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SOLAR-DRIVEN MOISTURE TRANSFER THROUGH ABSORBENT ROOFING MATERIALS

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ABSTRACT

A laboratory investigation into solar-driven moisture transfer through absorbent roofing materials is described. It is believed that this mechanism has not previously been investigated systematically. This work arises as a response to moisture problems which have been observed in New Zealand with "skillion" or "cathedral" roofs clad with cellulose-fiber-reinforced cement shingles. The moisture penetration is known not to be due to leaks; thus it was speculated that the moisture transfer through the roofing was caused by solar heating of the rain-wetted cladding material. A laboratory test rig, built to simulate the effects of rain followed by sun on different types of absorbent roofing materials, is described. The rig allows capture and measurement of any moisture that is driven through the cladding into the closed roof cavity below. Results with various absorbent claddings are presented, both alone and with various combinations of permeable and impermeable membranes placed under the cladding or interleaved between shingle layers. Cellulose-fiber-reinforced cement shingles transmitted considerable amounts of moisture under solar heat. Of the other absorbent roof claddings, wooden shingles transmitted the most solar-driven moisture. Permeable building paper placed under the cement shingles did not greatly impede the transfer of moisture, but an impermeable membrane interleaved between the shingles, as has become standard practice, reduced the solar-driven moisture transfer to nearly zero.*

* Roofs where the ceiling shares a common pitch with the roof, separated by a shallow cavity. Also called chapel roofs.

INTRODUCTION

This paper describes an investigation into the mechanism of solar-driven moisture transfer through absorbent roof materials. The significance and importance of this mechanism arose out of experience with the performance of certain New Zealand roofing materials. In New Zealand, most roof claddings are made of profiled sheet metal, usually galvanized steel or aluminum, profiled metal tiles, or concrete or clay tiles. Another type in use is cellulose-fiber-reinforced cement shingles or shakes. This latter material absorbs as much as 25% of its weight in water.

Recently, questions have been raised about the moisture performance of such absorbent roofing materials when applied to cathedral roofs. Instances have been reported of wetted ceiling insulation, wetted ceilings, and water dripping out of the eaves of the roofs. Inspections of these cases clearly indicate that the problems are not usually caused by water leaking through the roofs. Nor does the cause appear to be moisture from wet materials or rain trapped inside the relatively airtight roof cavity at the time of construction.

Thus, it has been hypothesized that moisture transfer through the roof occurs either because of capillary wicking of water through the absorbent roofing material itself or the material interfaces in the roofing system structure, or because moisture absorbed in the roofing material is driven through by solar heating of the exterior roof surface. In a somewhat analogous situation, solar heating of wood siding (wall cladding) has reportedly been one of the primary moisture transport mechanisms that has resulted in moisture problems in insulated walls (Lstiburek 1987). It appears that while solar heating of wetted siding evaporates some of the surface moisture into the exterior air, it also drives a significant portion of it through the back of the siding and into the wall. Raising the temperature of the outside surface of the siding relative to the interior portions of the wall creates a large vapor pressure difference that drives the moisture inward into the wall.

Handegord (1985) has also drawn attention to this mechanism in walls, and cites Wilson (1965), who describes the diffusion of moisture through masonry walls exposed to the sun as resulting in some condensation on the outside of the vapor barrier and elevated timber moisture contents in summer under certain conditions.

It should be noted that problems with moisture transfer under investigation here have been noted only in "cathedral"-type ceilings. These have relatively airtight roof cavities. No problems have been noted with absorbent roofing materials conventionally installed in hip-type roofs with an attic space. Apparently, any moisture that does transfer through the roof into an attic space has ample opportunity to disperse by natural ventilation.

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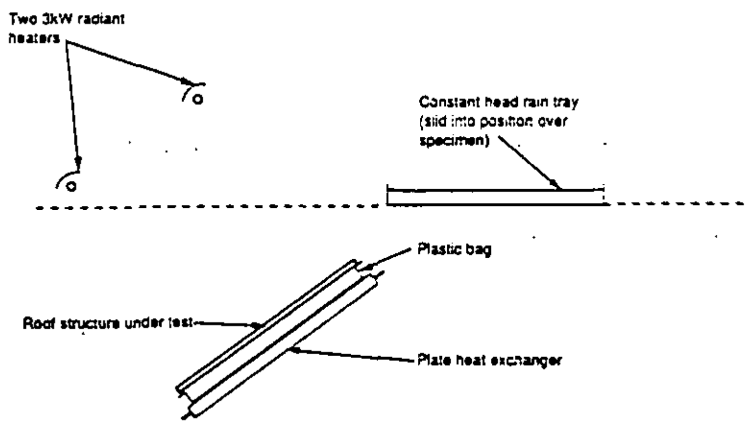

