Evaluation of the thermohygrometric behavior of wooden roofing systems with under tile membranes to ensure durability

C. Bertolini Cestari¹, C. Lombardi² and P. Oliaro²
(1) Department of Progettazione Architettonica, Turin Polytechnic, Italy
(2) Department of Energetica, Turin Polytechnic, Italy

ABSTRACT
For several years innovative membranes that combine moisture barrier capability with relatively high vapor permeability have been available. However, data are lacking that quantify their performance for specific roofing systems and, in particular, those used for historic building in Italy.

Therefore in the present study we have characterized the vapor transmission performance of several of these high permeability membranes and compared them with more traditional low permeability ones. The characterization was both experimental and numeric: timber roof and concrete roof test samples with different moisture barrier membranes were first submitted to steady climatic conditions on opposite sides in order to get severe conditions for moisture migration through the samples. The increase in moisture content of the samples over a period of four months was then used to calibrate a simulation model with the thermohygrometric parameters of the different test sample materials such that good agreement was obtained between the experimental and the calculated results. The simulation model was next used to estimate the behavior of the wood roof samples with the different membranes when exposed to one year climatic conditions of three Italian cities.

The results show that for all the test samples moisture accumulation developed in the cold season and was eliminated in warm season, but in the case of a cold - humid climate (Venice), important differences - for health problems and materials durability - appeared in the moisture accumulation within the test samples with innovative high permeability or traditional membranes.

RÉSUMÉ
Des membranes innovantes unissant les fonctions d'imperméabilisant et de couches ayant une bonne perméabilité à la vapeur sont disponibles depuis plusieurs années. Toutefois on ne dispose encore d'aucune donnée pour évaluer leur performance avec des systèmes spécifiques de toiture, et en particulier pour ceux utilisés dans les bâtiments historiques italiens.

La présente étude analyse donc les prestations de transmission de vapeur d'eau de ces membranes de haute perméabilité. Ces prestations sont comparées à celles de membranes plus traditionnelles à basse perméabilité. L'analyse des prestations a été à la fois expérimentale et numérique : des échantillons de toiture en bois et en béton armé ont été soumis à des conditions climatiques constantes, différentes des deux côtés afin d'obtenir des conditions particulièrement sévères de migration de la vapeur d'eau à travers les échantillons. L'augmentation de la teneur en eau des échantillons mesurée sur une période de quatre mois a été utilisée pour le calibrage d'un modèle de simulation avec des paramètres thermohygrométriques, pour les différentes couches, simulant les résultats expérimentaux et calculés. Le modèle de simulation a ensuite été utilisé pour la prédiction du comportement des échantillons de toiture en bois avec différentes membranes soumis pendant un an à des conditions climatiques typiques pour trois villes italiennes.

Les résultats montrent que pour tous les échantillons l'accumulation d'eau, qui se vérifie pendant la saison froide, est éliminé pendant la saison chaude. Néanmoins, en cas de climat froid et humide (Venise), des différences importantes – relatives aux problèmes de prévention et de durabilité des matériaux – apparaissent dans l'accumulation d'humidité entre les échantillons avec nouvelles membranes de haute perméabilité ou traditionnelles.
1. INTRODUCTION

The current repertoire of new technology related to the retrofit of warm roofs rather than cold roofs has brought on improvisation in construction methods, which are not always compatible with the building and have caused radical changes in the urban image. In addition, current working practice in Italy does not foresee a conservation or maintenance plan for roof systems.

The roof is thus often replaced with materials that are different from the original ones both in the structure and in its completion and covering.

Both in renovation and new structures, the building sector often foresees the use of new materials that are watertight, thermal and acoustic insulators, etc. In the long run they have often proved inefficient and sometimes damaging especially when used in the waterproofing of wooden structures.

The introduction of watertight membranes (water and unfortunately vapor tight) applies to these cases in non-ventilated insulated roofs where the thermohygroscopic equilibrium of the roof system is altered and the durability of the wooden structures is put at risk.

In repairs to restore functionality and in renovating attic spaces there is a need for thermal insulation and for the watertightness of the roof. If a moisture barrier layer is placed on the outside of the thermal insulation, or just under the roof covering, it then carries on the function of protecting the insulation from water and other environment agents. On the other hand, such placement means risking condensation and, in severe climates, the formation of ice within the insulation layer when the waterproof membrane has an elevated resistance to vapor flow from inside [1]. Unfortunately most traditional waterproofing layers behave this way; in the 1980s proposals were made to create two air spaces ventilated above and below the waterproof membrane to help drain off condensation and the entrance of water from the roof covering. However in several cases, even this solution made the situation worse [2].

