THE PERFORMANCE OF UNVENTILATED ROOF TILE UNDERLAYS

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In recent years, the use of unventilated roof tile underlays (also known as under-roofs, underlayments, or sarking felts) in sloped roofs has become more and more common. For this reason, new types of products with new performance properties have been developed. The products are of different materials but are usually very thin materials (magnitude 0.1 to 0.5 mm [4 to 20 mil]), supplied in roll form, that have very high water-vapor permeability. There is, however, no long-term experience as to the performance of such products and constructions. For this reason, a research project was initiated in order to find and study the most important properties of roof tile underlays. The results from computer simulations, laboratory tests, full-scale tests in a test house, and in-situ investigations have been utilized in order to assess the products and constructions. Most of all, problems related to the accumulation of moisture during winter were assessed because this was considered the greatest risk for this type of construction. Based on the findings of the investigations, a number of performance requirements have been stated.

KEYWORDS

Durability, moisture transport, performance testing, roof constructions, roof tile underlays, sarking felt, underlayments, under-roofs, unventilated sloped roofs.

INTRODUCTION

Previous tightening of the roof tiles and slates (e.g., with mortar, bitumen, or putty) was used to secure the roofs against penetration of water from the outside to the interior of the roof construction. For quite some years, it has been common practice to use underlays for roof coverings in sloping roofs instead of tightening the covering itself, especially in constructions where the ceiling and the roof covering are parallel. In addition, the use of underlays makes it possible to use roofs with lower slopes than previously. It is a prerequisite for underlay use that the construction allow the small amounts of moisture that penetrate from the interior of the building, even when a vapor retarder is used, to escape. If these requirements are not fulfilled, the roof will suffer from the accumulation of moisture and, eventually, the degradation of wooden parts because fungus and dry rot will take place.

Traditionally, roofs with underlays have been ventilated (i.e., with a ventilation cavity between the insulation and the underlay [see Figure 1]). The purpose of the ventilation is to remove the moisture penetrating through the ceiling. In such cases, water- and vaportight underlay materials perform very well, as long as the ventilation of the cavity functions properly (i.e., with sufficient height and sufficient openings to the surroundings).

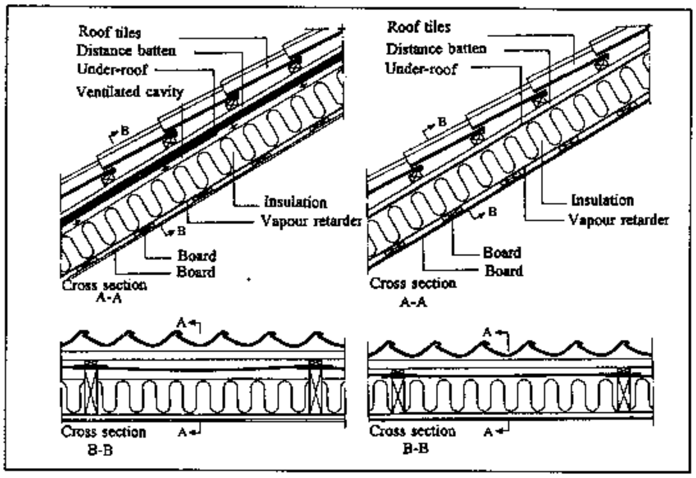

Figure 1. Cross section of ventilated (left) and unventilated (right) roof tile underlay.

During recent years, a new type of underlay material has been introduced to the market. These materials, which are very open to water vapor diffusion, are used in a different way than previously; they are placed directly on top of the insulation (i.e., it is no longer possible to remove moisture from underneath by ventilation; diffusion is the only method available). In a number of cases, these new constructions have caused problems, for which reason a project was initiated to investigate which requirements need to be fulfilled to ensure a satisfactory performance. The project primarily focused on requirements related to moisture transport in the roofs because this problem is normally considered to be the most important for the performance and the durability of the roof.