Figure 1 Schematic diagram of the test rig used

The issue is a serious one for those building owners affected and also is of considerable concern to the manufacturers, who need to know the best way to use their products. Thus, a building research association in New Zealand undertook an investigation to determine the cause of the moisture problems with "cathedral" roofs that utilize absorbent roofing materials. In order to understand the problem more generally and to be in a position to offer advice on the correct use of absorbent roof cladding materials, this investigation was carried out on various absorbent claddings, both alone and with various combinations of permeable and impermeable membranes placed under the cladding or interleaved between shingle layers.

EXPERIMENTAL DESIGN AND OBJECTIVES

The investigation was planned in three distinct phases.

Phase I: Demonstrate Existence of Solar-Driven Moisture Transfer

The objective of the first phase was to verify whether or not solar-driven moisture transfer through absorbent roofing materials did in fact occur. If so, then an additional aim of this phase was to determine suitable and appropriate conditions to be used in subsequent tests, including levels and durations of rain and solar radiation and the most appropriate roofing materials and configurations to be tested.

Phase II: Test Actual Roofing Systems

The objective of this phase was to determine the extent of moisture transfer in common roofing configurations. The approach taken was to first measure the solar-driven moisture transfer through the absorbent roofing material alone with standardized rain and sun conditions. Then, moisture transfer tests were repeated under the same conditions as additional roofing system components were added (e.g., building paper). This technique allowed the determination of the influence of each component on solar-driven moisture transfer through the roofing system. In addition, other more commonly used absorbent roofing materials (e.g., concrete tiles) were to be tested for comparison.

Phase III: Test Remedial Measures

The purpose of this phase of the investigation was to find ways of reducing or eliminating the solar-driven moisture transfer through the absorbent roofing materials. The main aim was to be able to isolate those design features that enable these types of roof claddings to perform well. Various design or application approaches were to be tested, including both old and new approaches specified by the manufacturer of the cellulose-fiber-reinforced cement shingles.

EXPERIMENTAL SETUP

General Experimental Approach

A laboratory test rig was designed and built that allowed the amount of moisture absorbed by the roofing materials, as well as the amount transferred through the materials into a "cathedral"-type roofing cavity, to be measured directly. Roofing materials were weighed before and after the rain to determine the amount of moisture absorption. Then the simulated solar heat was turned on, and the moisture transferred through the roofing materials was condensed on a heat exchanger simulating the room-temperature ceiling surface and collected in a specially arranged plastic bag. Finally, the moisture transferred through the roofing system was determined by removing the plastic bag and weighing it. The roofing materials also were reweighed to determine the overall weight loss due to solar-induced evaporation on the outer surface and moisture transfer out of the lower surface.

Laboratory Test Apparatus

A schematic of the test rig is shown in Figure 1. The rig included six main parts: the radiant heaters, the rain tray, the main rig support structure, the roofing assembly under test, the plastic bag that collected the moisture that transferred out of the bottom of the roofing deck, and a plate heat exchanger simulating the ceiling below the decking.

Solar radiation was simulated by two 3 kW electric radiant heaters placed about a meter (3.3 ft) above the specimen. The heaters were driven by variable transformers, and the heat flux at the surface of the roofing material was calibrated for various voltage settings using a precision net radiometer. The flux was found to be uniform to within 20% across the roof surface. A 10 a.m. level of solar flux on a horizontal surface for a summer day in New Zealand could be taken as 830 W/m^2 (see, for example, ASHRAE 1985). This corresponds to a normal flux on a 25° sloping surface of 750 W/m^2, which was the figure chosen to be used throughout the experiments described here. A reflective metal shield was put in place under the heaters to stop the solar heat input at a precise time.

Rain was provided from a constant head tray with holes in its bottom. The tray ran on rails and could readily be moved in and out of place over the roof assembly.