Introducing a new moisture barrier membrane that combines watertightness with an elevated vapor permeability theoretically minimizes the problem of condensation and formation of ice.

In the present study, which was conducted simulating severe winter conditions, we performed experimentation to examine the different performance that traditional low permeability and innovative permeable membranes have on the test sample of a typical old Italian wooden roof (remade with the addition of insulation materials) and on a reinforced concrete roof of a new building.

Thus our study was divided in the following phases:

- study of the performance of new membranes in the presence of rain water on the exterior surface of the test samples.

2. TEST SAMPLES

With the aim to test the thermohygroscopic behavior of roofing systems made from wood or reinforced concrete, full scale test samples in terms of materials, composition and thickness were prepared. The samples were then inserted between two environments representing an inside climate with \( t = 20 \degree C \) and RH = 50 % and an outside climate with \( t = -10 \degree C \) and RH \( \approx 70 \% \).

2.1 Wooden test samples

Eight pitched roof test samples were made of wood. Each had an identical construction except for the moisture barrier membrane used as the roof covering. The 4 functional layers of each sample (dimensions 58 x 69.5 cm) are in order:

- planking (4 cm thick) in larch (Larix europaea Mill.)
- thermal insulating material: 5 layers of wood fiber board (each layer 1.9 cm thick, density 280 kg/m³)
- moisture barrier membrane.

The wood for the test samples came from the demolition of a roof taken from a building of the 1600s; the single pieces of this material were weighed and assembled with metal nails taking care to make test pieces equal in mass per unit area. The 5 layers of wood fiber board were anchored together and to the planking with staggered self threading screws to avoid creating thermal bridges. The moisture barrier membranes have the characteristics given in Table 1. In the table the initial A refers to the new generation of vapor permeable membranes fabricated of flash spun polyethylene, the initial B refers to the traditional low permeability membranes like a bituminous sheath (B3), a sheet of reinforced polyethylene (B1) and two other micro-perforated membranes available on the Italian market; the vapor diffusion thickness \([6] \) \( S_d \) is the one published by the membrane manufacturer. \( S_d = \mu \cdot d \) (vapor

<table>
<thead>
<tr>
<th>Table 1 – Mass per unit area, thickness and vapor diffusion thickness ( S_d ) for the 8 test membranes</th>
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<tbody>
<tr>
<td>MEMBRANE INITIALS</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>A1</td>
</tr>
<tr>
<td>A2</td>
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<tr>
<td>A3</td>
</tr>
<tr>
<td>A4</td>
</tr>
<tr>
<td>B1</td>
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<td>B2</td>
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<td>B3</td>
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<td>B4</td>
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\( S_d \) has the dimension of a length and represents the thickness of an air layer having the same vapor resistance as the membrane. In reference [6] \( S_d \) is called “vapor diffusion thickness” without a special symbol, but in the technical notes of the manufacturers is often reported as \( S_d \).
resistance factor $\mu$ multiplied by the thickness $d$ of the membrane).

An expanded view of the test sample is found in Fig. 1.

![Expanded view of the wooden test sample](image)

Fig. 1 – Expanded view of the wooden test sample.

2.2 Concrete test samples

For comparison, 8 test samples of pitched roofs built of ordinary concrete were prepared. The dimensions were 58 x 70 cm. These samples consisted of the following layers:
- a 1 cm plaster layer;
- a 8 cm thick concrete layer with interior metal reinforcing electro-welded mesh (10 x 10 cm, diameter of the wire 5 mm);
- an expanded polystyrene layer having a density of 25 kg/m² and a thickness of 5 cm;
- the moisture barrier membrane;

The membranes used are the same as described in Table 1.