PERFORMANCE PROPERTIES

A list of performance properties was made based on an analysis of the functions of roof underlays and on the agents acting on them. This analysis was carried out partly as a brainstorm, partly as a study of existing literature. As an example, the agents found by the analysis are shown in Table 1. It should be noted that some functions are only relevant for some materials and/or constructions (e.g., only board materials are able to contribute to an improvement of the stability). Similarly, some of the agents might only act for a limited period (e.g., UV light will normally act only during the construction period).

In this study, only properties related to moisture transport and accumulation have been investigated. They are found to be:

- *Tightness against precipitation*—this property is especially

- water from above (precipitation rain, snow, hail)
- water from below condensation
- water vapor
- sound
- wind
- dynamic load persons, tools
- static load fastenings, self weight, etc.
- UV light
- high and low temperatures and temperature variations
- compatibility with other materials (e.g., insulation)
- fire
- dirt

Table 1. A list of agents acting on underlays.

required during the construction period until the primary roof has been laid. Besides, it is important as secondary protection from wind-driven rain and drifting snow and when tiles are broken or blown off.

- *Tightness against water*—this property covers standing water as well as water running on the surface. When well-constructed, no ponding should occur on the roof tile underlay.
- *No tent effect*—tent effect refers to the well-known fact that touching the inside of a tent during rain may cause penetration of water. For underlays laid directly on wood and insulation, no tent effect should occur, as it would impair the watertightness.
- *Water vapor permeability*—for unventilated constructions, it is evident that moisture from the interior of the building can escape through the underlay only by diffusion. Consequently, the material shall be very permeable to the diffusion of water vapor.
- *Moisture-accumulating property*—is a supplementary asset if all other requirements for the roof are fulfilled. It allows the take-up and accumulation of moisture during periods with high exposure and the removal of moisture during other periods.
- *Dimensional stability against changes in relative humidity (RH)*—is an important property, especially for board materials, but is not considered a problem with current materials in the form of membranes.

INVESTIGATIONS

Based on the findings of the analysis, it was decided to perform various studies, namely a computer simulation of the moisture conditions in unventilated roofs, exposure to indoor and outdoor climates in a full-scale test house, a number of laboratory tests, and a number of in situ tests. The investigations dealt with the new type of materials, as well as the changed requirements for the entire roof construction to which this might lead.

Computer simulation of moisture transfer

The planning of the full-scale tests was supported by computer simulation of moisture transfer in a roof construction by means of the computer simulation program MATCH.[2] MATCH is a one-dimensional model for combined heat and moisture transfer in composite constructions. The model makes it possible to simulate the temperature and moisture conditions on an hourly basis in the individual layers of the construction. The model is based on knowledge of the material properties of the individual layers and on knowledge of the boundary conditions to which the construction is subjected. It takes vapor, as well as liquid, transfer into account (but not precipitation). Figure 3 shows an example of the moisture content as calculated with the MATCH program.

As expected, the simulations showed that if materials with low water-vapor resistance are used (i.e., with Z-values around [1 GPa s m^2/kg*]) on the inside of a roof construction, moisture will accumulate in the roof. On the other hand, if a perfect vapor retarder is used, problems will never occur; a membrane with a high Z-value and good airtightness to airflow by convection is considered to be a perfect vapor retarder. For practical purposes, a vapor retarder installed in a building might be expected to have a Z-value of approximately 30 GPa s m^2/kg ($5 \cdot 10^4$ $perm^{-1}$). On the safe side, a Z-value of 8 GPa s m^2/kg ($1.4 \cdot 10^4$ $perm^{-1}$) was chosen for the calculations. With this assumption, the simulation showed that depending on the properties of the roof tile underlay used, condensation might occur occasionally.

Full-scale test house

To investigate the behavior of unventilated roofs, a new roof construction was made on the test house at the Danish Building Research Institute (SBI). The roof has a slope of 40 degrees and consists of 11 pairs of elements, each pair with one element oriented toward the north and one element toward south. Figure 2 shows the mounting of test elements in the test house.