The entire rig was carried on a light space frame, including the radiant heaters, the rain tray, and a water-cooled plate heat exchanger. The surface of this heat exchanger was located 110 mm (4.3 in.) below the bottom of the roofing corresponding to the location of the top of the ceiling (typically gypsum board or reconstituted wood board). The heat exchanger surface temperature was usually in the range of about 13° to 20°C

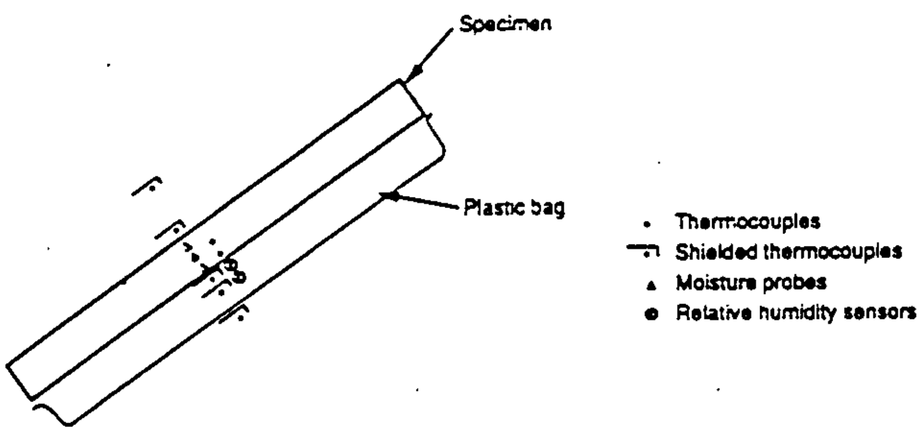

Figure 2 Location of sensors

(55° to 68°F). A slightly higher temperature may have reproduced field conditions somewhat more accurately; other constraints made the provision of a warmer water supply impractical. A plastic bag was located with its bottom on top of the heat exchanger surface in order to condense and collect any water vapor transferred into the enclosed cathedral roofing system cavity. The edges of the bag were gasketed between the edges of the roof above and the walls of the cavity below to prevent the escape of moisture except out from the top exterior surface of the roofing material or from the bottom surface into the enclosed roof cavity. The bag could be easily removed for weighing without loss of any trapped moisture. There was some air leakage because of the spaces between the shingles. The exchange rate of air into and out of the "closed" roof cavity below the roofing materials was measured by a tracer gas technique (SF_6 decay); typically values of about 1.5 air changes per hour (ach) were found.

Roofing Materials

Most of the absorbent roof cladding samples tested were made of 6 mm (0.24 in.) thick cellulose-fiber-reinforced cement. The three types of that material included lapped shingles, 1640 mm by 293 mm (64.6 in. by 11.5 in.); lapped shakes with a rough exterior surface, in 3 sizes: 300 mm, 200 mm, and 150 mm (11.8 in., 7.9 in., and 5.9 in.) width by 550 mm (21.7 in.) length; or single plain sheets. Some of the shingles tested were an older four-tab version no longer available, and some were the newer single-tab type more like the shakes. All of the shingles and shakes were shipped from the factory with a thin, porous coat of clear acrylic paint on the exposed face. Some of the materials were new, others were unused but stored at least a year, while others were older weathered shingles removed from an existing roof.

A few preliminary tests were carried out with single plain 1 m² (10.8 ft²) sheets of cellulose-fiber-reinforced cement without any other roof components. Other samples were initially tested in an assembly that supported the cladding on metal battens spaced at the normal wooden batten spacing. Metal battens were used to ensure that the solar-driven water vapor transmission mechanism under study was not confused by other issues such as hygroscopic storage. Then, in later runs, underlay materials were added, such as permeable building paper in continuous sheets directly under the bottom of all the cladding material, a common New Zealand building practice, or building paper with a layer of polyethylene bonded to it, interleaved between the lapped shingles with the polyethylene layer uppermost. One run examined the effect of offsetting the building paper to provide a 45 mm (1.8 in.) thick air space between it and the roofing shingles. In some of the runs the shingles were painted on both faces and/or their edges were sealed.

For comparison, commonly used concrete tiles and unglazed clay tiles were tested. In addition, wooden shingles were tested because they are a product just beginning to enter the New Zealand market.