3. EXPERIMENTAL APPARATUS AND TEST METHODOLOGY

The test samples were inserted and sealed in metal drawers built specifically to be slid into a vertical metal frame; once mounted the drawers make up a wall that separates the two rooms at different temperature and humidity; the temperatures and humidity values are intentionally chosen to provide an extreme example of Italian winter environmental conditions. The seals were done with polyurethane foam expanded “in situ”; for the wooden and concrete test samples, the wooden and plaster layer, respectively, were oriented towards the warm environment (+20 °C, 50 % RH) and the membranes towards the cold environment (-10 °C, ~70 % RH). With appropriate thermal cuts in the frame and on the steel drawers, care was taken to avoid thermal bridges. To prevent the air convection through the wood fiber insulation, two light coats of varnish were put on the side exposed at +20 °C. The scheme of the installation and a view of the “wall” are found in Figs. 2a and 2b.

![Installation scheme and front view](image)

Fig. 2a - The installation scheme for reaching the desired temperature and humidity: 1- Cooling unit, 2- Circulation pump, 3- Inertial Tank, 4- Three way valve, 5- Process pump, 6- Battery temperature control gauge, 7- Electric command and control panel, 8- PC, 9- Resistance humidifier, 10- Vapor distributor, 11- Temperature control gauge in test chamber, 12- RH test chamber control gauge, 13- Post heating resistance, 14- Ventilated battery, 15- Inertial battery, 16- Mixed bed demineralization system, 17- On-off valve, 18- Damper separator, 19- Outdoor equipment trolley, 20- Framework section.

Fig. 2b - Front view (warm side) of the “wall” dividing the two rooms; wooden test samples.

2b. Inside the room maintained at 20 °C a weighing balance with a maximum capacity of 150 kg and a 1 g resolution was placed. The drawers were weighed with this balance.

The tests on wooden test samples lasted approximately 4 months: the weighing of the 8 drawers occurred every 2 days for the first 2 weeks and successively at a rate of 3 measurements every 10 days. After 3025 hours the surfaces exposed at -10 °C were sprayed with drops of water with different surface density; the formation of ice on the surface and its successive evolution was documented photographically. This test was done to determine whether the presence of rain water on the outer surface of the membrane could affect the rate of the test sample mass increase.

The tests on the reinforced concrete test samples lasted approximately 2 months.

4. EXPERIMENTAL RESULTS

The results of the first tests are reported in Figs. 3 to 6.
In Fig. 3, for each test sample the percentage of increase in mass over time is reported. Two groups of results are readily distinguished:

- one group, that gives the test results for the type B membranes, shows a linear increase after the first 240 hours. The values at 3025 hours show mass increase between 15.5% and 20%. In these test samples, over time, with the naked eye and by touch one could detect the progressive formation of ice between the moisture barrier membrane and the low temperature surface of the fiberboard insulation;
- a second group, that includes the tests with type A membranes, had an asymptotic trend and after 3025 hours had reached a nearly constant value that was between 2% and 5% greater than the mass of the original specimen.

It can be seen that the trend of the percentage increase in mass is steeper when the vapor diffusion thickness of the membranes is greater. This 5d index is significant in predicting the performance of these roof systems to moisture migration.

In Fig. 4 the mass increase is reported in a time interval around the spray wetting of the samples, for wooden test samples having type A membranes.

In Fig. 4 the peak that appears in the curves represents the increase in mass at the moment of spray wetting. The peak disappeared in the next weighing (after 24 hours): the drops of water on the surface became ice rapidly but tended to sublime as shown in Figs. 5 and 6.

The overall trend of variation in mass over time did not change with further increase in time. Only in the case of wetting at a surface density of 160 g/m² was a small quantity of water retained permanently in the panel.

The results for the concrete test samples are quite different from those previously discussed for the wooden test samples. In the case of the concrete, the samples are still losing mass even though they were kept in the laboratory at approximately 20 °C with a relative humidity of 35% for about 4.5 months after the casting.

The 5d of the 5 cm polystyrene (density 25 kg/m³) is approximately 2.5 m (from literature) and there is no difference in sample mass loss between the various membranes since the 5d of the polystyrene dominates and water is probably transferred to the warm room. The results of the second series of test performed using the concrete test samples are reported in Fig. 7.

5. SIMULATIONS

5.1 Model used for the simulation of the wooden test samples

After the tests, a calculation was made to verify the utility of using new generation membranes in retrofitting wooden roofs for the hypothetical use of the attics as dwellings in the various climatic conditions found in the Italian peninsula.