Each element is 1 m (3.3 ft) wide and has a height of 240 mm (9.5 in). Ten pairs are unventilated, and the last one, which acts as a reference, is ventilated. The roof tile underlays tested are different commercially available types comprising surface-treated plywood, gypsum board, wood fiberboard, and different types of membranes made from

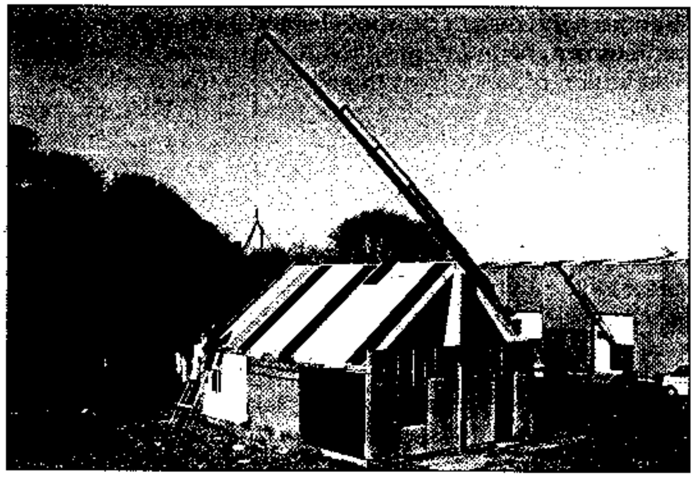

Figure 2. Mounting of roof elements in the test house.

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* The Z-value of a sheet material is defined as the ratio between its thickness, d (m), and its water-vapor permeance (kg/s m GPa). Low values indicate permeable materials.

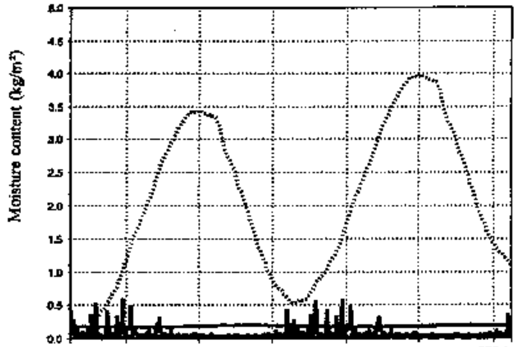

Figure 3. Moisture content of roof elements as calculated with the MATCH program. For the purpose of this investigation, the interesting thing is the dotted line showing the variation of the moisture content over the year.

micro-perforated plastics, nonwoven fibers, etc. The elements have two timber members as sides and a gypsum board as the interior cladding. There is no vapor retarder, but the gypsum board is painted to achieve a desired watervapor permeability. The elements are totally filled with mineral wool (240 mm) as thermal insulation. On the outside, the roof tile underlay is placed directly on top of the insulation material. The roof tile underlay is nailed to the top of the timber members, and a counter batten of 22 mm (0.87 in) is attached over it. The counter batten is used to ensure that water penetrating the roof tile to the underlay can be drained away, and at the same time, it secures the attachment of the roof tile underlay as the underlay is squeezed between the counter batten and the timber members. The roof is finished with traditional battens and roof tiles.

The climate in the test house was controlled in winter to 23°C (73°F) and 60 percent RH, which is a rather high humidity level in a dwelling.

Measurements in the test house

The test house is equipped with a range of sensors for temperature and humidity measurement. The moisture content at the bottom and the top of the timber members and in counter battens is monitored by measuring the electrical resistance between two electrodes (nails) placed in beech dowels embedded in the timber members and the counter batten. This method for measuring the moisture content is described in Nordtest NT Build 420.[5] A total of 136 sensors of this type are installed; 60 are datalogged every six hours.

Temperatures are measured using thermistor sensors. A total of 28 thermistors are installed. The thermistors are used for the temperature compensation of electrical resistance of the moisture-content sensors.

Furthermore, a number of the elements are supplied with humidity sensors glued to the underside of the underlay. These Wetcorr-type sensors are developed to measure the time of wetness (TOW),[4] and they are used here to determine whether condensation occurs on the underside of the underlay. A total of 16 TOW sensors are installed. Each sensor consists of an impedance grid of gold and is also equipped with a thermistor. The sensors are datalogged every 10 minutes.

In two pairs of elements, tipping bucket rain gauges are mounted for monitoring the amount of water running on the roof tile underlay. Similarly, for two pairs of elements, the surface temperature on the underside of the tiles is measured with thermocouples.