Sensors

The physical parameters monitored were temperatures, relative humidities, and moisture contents. The locations of the sensors are shown in Figure 2. They all were located in the vertical midplane of symmetry of the roofing test section. Up to seven T-type, 24-gauge thermocouples, appropriately radiation shielded if required, were used to measure air and surface temperatures. Two thin film capacitive-type relative humidity sensors were used to monitor changes in the relative humidity of the air inside the roof cavity 5 mm and 35 mm below the roofing. Two or sometimes three sets of resistance-type moisture sensor electrodes were located within the absorbent roofing materials at different locations to monitor the changes in the moisture levels of the cladding caused by the simulated rain or solar heating. They were not calibrated because they were intended only for examination of qualitative changes in moisture contents of the roofing materials under test.

Data Logger

The sensors were connected to a multichannel data logger. Readings of the sensor quantities were made every 6 minutes over the 20- to 21-hour duration of each of the test runs. The variation with time of each of the sensor quantities was graphed for each test run in order to visually analyze and compare the performance of the various roof cladding materials and arrangements.

Other Instrumentation

Those items that needed to be weighed, such as the roofing material, the roofing test assembly, and the plastic bag with or without water transferred into it, were weighed before and after the tests, using precision balances and were recorded with a resolution of 1 g. In addition, the relative humidity of the laboratory air was measured at the beginning of the test runs using an aspirating psychrometer.

Accuracy of the Instrumentation

The system-wide accuracy of the quantities measured was estimated to be: temperature, ±0.25°C; relative humidity, ±4% RH; and mass, better than ±1 g.

TESTING

Test Program

Prior to the formal test runs, a number of preliminary tests were undertaken in order to examine the moisture absorption properties of the materials under test, modify and commission the experimental apparatus, and establish the solar heating and rain amounts and durations to be used in all further testing.

Test Procedure, Conditions, and Rain/Solar Flux Duration

Prior to putting together the roofing assembly for a particular test run, the roofing material was preconditioned in a constant climate room (20°C, 65% RH) for at least a week and then weighed. Before each run, the roof assembly, any underlay or interleavement, and the plastic bag and gasket materials were weighed.

The rain rig was then moved into position and the rain started. The rain impinged on the roof for 16 hours, during which the roofing material absorbed some of the water. The simulated rainfall gave a runoff over the specimen that was equivalent to about 13 mm (1/2 in.) of rain over a full roof during the 16-hour period. That was deemed sufficient to allow the roofing material to absorb moisture, but not so much as to be atypical. After the rain cycle ended, the roof assembly and the plastic bag and gasket materials were reweighed to determine the amount of water absorbed by the roofing material. That allowed a check to be made to see if any moisture transfer into the plastic bag had occurred prior to solar heating.

Next the roof and bag were reassembled and the simulated solar heating was initiated for about four hours at the equivalent of a normal solar flux value of 750 W/m^2. By the end of the solar heating, the roofing surface temperatures and roof cavity air temperatures had become fairly stabilized. The outer surface of the roofing materials typically rose to a temperature of about 60° to 65°C (140° to 149°F). After the solar heating period, the roof was disassembled and the materials were reweighed.

RESULTS

Preliminary Testing

The water absorption test established that the cellulose-fiber-reinforced cement shingle/shake roofing material, when soaked overnight, absorbed about one-quarter of its starting weight of water, showing the material to be highly absorbent. Further tests then provided the first experimental verification that the material did indeed transmit large amounts of its stored moisture when solar heated. In addition, during these early tests the test rig was modified to the final form used in the remaining tests, as described above.

Phase I: Demonstrate Existence of Solar-Driven Moisture Transfer

The first step in demonstrating the existence of solar-driven moisture transfer through absorbent roofing materials was to test a plain single sheet of unused material stored for about a year. It is stressed that plain sheets are not used in the field as a roof cladding; this run was done for demonstration purposes. A 1 m^2 (10.8 ft^2) sheet with an initial weight of 7187 g absorbed 1779 g of water from the rain. At the end of the rain cycle, no water was observed to be transmitted through the material. However, after four hours of simulated solar radiation, 16% of this uptake (279 g) was driven through the material and into the plastic bag below it. The weight measurements showed that 1096 g were evaporated off the outer surface of the material. Continued heating would have resulted in an even greater weight gain in the bag. This test clearly verified the earlier preliminary result that solar heating was the cause of the moisture transfer through the absorbent roofing material.

