthetic product is less pronounced as the material is only moderately hygroscopic. In the case of the skillion roof, there are moisture content increases of 3-5% while in the case of pitch roof it stays roughly constant.

It has been noted that on the underside of the cladding no droplets of condensate were observed. That seems to exclude that the increase of moisture content in the roof underlay was due to droplets of water dripping from the underside of the cladding onto the roof underlay. The variation in moisture content should then mainly be attributed to the hygroscopic behaviour of the underlays and to surface condensation. The cooling of the cladding makes the RH in the cavity between underlay and cladding increase and as a consequence the moisture content increases following the sorption curve of the material. Once reached a RH of 100% condensation could create a film of unbound water at the surface of the underlay that would lead to a further weight increase.

The moisture content reached at its highest around 24% for Wrap F (paper-based) and around 5% for Wrap C (synthetic trilaminate). Comparing these values with the sorption curves for Wrap F and Wrap C presented in Figure 7, we can observe that in both cases the moisture content remained in the hygroscopic region, below or near saturation. This would point to the fact that there was no unbound water condensing at any time on the surface of the underlay.

The difference in behaviour of the paper-based underlay, and to a minor extent of the synthetic underlay depending on the type of roof (pitch or skillion), could hint to the role of ventilation. In a skillion roof two rather small cavities separate the underlay from the underside of the cladding and from the top of the insulation. In a pitch roof there is a small cavity between the underlay and the underside of the cladding, but a much larger space under the underlay (the roof space). Ventilation in the roof space probably inhibits the absorption of moisture by the underlay.

Further investigations and modelling are needed to fully understand the dynamics of absorption and release of moisture by the underlay. But the most notable observation is that even under prolonged conditions of night sky radiative cooling no evidence of dripping condensation from the underside of the cladding onto the underlay was detected.