Supplementary to the measurements in the roof elements, the air temperature inside and outside the house, the relative humidity inside and outside, precipitation, the number of hours with sunshine, and the solar radiation are datalogged every hour.

Laboratory tests

Laboratory tests are carried out for the most important of the performance properties related to moisture transfer, that is:

- water vapor permeability
- tightness against precipitation
- tent effect

The water vapor permeability was tested according to ASTM E 96 wet-cup (i.e., with 100 percent RH in the cup and 50 percent outside [wet-cup test]). Some 25 materials were tested, including the old types, as well as the new types, of underlay materials. The new types of materials that are currently available on a commercial basis all had Z-values below 3 GPa s m²/kg ($5 \cdot 10^{-5}$ perm^{-1}), whereas the old type had Z-values ranging from 30 to 500 GPa s m²/kg ($5 \cdot 10^{-4}$ perm^{-1} to $9 \cdot 10^{-3}$ perm^{-1}).

The tightness against precipitation was tested at the wind tunnel of the private company Velux (a major European roof light producer). Two different investigations were carried out.

The first one was primarily intended to judge the differences in the amounts of water penetrating various roof coverings (tiles and slates) and various underlays. The tests were made on a test roof of 2.6 m by 3.6 m. The tests on underlays were made with the slopes of 25 degrees and 45 degrees and wind directions of 0 degrees and 22 degrees (0 degrees is wind perpendicular to the roof). For roof coverings, slopes of 25 degrees, 35 degrees, and 45 degrees and wind directions of 0 degrees, 22 degrees, and 45 degrees were used.

For this first test round, a test simulating driving rain was used. The water is equivalent to a precipitation of 120 mm/h m² (4.7 in/h), and the wind is a dynamic wind profile with wind gusts up to 20 m/s (66 ft/s) and 30 m/s (798 ft/s) for underlays and roof coverings, respectively.

The results for roof tile underlays showed that considerably more water penetrates past underlay in the form of a membrane when it is mounted perpendicular to (horizontal mounting), instead of parallel to (vertical mounting), the rafters. For the board materials tested, water penetrated the joints irrespective of whether these were made by the boards overlapping each other or with special profiles for connecting the boards.

The results for roof coverings showed that no water penetrated some of them whereas considerable amounts penetrated others. The amount of water penetrating the roof covering depends on the slope and the wind direction, but the dependence varies from roof covering to roof covering.

In the second test round, a membrane underlay was mounted perpendicular to the rafters and was tested together with the roof covering, which when tested alone, gave the highest amount of water penetrating. The result was that no water penetrated past the roof tile underlay when the roof covering was present. The problem with water penetration of the roof tile underlay is, therefore, considered to be a problem mainly during the construction period.

In the second test round, a standard test to assess the watertightness of the underlay also was carried out. The test method was Nordtest Build 118.[5] The test is made on a test specimen of 0.77 by 1.3 m (2.53 by 4.27 ft) (≈1 m^2). The test was for all materials and used three different slopes, namely 15 degrees, 30 degrees, and 45 degrees. The test comprises 35 mm/h m^2 (1.4 in/h) rain and a wind velocity of 12 to 14 m/s (39 to 46 ft/s). All products were classified watertight.

For the testing of tent effect, no existing methods were found to be suitable. Instead, a proposal for a new test method was developed. The test method uses a specimen composed of a flat aluminum tray to collect water that might penetrate the roof tile underlay during the test. A batt of mineral wool is placed in the lower end of the tray, and a piece of ply wood is placed in the upper end. Both materials are slightly higher than the aluminum tray. The underlay is mounted on a wooden frame that fits around the aluminum tray. After mounting the underlay, the frame is placed around the tray, so that the underlay is supported by the mineral wool and the plywood. The underlay is held in place by the dead weight of the frame and the underlay; this simulates the conditions in a real roof. Water was sprayed from a nozzle over the entire surface of the specimen for six hours. In the first tests, water was supplied to the top of the specimen and allowed to run freely over the underlay. However, on the virgin products, the water followed the same paths all the time and did not cover the entire surface. Therefore, it was decided to use nozzles instead. Low water pressure was used to simulate fine rain.