The next step was to test the different types of actual shingles without any underlay or interleavement. The first test was on a roof assembly made up of new single-tab shingles attached to metal battens. The solar-driven moisture transfer in this case was 98 g, which was 6% of the 1618 g of water absorbed. This was less than for the single sheet, probably because the roofing assembly of overlapping shingles produced a greater overall thickness through which to transfer.

Subsequently, a roof assembly was tested that was made up of unused shingles of the four-tab variety that had been stored for about a year. The solar-driven moisture transfer (88 g) was about the same as with the newer single shingles. Since it appeared that weathering of the shingles might affect their performance, weathered shingles from an existing roof, several years old, also were tested. The moisture transfer of 203 g was more than double that with the non-weathered shingles.

The results from all the tests for the first phase of this research investigation are presented in Table 1.

TABLE 1
Summary of Phase I Results

Test No.	Roofing Material	History	Underlay Material	Solar-Driven Moisture Transfer (g)
1	Plain sheet	Stored*	None	279
2	Shingles	New (Base Case)	None	98
3	Shingles	4-tab, stored*	None	88
4	Shingles	4-tab, weathered	None	203

*Stored indoors for about 1 year.

Phase II: Test Actual Roofing Systems

Since shingle roof assemblies often include some type of underlay such as building paper, the next set of tests was undertaken to examine the influence of that additional component. The first test involved the addition of a single continuous sheet of building paper directly below and in contact with new shingles. The building paper was a conventional permeable-type building paper made of heavy-duty kraft paper fully saturated with bitumen (asphalt) with a nominal area density of 450 g/m^2. Its addition reduced the moisture transfer to about two-thirds (62 g) of its value without underlay.

The influence of offsetting the continuous building paper below the shingles (forming an air space about 45 mm thick) also was examined. This resulted in an increased moisture transfer (77 g) relative to the case with no offset (62 g). Lack of underlay directly below the shingles probably allowed moisture to transfer through the shingles, some of which then transferred through the permeable building paper.

In addition to testing the solar-driven moisture transfer through the absorbent cellulose-fiber-reinforced cement shingles, three other absorbent roofing materials were tested for comparison. No underlay was in place during any of these tests. The unglazed clay tiles and the wooden shingles were found to directly leak a little rain—10 g in the case of the unglazed clay tiles, and 26 g in the case of the wooden shingles. Concrete tiles and unglazed clay tiles gave solar-driven moisture transfer amounts of 110 g and 136 g, respectively, both results being slightly greater than that found for the new shingles (98 g). New wooden shingles gave the greatest solar-driven moisture transfer of any of the tests (162 g).

In summary, the results for the second phase of this research investigation involving tests of actual roofing systems are presented in Table 2. The phase I base case result—Test No. 2—is shown for comparison.

TABLE 2
Summary of Phase II Results

Test No.	Roofing Material	History	Underlay Material	Solar-Driven Moisture Transfer (g)
2	Shingles/Base Case	New	None	98
5	Shingles	New	Building paper	62
6	Shingles	New	Offset bldg paper	77
7	Concrete tiles	New	None	110
8	Clay tiles	New	None	136
9	Wooden shingles	New	None	162

Phase III: Study of Remedial Measures

During this phase of the investigation, several different ways of possibly reducing or eliminating the solar-driven moisture transfer were tested. The first approach was suggested by the manufacturer of the shingles: to replace the continuous permeable building paper with a non-continuous but impermeable building paper consisting of conventional building paper with a thin layer of polyethylene bonded to it. This was interleaved between the layers of shingles. Its use dramatically reduced the solar-driven moisture transfer to only 6 g, even though the shingles absorbed 1535 g of water during the rain period. The quantity of water transferred is about one-tenth of that measured when conventional permeable building paper was used as an underlay.

A similar test using the interleaved polyethylene-coated building paper was repeated, but with absorbent cellulose-fiber-reinforced cement shakes rather than the shingles. They had a rough upper surface rather than a smooth surface. The results were almost identical, with a measured moisture throughput of 8 g.

The next remedial measure tested was spacing the shingle layers apart by about 4 mm without any underlay in place. This gap was created vertically between the shingles by using round head screw fasteners. Spacing reduced the moisture transfer over the base case by about 50% (to 49 g).