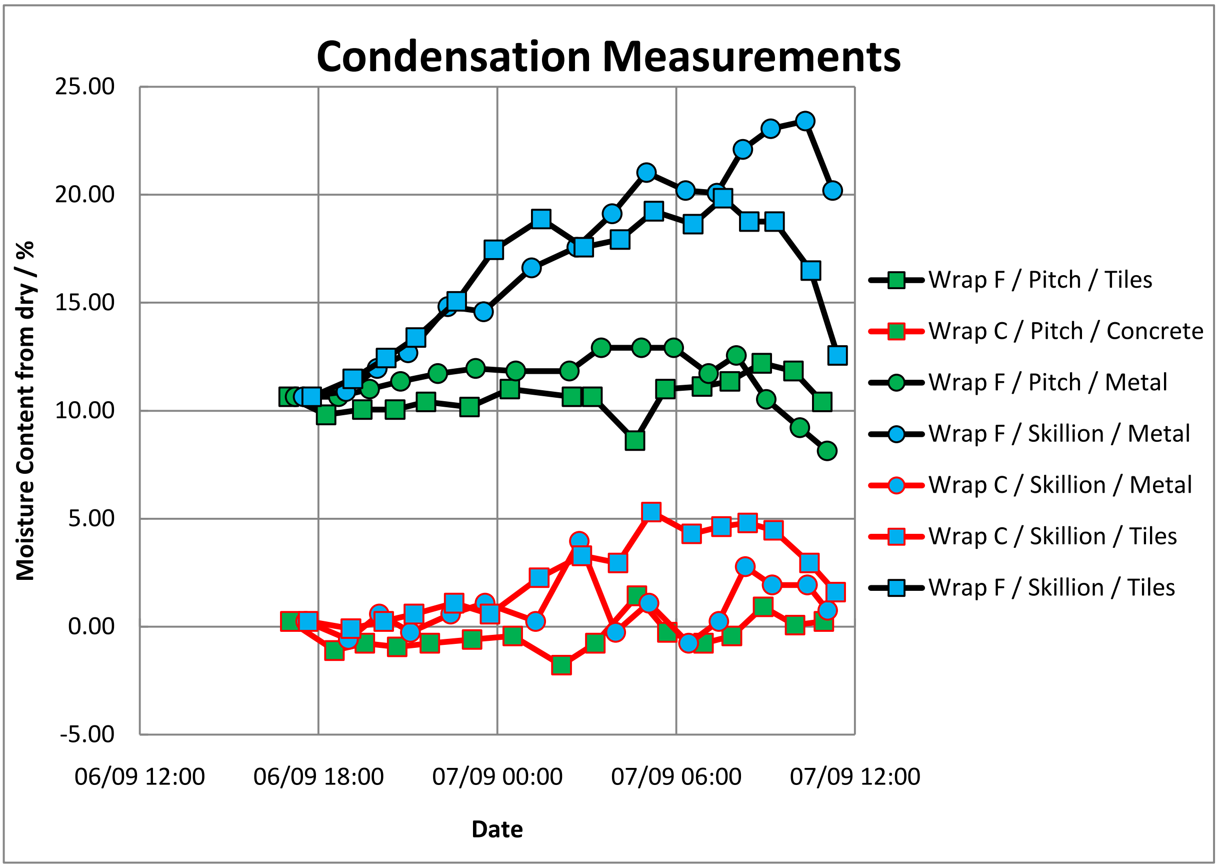

Figure 18. Gravimetric condensation measurements corresponding to the night sky radiative cooling presented in Figure 17. The weight of the section of underlay (part of the condensation apparatus) was measured at regular intervals during the event, then it was converted to moisture content using the area density of the dry material reported in Table 1.

6.2 Negative observation of solar driven moisture

The phenomenon of solar-driven moisture is the one by which moisture is driven inside a structure by solar radiation. In roofs, the phenomenon is only possible with absorbent claddings like fibre-cement or concrete tiles. During a rain event, tiles can absorb a considerable portion of their weight in water. When solar radiation shines on a wet tile, it makes the most of the absorbed water evaporate but also drives a fraction of the absorbed water towards the inside of the structure into the cavity above the underlay. The temperature difference between the side of the tile exposed to the solar radiation and the unexposed one creates a large vapour pressure gradient that drives a fraction of the absorbed water inside while the majority of the water evaporates.

Some experiments have been done in order to estimate the importance of this phenomenon. In order to possibly enhance the effect of solar-driven moisture, we artificially water the roof specimens with concrete tiles during a night preceding a sunny day. The watering was done using a hose pipe in the shape of a ribbon with many little holes along its length in order to achieve a more or less even irrigation along the width and the slope of the roof specimens. The watering of the roof specimens was done at night in order to avoid evaporation and solar gain. In the morning, the water was turned off and measurements using the condensation apparatus were made. The weight of the modified tile and of the weight of the 140 mm x 140mm square of underlay were monitored regularly for a period of a few hours. The aim was to detect a rise in moisture content of the underlay due to moisture absorbed by the tiles driven towards the inside of the structure. The tile and the underlay were weighed before starting watering the roof and Figure 19 and Figure 20 shows their weight increase after the watering. The underlay used was Wrap F, a paper-based roof underlay.