Some of the materials tested using this method showed considerable penetration of water during the test, which is unsatisfactory because water will come into contact with the roof tile underlay in most roofs and, therefore, presents a potential risk for water penetration.

The results from the laboratory tests on the actual materials and the information about the climactic conditions in the exposure period shall be used for new calculations to verify the simulation model and to improve the material database used for the simulations.

Figure 4. Testing of tent effect in the laboratory.

In situ investigations

As a supplement to the tests in the test house and in the laboratory, a small number of in situ investigations were made in the winter of 1995-96. The experience gained at these investigations revealed that some of the roof tile underlays suffered from water leakage probably because of tent effect. Besides, in a few cases, it was reported that ice had formed on the underside of the underlay in periods with strong frost. Visual inspections in a number of identical houses showed that the problem was especially pronounced where the vapor retarder had been perforated. Visual inspections in the test house showed that ice had formed on the underside of one of the two underlays, which could be inspected visually. This stresses the importance of an airtight construction. It is especially important to avoid convection, which might transport more water vapor up into the roof construction than can be removed by diffusion through the roof tile underlay.

Finally, it was found that there was a considerable amount of problems associated with the detailing and the workmanship of the underlays. For example, it was found that if the roof tile underlay had not been mounted sufficiently tight, it might flap, thereby creating considerable noise and eventually puncture of the material where it touched the tile clips.

RESULTS OF THE EXPOSURE IN THE TEST HOUSE

As expected, the humidity level in the roof construction showed a variation over the year with a rather high level in winter and drying out to a low level during the summer (Figures 5 and 6 show results from the south- and north-facing sides, respectively). As expected, the moisture content on the north side was somewhat higher than on the south side, where the drying capacity due to the influence of the sun was greater. Even though the moisture content in winter was high, it was not assessed to be alarming considering the use conditions with 23°C (73.4°F) and 60 percent RH in the test house, which is a considerably high humidity level; the normal relative humidity in winter often will go below 30 percent in periods of cold weather. Besides, it should be remembered that the roof construction has no vapor retarder but only a surface treatment providing a water vapor diffusion

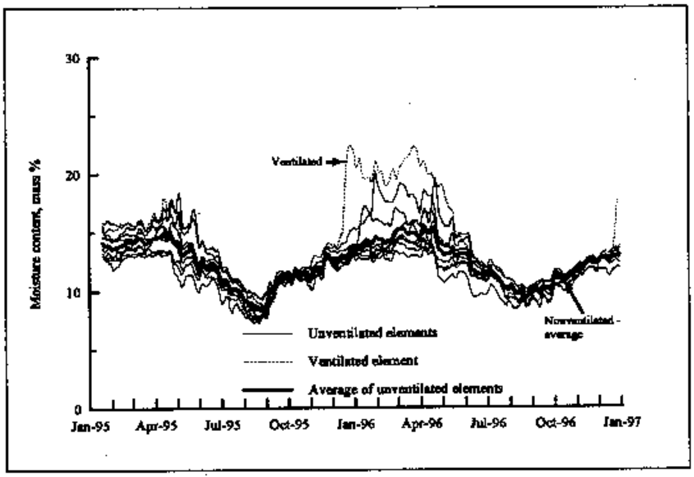

Figure 5. Moisture content in the upper part of timber members in south-facing elements in the test house as function of time. The dotted line marked with an arrow is for the ventilated element whereas the bold, full line marked with an arrow is an average of all unventilated elements. The individual results are shown with thin lines.