A final series of remedial action tests involved determining the effects of extra painting of the outer and inner surfaces of the shingles and/or sealing the edges. The paint used was a micaceous acrylic with

TABLE 3
Summary of Phase III Results

Test No.	Roofing Material	History/ Underlay	Remarks	Solar-Driven Moisture Transfer (g)
2	Shingles	New/None	Base case	98
10	Shingles	New/Poly	Underlay interleaved	6
11	Shakes	New/Poly	Underlay interleaved	8
12	Shingles	New/None	Spaced shingles	49
13	Shingles	New/None	Edges sealed	79
14	Shingles	New/None	Painted, edges unsealed	66
15	Shingles	New/None	Painted, edges sealed	39

*All cellulose-fiber-reinforced cement.

two coats, each applied at the rate of 25 m²/L. The area of edge material exposed to water was roughly one-tenth of the exposed surface area. No underlay was in place. With edges sealed but no extra coats of paint, the moisture transfer was measured to be 79 g. Applying two coats of paint but not sealing the edges was more effective at reducing the moisture throughput (66 g). Lastly, both surface painting and edge sealing reduced the moisture transfer to 39 g, which is a slightly greater reduction than the sum of the individual effects.

The results of the third phase of this research investigation involving tests of potential remedial measures are presented in Table 3. The phase I base case result—Test No. 2—is again shown for comparison.

Repeatability Runs

A specimen similar to that used in test 5 was built (cellulose-fiber-reinforced cement shingles with building paper) and tested four times, with 14 days in the controlled climate room between each run. The moisture transferred was 75 g, 76 g, 76 g, and 78 g, giving a mean of 76.3 g and a standard deviation of 1.3 g. This measurement gives confidence that all other results should be reproducible to within 2 or 3 g.

DISCUSSION

All absorbent materials tested without an impermeable building paper in place showed considerable quantities of moisture transferred when heat simulating solar radiation was applied to the rain-wetted materials. The much higher moisture transfer through the weathered cellulose-fiber-reinforced cement shingles may be partly explained by differences in pigmentation and surface treatment of this older product, as well as any weathering effects due to its use in the field. When it is considered that the test area was only about one square meter, and that only one cycle of rain and solar heating took place, the amount of water transferred through the materials into the roofing cavity below as a result of solar heating is on the order of 100 g/m², which must be considered substantial and significant.

Problems in New Zealand have only been noted with the cellulose-fiber-reinforced cement shingles, in spite of the fact that the use of concrete tiles is more widespread. This probably stems from the fact that roofs built with concrete tiles have better natural ventilation and possibly because they are used less widely in cathedral-type roof applications (construction must be heavier to take the load of the heavier concrete tiles).

Using an impermeable membrane interleaved between the cellulose-fiber-reinforced cement shingles or shakes was found to be a very effective remedial measure, reducing the solar-driven moisture transferred through the cladding by about 93%. Other measures, such as the use of a permeable building paper, creating a gap between the shingles, or painting and/or sealing the shingles, did reduce solar-driven moisture transfer (by 37%, 50%, and around 50%, respectively), but not by a large enough factor to be confident that these measures would cure the problem.

New wooden shingles were tested because they are now entering the market in New Zealand. Moreover, their use in cathedral roofs in the United States is rather common. In addition, they are used as an exterior facing for walls, which also have an adjacent closed cavity. Tests of the roofing assembly with wooden shingles resulted in the greatest moisture transfer of any of the tests (162 g). This suggests that there may be moisture problems with shingles if they are applied conventionally with permeable underlay on a cathedral roof. Moreover, applying the shingles over plywood sheathing, even in an attic-type roof construction, may trap moisture between the shingles and the plywood and cause serious moisture problems.

The use of a non-permeable underlay, such as one with polyethylene attached, may not be the appropriate or the best remedial approach with wooden shingles, which can rot. It may not be acceptable to prevent the shingles from breathing on their unexposed side, especially with cathedral roofs. Furthermore, there are cases where wooden shingles are being applied over continuous plywood sheathing rather than over the traditional wooden battens with air spaces in between. In that case, solar heating may transport moisture into the closed space between the unexposed side of the shingles and the plywood. Inability of the shingles to dry out could lead to conditions that would result in wood decay and structural damage over the long term, which could occur with both attic-type roofs and cathedral types. In fact, it is well accepted within the U.S. roofing community that applying wooden shingles over continuous plywood sheathing rather than spaced wooden battens reduces the lifetime of the shingles. Thus, it would appear that solar-driven moisture transport could be an important mechanism related to the shortened lifetime.