In past years the international scientific community has come out with many simulation models of thermohygrometric behavior of construction elements [3]. Since the physical phenomena involved in a wall behavior are multiple and are often coupled together [4], these models, in order to better represent the total phenomenon for certain layers of material, for specific geometry and climates, take into account some transfer phenomena while
5.2 Optimizing the properties of the materials

The model can evaluate the effects of the aforementioned phenomena only if the values of all the thermohygrometric properties of each material, as well as the coefficients for calculating the variation of those values with temperature and humidity are available.

In the laboratory the thermal conductivity and the mass per square meter of the dry wood fiber insulation board were measured, whereas for the other properties, those of similar materials were used as reported in “Material Properties” published by the International Energy Agency at the end of Annex 24.

An analysis of the sensitivity of the program to different parameters and a comparison between the mass increase measured and simulated, allowed us to perfect, as much as possible, the thermohygrometric properties used.

Table 2 gives a comparison between the measured increase in mass of the samples after 3025 hours and the calculated value.

In Fig. 8 the calculated trends are reported.

Qualitatively the measured rate of the mass increment of the samples is fairly close to the calculated one. Specifically, we can see that the samples with a type A membrane had an asymptotic increment in mass both when measured and in the calculations, while the samples with a type B membrane had in both cases a constant increment in mass over time.

On a quantitative level some differences are shown between the measurements and the calculations. For the samples with a type A membrane, the differences were limited in 2 cases (A1, A3) and more important in the other 2 (A2, A4); the tendency was to overestimate the calculated increase in the sample’s mass. This might have been due to the uncertainty of the calculated increase.

For samples with type B membranes there was a tendency to underestimate the calculated increase in mass. The finding is considered to be linked to the hygrometric properties of the wood fiber insulation board. The selected values of the properties related to the vapor diffusion in this material were those published for similar materials in the literature. The parameter values for water (liquid) diffusion were also adopted from the literature. Using the literature values, in the case of high relative humidity, we foresaw a reduced level of water diffusion with resulting underestimation of the water held by the samples. We preferred to assume altogether the properties of one material and did not seek to modify them in a drastic way to make the calculated masses come closer to those of the experimental tests. The reasoning was that, on one hand, we

<table>
<thead>
<tr>
<th>Test sample with</th>
<th>ΔM measured [kg/m²]</th>
<th>ΔM calculated [kg/m²]</th>
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<tbody>
<tr>
<td>A1</td>
<td>1.367</td>
<td>1.63</td>
</tr>
<tr>
<td>A2</td>
<td>1.958</td>
<td>1.72</td>
</tr>
<tr>
<td>A3</td>
<td>1.165</td>
<td>1.72</td>
</tr>
<tr>
<td>A4</td>
<td>0.852</td>
<td>1.52</td>
</tr>
<tr>
<td>B1 (Polyethylene)</td>
<td>7.581</td>
<td>5.43</td>
</tr>
<tr>
<td>B2</td>
<td>7.610</td>
<td>5.30</td>
</tr>
<tr>
<td>B3 (bituminous sheath)</td>
<td>6.089</td>
<td>5.10</td>
</tr>
<tr>
<td>B4</td>
<td>6.414</td>
<td>3.97</td>
</tr>
</tbody>
</table>
would obtain a “fictitious” material and, on the other hand, we found a great uncertainty in the properties determined without the support of specific experimental tests. Also a certain number of coefficients are not even available in the literature. Assuming the thermohygrometric properties of a material such as a wood fiber insulation without substantial modifications generated discrepancies between laboratory and calculated mass changes. However we believe that the calculated results over a long period are more reliable if actual measured properties are assumed.

5.3 Evaluation of behavior over a long period of structures equipped with different membranes and undergoing three types of Italian climate

For the climatic conditions in Venice or, in other words, for cold and humid climates, a major difference in behavior is shown between the sample with the innovative membrane (A1) and the one with the traditional (polyethylene) membrane (B1). For both there is an accumulation of moisture in winter and a complete loss in summer. However, for the test sample with polyethylene film, the maximum mass accumulation is much more important and in particular the accumulated moisture remains in place for a longer period of time.

Looking at the health and durability risks, the following remarks can be stated for wooden materials:

- in estimating risk, we reference the indexes u [%] (u = mass of moisture per unit mass of the dry material) or RH [%];
- we distinguish between mould growth and rotting risk, the first one affecting health and the second affecting durability;
- for mould growth, no risk occurs for u < 15% or RH < 70% and serious risk occurs for u > 20% or RH > 85% [7];
- for rotting, no risk occurs for u < 16% or RH < 75% and serious risk occurs for u > 25% or RH > 95% [7].