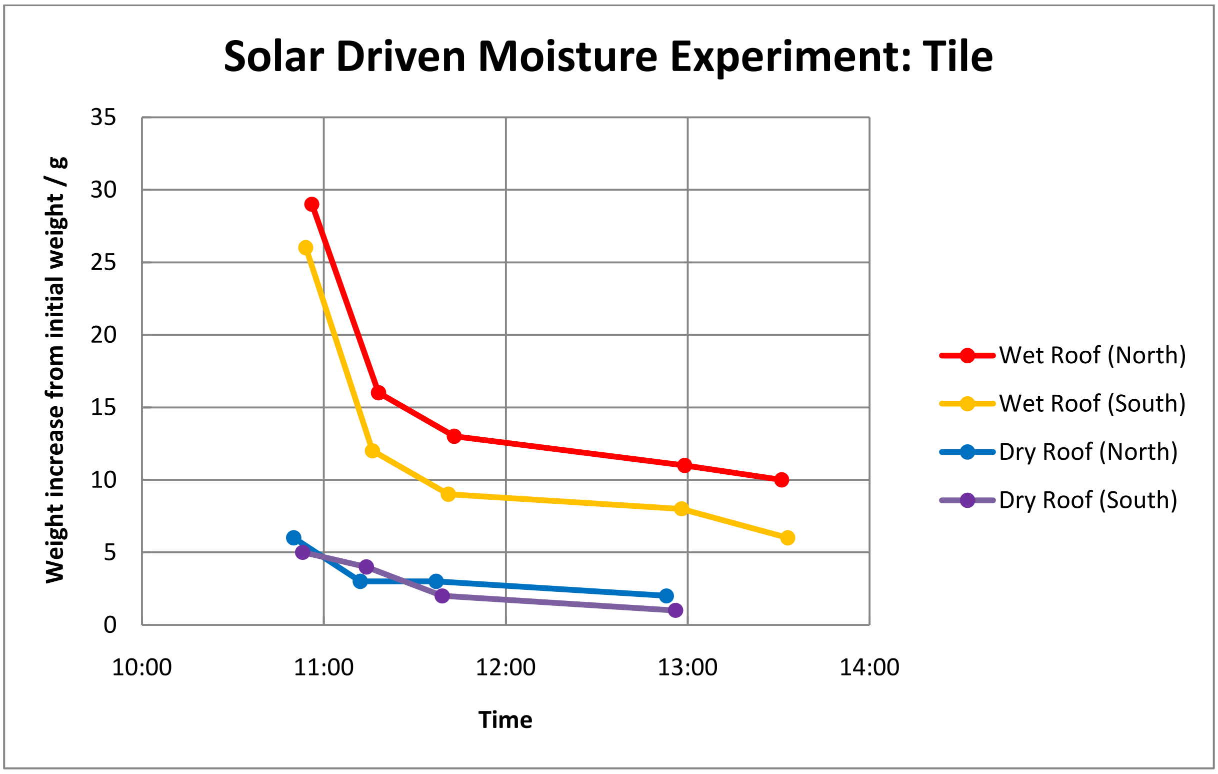

Figure 19. Difference between the weight of the modified tile of the condensation apparatus after watering the roof specimen and its weight just before starting watering the roof (called "initial weight"). One roof specimen was watered during more than 18 hours simulating the equivalent of 100 mm of rain and one was left dry. The graph represents the evolution of the weights after the watering was stopped and while solar radiation dried the roof