Therefore, this situation needs to be studied in more detail. The situation is different from and more complex than that investigated in this study. Not only is it necessary to study the solar-driven moisture transfer that supplies moisture to the closed roof cavity or the underlay/shingle interface, it is also necessary to examine the possible drying processes and any potential remedial measures. In view of the new interest in wooden shingle roofs in New Zealand and the long-standing interest in wooden shingles for both roofs and walls in the United States and in other countries, it is strongly recommended that a detailed study of solar-driven moisture transfer in wooden shingle roofs be undertaken. As was the case in this study, such an investigation could very well lead to quantitatively verified measures that greatly reduce or eliminate some of the moisture-related problems associated with wooden shingles. It is perhaps worth noting that elevated moisture contents were noted in wall cavity wood members in homes sided with painted wood shingles (Tsongas 1985). They were wetted by rain or snow melt dripping off roofs without gutters, hitting the frozen winter ground, and bouncing up under the bottom unprotected edges of the shingles. Whether or not solar heating had a role in transferring any of the absorbed moisture into the members is not known. However, it certainly is possible. Moreover, as noted in the introduction, solar heating of wood siding was an important moisture transfer mechanism in a study of siding moisture damage (Lstiburek 1987).

In attempting to better understand the physics of the solar heating moisture transfer mechanism, vapor pressure differences across the cellulose-fiber-reinforced cement shingles were calculated using the measured test results. Figure 3 shows vapor pressures developed during a typical run (Test No. 5—new shingles with permeable building paper). Vapor pressures in excess of 5000 Pa are seen to be generated just below the bottom surface of the roofing material. Figure 4 shows temperatures generated on the top surface of the roofing material. While the top surface is saturated, vapor pressures of around 20,000 Pa will be generated. This results in a vapor pressure difference across the shingles of about 15,000 Pa and a massive vapor pressure gradient of 7.5×10^5 Pa/m. The temperature gradient of about 500°C/m also is large. These values are an order of magnitude above those usually encountered in building physics and provide the driving force for the phenomenon of solar-driven moisture transfer investigated in this work.

Generally, understanding the performance of a structure when solar-driven moisture transfer might be important is a system problem. It requires knowledge in particular of the material properties and of the air leakage characteristics of the structure, and a deeper understanding of how moisture moves under the very large vapor pressure and temperature gradient conditions encountered; see, for example, Kumaran (1987). The deeper understanding of the physics of solar-driven moisture transfer thus requires that additional study of this potentially important mechanism be undertaken.

CONCLUSIONS

Because moisture problems were noted in the field when cellulose-fiber-reinforced cement shingles were applied to cathedral roofs in New Zealand, a laboratory research investigation was initiated to determine the cause and possible remedial actions. It was speculated that these problems were caused by solar-driven moisture transfer through the absorbent roofing material.

The results and findings of this laboratory study clearly indicate that the shingles in question do in fact absorb substantial amounts of water when exposed to rain; none of this water penetrates the roof cavity at this stage. On the other hand, when the moisture-laden shingles are solar heated, substantial moisture transfer occurs through the shingles into the space below.

Figure 3 *Typical vapor pressures developed under roof with simulated solar heating*