For the two test samples (A1+B1) mould growth and rotting risks were evaluated for each wood fiber board layer.

Regarding to the mould growth for the Venice climate (referring to u values), no significant risk occurred in the test sample with the innovative membrane (A1), whereas significant risk occurred for 56 days in the outer wood fiber board layer of the B1 test sample. Furthermore a medium risk appeared for 23 days only in the outer wood fiber board layer of the A1 test sample. On the other hand, at least a medium risk of mould growth was expected for 92 days for the outer layer in the B1 test sample.

Similar trends in mould growth risk are estimated using the RH index, but the risk periods are longer.

As far as the potential for rotting in the Venice climate is concerned, no significant risk occurred for either test sample (A1+B1) when estimated using either indexes. Medium risk occurred for 56 days in the B1 test sample and no risk occurred in the A1 test sample. Same indications were obtained using RH.

For the climatic conditions in Rome, one can still detect a different behavior between the two test samples (A1+B1) even if the maximum moisture content is quite similar. However, for both types of membranes, the moisture contents remain below levels at which health (i.e. mould growth) or durability (i.e. rotting risks) would be expected to be encountered.

Last, in the case of Trapani, practically no difference can be seen as the climatic conditions ensure the absence of notable moisture accumulation even in winter. The high Trapani external temperature prevents condensation and the high external vapor pressure results in weak driving forces for the moisture migration through the sample.
6. CONCLUSIONS

Eight roof test samples used in historic building renovations and eight used in new constructions were prepared; each had a moisture barrier membrane. Four membranes were of the innovative type with high permeability to vapor, whereas the other four were traditional with less permeability to vapor.

Laboratory tests were carried out inserting the test samples between two environments at different thermohygrometric conditions (t = 20°C, RH = 50% on one side, t = -10°C, RH = 70% on the other side) so that to realize severe protracted (4 months) climatic conditions for moisture migration through the test samples.

From laboratory tests it was found that test samples with the innovative membranes had accumulated moisture (condensation and frost) having an asymptotic trend with a ceiling limit. The other four membranes caused accumulation of moisture with linear increase over time and without ceiling.

In addition the experimentation with the wetting of the surface insured against an eventual change in behavior in presence - as often actually happens - of rain droplets infiltrating between the membrane and the covering. In fact, the trend in mass increase amongst the test samples in the case of innovative membranes remained unchanged over time, as discussed in paragraph 4.

The same trends in mass change were extracted numerically: this demonstrates the ability to predict at least qualitatively the performance of the membranes using a model. For several test samples a good agreement was quantitatively reached between experimental and numerical results, whereas with other test samples this was less satisfactory. The importance of having well characterized hygrometric properties of the materials was discussed: unfortunately the data base for material properties used in the present study and available in the literature is quite limited. Experiments to measure such properties are beyond the scope of this study.

Finally, simulations for one year period were run to evaluate the behavior of the test samples with different membranes under varying moisture drive conditions. The calculations were made for three representative Italian climatic conditions (Venice, Rome, Trapani). For all the test samples moisture accumulation developed in the cold season and was eliminated in warm season, but in the case of a cold - humid climate (Venice), important differences appeared in the moisture accumulation within the test samples, as shown in Fig. 9. This generated important differences on the mould growth and rotting risks. The benefit of the innovative membranes tended to be limited in intermediate climates (Rome) and were practically absent in hot climates (Trapani) (Figs. 10 and 11).

The tests run on reinforced concrete did not discriminate between the vapor resistance properties of the two types of membranes. This is due to the intrinsic properties of the concrete, which itself lost water for more than the 28 days of setting time after casting. Also, the presence of a layer of thermal insulation between the concrete and the membrane such as the polystyrene provided a significant resistance to vapor flow.

In conclusion the new generation vapor permeable membranes can contribute to an increase in the performance of the wooden roof system and of its components particularly in cold humid climates. In such climates, moisture accumulation in the roof system is reduced due to the innovative membrane with an accompanying reduction in the risk of mould growth and rotting of wood.

ACKNOWLEDGEMENT

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