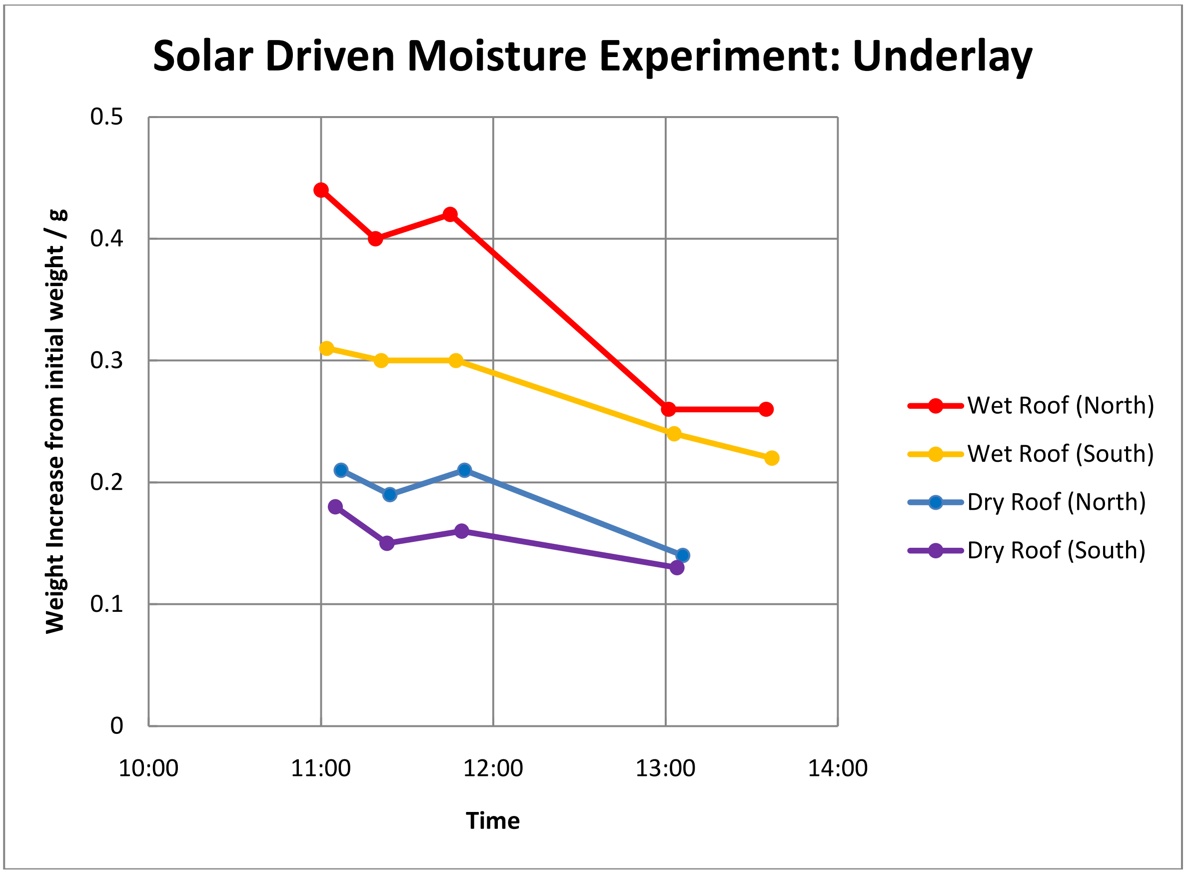

Figure 20. Difference between the weight of the section of underlay of the condensation apparatus after watering the roof specimen and its weight just before starting watering the roof (called "initial weight"). One roof specimen was watered during more than 18 hours simulating the equivalent of 100 mm of rain and one was left dry

The graph represents the evolution of the weights after the watering was stopped and while solar radiation dried the roof.

The weight of the square of underlay and of the modified tile of the condensation apparatus were weighed before starting watering the roof tiles and then at regular intervals after the hose was turned off. No measurement was made while the water was running down the slopes of the roof specimens.

The tiles of the roof specimens which were not watered show a slight weight increase compared to the weight the day before, followed by a decrease. The initial weight increase is probably due to spray carried from the neighbouring watered roof specimen. In comparison, the tiles of the roof specimens which were watered show a far more pronounced weight increase compared to the weight the day before, because of absorption of water. Most of the absorbed water then quickly evaporates.

The weight of the 150 mm x 150 mm square of roof underlays exhibits an initial weight increase compared to the weight the previous day. The weight of the underlay in the roof specimens which were not watered decreased only slightly during the measurements period. The decrease is more pronounced for the square of underlay in the roof specimen which was watered. Figure 21 shows the behaviour of the RH in the cavity between underlay and cladding of the two roof specimens. From around 9am the RH starts decreasing due to the effect of the solar radiation shining on the roof specimen which was not watered. From around 11am to 2pm, the period covered by the measurements, the RH in this roof specimen stayed approximately constant and that agrees with the fact that the weight of the underlay only changed marginally. In the roof specimen which was watered, the RH only started decreasing at around 11am, when the watering of the roof stopped, and continued during the period covered by the measurements. This is an agreement with the decrease in weight of the underlay.