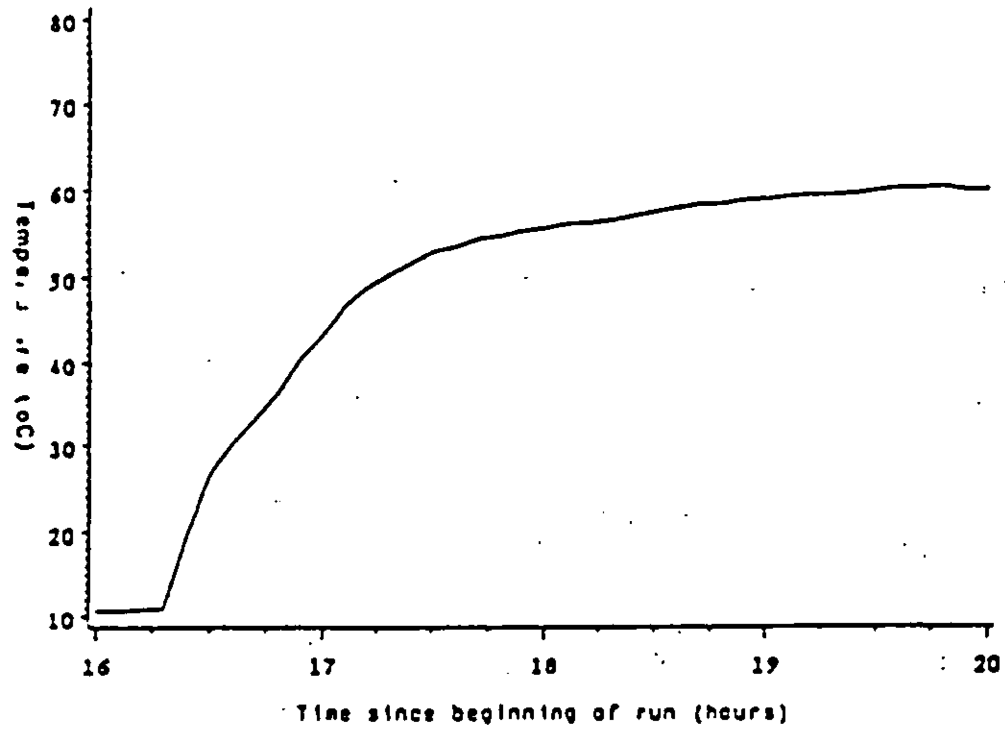

Figure 4 *Typical top surface roof temperature with simulated solar heating*

When moisture transfer occurs into an attic space, no problems have been noted, as the moisture is probably removed by natural ventilation or air leakage. However, when the moisture transfer occurs into a closed roof cavity, such as in the case of a cathedral roof, then the moisture does accumulate and becomes a problem in some cases.

The experimental results indicated that solar-driven moisture transfer occurred with conventional permeable asphalt-impregnated building paper in place below the shingles, but was dramatically reduced and nearly eliminated when building paper with polyethylene bonded to it was interleaved between the shingle layers. That approach, which has been adopted by the manufacturer, is recommended for future cathedral roof applications of absorbent shingles. However, based on the lack of problems noted in the field, it appears satisfactory to use building paper as the underlay in attic-type roofs. Other remedial measures described here did not come close to eliminating the moisture throughput.

Tests of other absorbent roofing materials, such as concrete or clay tiles or wooden shingles, indicated even greater moisture transfer than with the absorbent shingles, at least in their new state. This mechanism could pose a problem with wooden shingles, particularly if they were laid on plywood; a detailed study of this situation is called for.

Generally, understanding the performance of a structure when solar-driven moisture transfer might be important is a system problem. It requires knowledge in particular of the material properties and of the air leakage characteristics of the structure, and a deeper understanding of how moisture moves under the very large vapor pressure and temperature gradient conditions encountered.

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REFERENCES

ASHRAE. 1985. *ASHRAE handbook—1985 fundamentals*. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Handegord, G.O. 1985. "Prediction of the moisture performance of walls." *ASHRAE Transactions*. Vol. 91, Part 2B, pp. 1501–1509.

Kumaran, M. 1987. "Moisture transport through glass-fiber insulation in the presence of a thermal gradient." *J. Thermal Insulation*, Vol. 10, April, p. 243.

Lstiburek, J. 1987. "How insulation can peel your paint." *New England Builder*, June, pp. 27–31.

Tsongas, G.A. 1985. "The Spokane wall insulation project: a field study of moisture damage in walls insulated without a vapor barrier." *Proc. ASHRAE/DOE/BTECC Conference on Thermal Performance of the Exterior Envelopes of Buildings III*, Clearwater Beach, FL. December 2-5, pp. 556–569; also DOE/BP-541, Bonneville Power Administration, U.S. DOE, Portland, OR, September.

Wilson, A.G. 1965. "Condensation in insulated masonry walls in summer." RILEM/CIB Symposium, Helsinki, pp. 2-7.

DISCUSSION

J.T. Reardon, Research Officer, National Research Council of Canada, Ottawa, Ontario: How did you account for evaporative losses of water from the sides of your apparatus, which, in your photos, appeared open to ambient lab air? Do you feel this may have been important in achieving a balance between supply water and water caught and weighed in the trough and plastic bag traps?

G.A. Tsongas: The sides of the apparatus were indeed open *above* the roofing material; thus, some of the simulated rain water absorbed by the roofing material did evaporate from its upper sur-

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