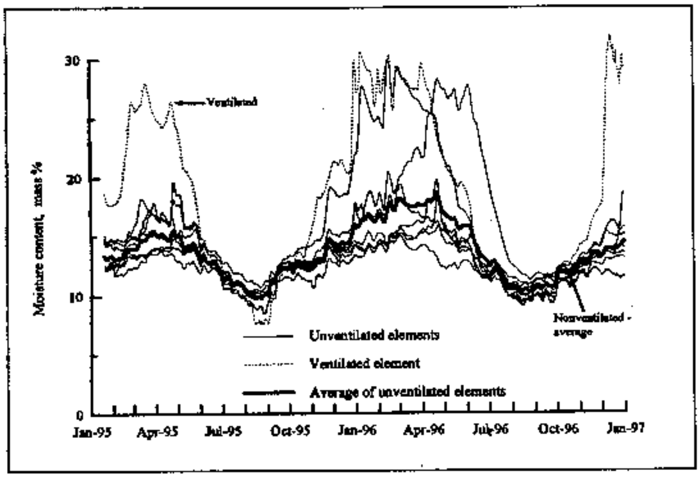

Figure 6. *Moisture content in the upper part of timber members in north-facing elements in the test house as function of time. The dotted line marked with an arrow is for the ventilated element whereas the bold, full line marked with an arrow is an average of all unventilated elements. The individual results are shown with thin lines.*

coefficient of approximately 17 GPa s m^2/kg ($3 \cdot 10^{-4}$ $perm^{-1}$) in contrast to at least 25 to 30 GPa s m^2/kg ($4.4 \cdot 10^{-4}$ to $5.2 \cdot 10^{-4}$ $perm^{-1}$) provided by a normal vapor retarder. Finally, it should be mentioned that the last winter of exposure was very cold and had a lot of drifting snow (compared to normal Danish conditions).

Only the reference roof was found to be very wet, which is explained by unsatisfactory ventilation. There is no connection from eave to eave, and consequently, there are very restricted possibilities for the wind to pass through the construction.

The water running on the surface of the underlay was found to be 3 to 5 l/m^2 (9 to 16 fluid ounces/ft^2) per year. About half of the water came from drifting snow.

DISCUSSION AND CONCLUSION

The investigations showed that for roof tile underlays without a proper ventilation cavity underneath, certain performance requirements have to be fulfilled in order to function in a temperate climate, as in Denmark.

- *The underlay shall be tight against precipitation, including driving rain*—The underlay shall pass a test according to Nordtest Build 118 without water penetration.
- *The underlay must have no tent effect*—No water is allowed to pass the underlay when tested according to the method described in Chapter 3.3. The test method is still under development, and a final requirement has not yet been stated. The Danish Building Research Institute has received a grant from Nordtest to develop the method to become a Nordtest Method. This will include some sort of (accelerated) aging of the surface prior to testing in order to simulate the effect from sun, wind and rain during the construction period.
- *The inside of the roof construction is sufficiently tight to diffusion, as well as against convection*—The tightness shall be seen in relation to the permeability of the underlay. The Z-value of the materials on the warm side of the insulation should at least be greater than 30 GPa s m^2/kg ($5.2 \cdot 10^{-4}$ $perm^{-1}$). Normally, this is achieved by using a vapor retarder that, well-mounted with sealed overlapping joints and no perforations, will fulfill the requirements not only for permeability but also for airtightness, thereby securing the roof construction against diffusion, as well as convection.
- *The water vapor permeability of the underlay shall be low*—The Z-value shall be very low to ensure that no water vapor is accumulated in the roof construction. As a rule of thumb, the outer vapor barrier (the roof tile underlay) shall be 10 times more permeable than the inner barrier (the vapor retarder). The calculations also confirm that a low resistance to water vapor is necessary. Based on this, a requirement for the Z-value to be less than 3 GPa s m^2/kg ($5 \cdot 10^{-5}$ $perm^{-1}$) was stated. In the full-scale tests, all of the products had Z-values below the required Z-value.

The in situ investigations showed that in addition to the performance requirements of the underlay, detailing and workmanship are crucial to the overall performance of the roof construction. The details of the underlay, the roof covering, etc., shall meet the same performance requirements as the materials themselves and, in principle, they should be tested using the same methods. In the project, a number of common details are currently being improved based on experience from use and may be issued in a sort of "details catalogue." At the same time, informational material dealing with installation techniques, quality assurance, etc., will be made available.

Experience also shows that with some of the roof tiles and details currently used, sunlight might reach the roof tile underlay, stressing the importance of resistance to UV-light.

If the above-mentioned performance requirements are fulfilled and the design and workmanship are up to standard, unventilated roof tile underlays are assessed to be able to function properly.

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