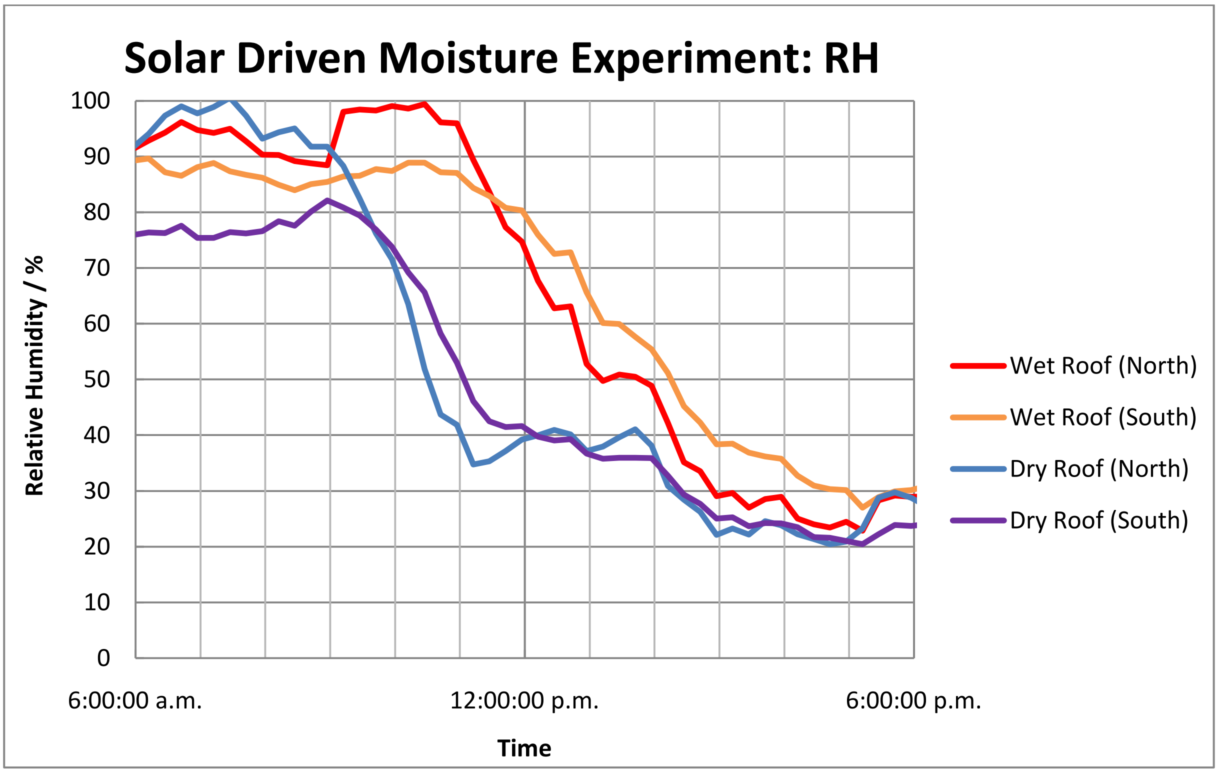

Figure 21. Evolution of the relative humidity in the cavity between underlay and cladding during the final phase of the watering and during the drying of the roof specimens. One roof specimen was watered for 18 hours simulating the equivalent of 100mm of rain and one was left dry. The sun rose at around 6.30am and the watering was stopped at around 11am

If the phenomenon of solar-driven moisture was significant the behaviour of RH and of the weight of the underlay should be quite different. If solar radiation drove detectable quantities of moisture into the structure while the sun was shining on a wet absorbent cladding, the RH should remain at high levels for a certain period of time after the watering of the roof specimen has stopped. Instead the RH starts dropping as soon as the watering of the roof ends. Between 9am and 11am the RH of the north slope of the roof specimen which was kept wet rose sharply. That could be an indication of the presence of some solar-driven moisture when the water was still continuously running down the slope of the roof but the sun had already risen and was heating up the concrete tiles.

Even if the phenomenon of solar-driven moisture was active, its effect on the hygrothermal environment seems very marginal. Visual inspection of the underlay did not show any evidence of dripping condensation from the underside of the concrete tiles.

7. CONCLUSIONS

Roof underlays constitute the second line of defence of the roof envelope. They contribute, among other functions, to the management of moisture accumulation in roof cavities. If moisture forms under the cladding and it starts dripping, the underlay protects the roof framing and the insulation from it. This report has presented some experimental results of an investigation aimed at understanding how roof underlays work under New Zealand conditions and which physical properties they require to fulfil their tasks.

Measurements of the moisture-related physical properties of a range of building wraps have been given. Besides the properties referenced in several standards, sorption curves of some of these building wraps have been studied. This shows how differently paper-based products and synthetic products behave from the point of view of moisture storage. The measurement of these properties is also important for the theoretical modelling of roof underlays which is currently underway.

A description of a building dedicated to the study of roof underlays has been given. This building allows studying the behaviour of a range of roof underlays under different claddings (corrugated metallic sheets and concrete tiles) and with different typologies of roof (pitched and skillion).

Two of the main phenomena which can generate moisture accumulation in the interstices of the roof envelope have been investigated: condensation generated by night sky radiative cooling and moisture transfer in a wet adsorbent cladding driven by solar radiation. In both cases, the main result is that no sign of dripping condensation has been observed. The roof underlay responds hygroscopically to changes in RH and its moisture content changes accordingly but a preliminary conclusion is that its moisture content does not reach levels above saturation.

Further work is underway aimed at artificially creating condensation under the metallic cladding and to study the response of the underlay. This allows studying of the theoretical situation where there is a substantial amount of condensation that could drip on the underlay. Some preliminary tests have shown that where there is a region of contact between cladding and underlay (for example along the valleys of a corrugated metal sheet) condensation can be transferred to the underlay without the need of dripping. In order to enhance this process, these experiments will be done using ribbed metal sheets that present a larger area of contact with the underlay.

8. BIBLIOGRAPHY

Hagentoft, Carl-Eric. 2001. *Introduction to Building Physics.* Sweden : Studentlitteratur, 2001.