Historic England

Building and Landscape Conservation

# The Variability in Resistance Moisture Meter Readings obtained from Medieval Roofs

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Discovery, Innovation and Science in the Historic Environment


Research Report Series no. 207/2020

# The Variability in Resistance Moisture Meter Readings Obtained from Medieval Roofs

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ISSN 2059-4453 (Online)

## FOREWORD

Water is responsible for the deterioration of many building materials. Therefore, assessments of moisture content and distribution are often needed to identify sources of water ingress, diagnose faults, and appraise the risk of harm. They are also helpful in determining the remedial measures that might be required.

Numerous techniques and devices for assessing moisture are available to the conservation practitioner. For instance, the moisture content of a material can be measured directly by gravimetric methods, but these are destructive as material samples have to be extracted. Alternatively, indirect methods may be used. These are non-destructive and rely on detecting variations in material properties, such as electrical resistance or permittivity, which are caused by the presence of moisture. However, these properties are affected by factors other than moisture, such as temperature or the presence of salts. This can lead to inaccurate and misleading meter readings.

Historic England is undertaking an on-going programme of research to gain a better understanding of the use and limitations of various moisture assessment techniques.

For more information about this research see:
https://historicengland.org.uk/research/current/conservation-research/care-of-buildings

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SUMMARY
This report presents the findings of research into factors affecting resistance moisture meter readings obtained from timbers in three medieval roofs. Resistance moisture meters are commonly used as a survey tool to measure the moisture content of building timbers. However, analysis of data obtained in this project shows that variations in the properties of new and ancient timbers affect their response to fluctuations in ambient humidity and the readings obtained from resistance moisture meters.

To avoid erroneous diagnoses, the report concludes that assessments using resistance moisture meters should include readings taken at depth as well as on the surface of timbers. Where repairs have been carried out, the moisture contents of the full range of timbers present should be compared. In addition, variations in humidity and moisture content throughout the year should be taken into account when interpreting moisture meter readings.

ACKNOWLEDGEMENTS
The author would like to thank Iain McCaig and Jessica Hope for their assistance in preparing this report for publication.



ARCHIVE LOCATION
Swindon. Registry file number: AA008823/1521

DATE OF RESEARCH
2018 (using data from 1994-1997)

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FRONT COVER
A surveyor assesses the moisture content of roof timbers using a resistance moisture meter with a hammer probe. ©Brian Ridout

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## GLOSSARY

Abbreviations used in text and graphs:

| | |
|---|---|
| %MC | Percentage moisture content |
| Apr | Principal rafter at apex |
| Atb | Upper tie at apex |
| CHPR | Central high principal rafter |
| CMTB | Central mid-level tie |
| D | Depth (in reference to moisture content) |
| Ex Temp | External temperature |
| Inp | Inner plate |
| MC predict | Predicted moisture content |
| Mtb | Mid line of tie beam |
| N | North |
| NCBL | Nave central beam low level |
| NCTBL | Nave central tie beam low level |
| NELP | North side eaves level |
| NELPR | North eaves low level principal rafter |
| NEMPR | North eaves mid-height principal rafter |
| NEMTB | North eaves mid-height tie beam |
| NND | New (oak) North side deep moisture content readings |
| NNS | New (oak) North side surface moisture content readings |
| Outp | Outer plate |
| Post C | Central post |
| Praf | Principal rafter |
| Praf | Principal rafter |
| Purlin | Purlin |
| Raf | Rafter |

| | |
|---|---|
| RD | Deep moisture content in rafters |
| RH | Relative humidity |
| RH/temperature | Relative humidity/temperature |
| RS | Surface moisture contents rafters |
| S | South |
| S | Surface (in reference to moisture content) |
| SELP | S eaves level plate |
| SELPR | S eaves principal rafter |
| Surftemp | Surface temperature |
| T | Temperature |

# 1) INTRODUCTION

Resistance moisture meters were developed originally to assess the moisture content of freshly-felled timber during industrial drying and seasoning. However, their commercial potential as a building survey tool was soon recognised, and they are now widely used for this purpose. However, the properties of old timbers in historic buildings can be different to those of their modern counterparts. If meter readings are not understood or misinterpreted, an incautious user might well draw incorrect conclusions.

The study described in this report used data obtained during a EU funded woodcare project undertaken between 1994-1997, coordinated by English Heritage, and carried out by Birkbeck College, Netherlands Organisation for Applied Research (TNO) and University College, Dublin. The primary purpose of this three-year research project was to investigate death watch beetle and oak rot fungus (*Donkioporia expansa*) with which the beetles are frequently associated.[1]

As part of this investigation timber moisture content and environmental conditions were monitored in roofs at Lincoln Cathedral, Winchester Cathedral and Bishopstone Church, near Salisbury for a year. This task was undertaken because it was known that a beetle infestation would not thrive if the wood moisture content remained below 15%, but the seasonal moisture fluctuations in medieval timbers were unknown. In the event, there were too many other aspects more directly relevant to the woodcare project so the environmental data were never used. However, they were retained as daily averages (an appropriate time interval for timber equilibration) and have now been analysed and the findings are presented in this report.

The aim has been to understand how surface and depth moisture contents varied with environmental fluctuations, and thereby assess the uses and limitations of resistance moisture meters in medieval timber roofs.

[1] Understanding the relationships between death watch beetle, wood decay fungi and timber ageing in European historic buildings in order to develop alternatives to current harmful and ineffective treatments (Grant agreement ID: EV5V0517) https://cordis.europa.eu/project/id/EV5V0517

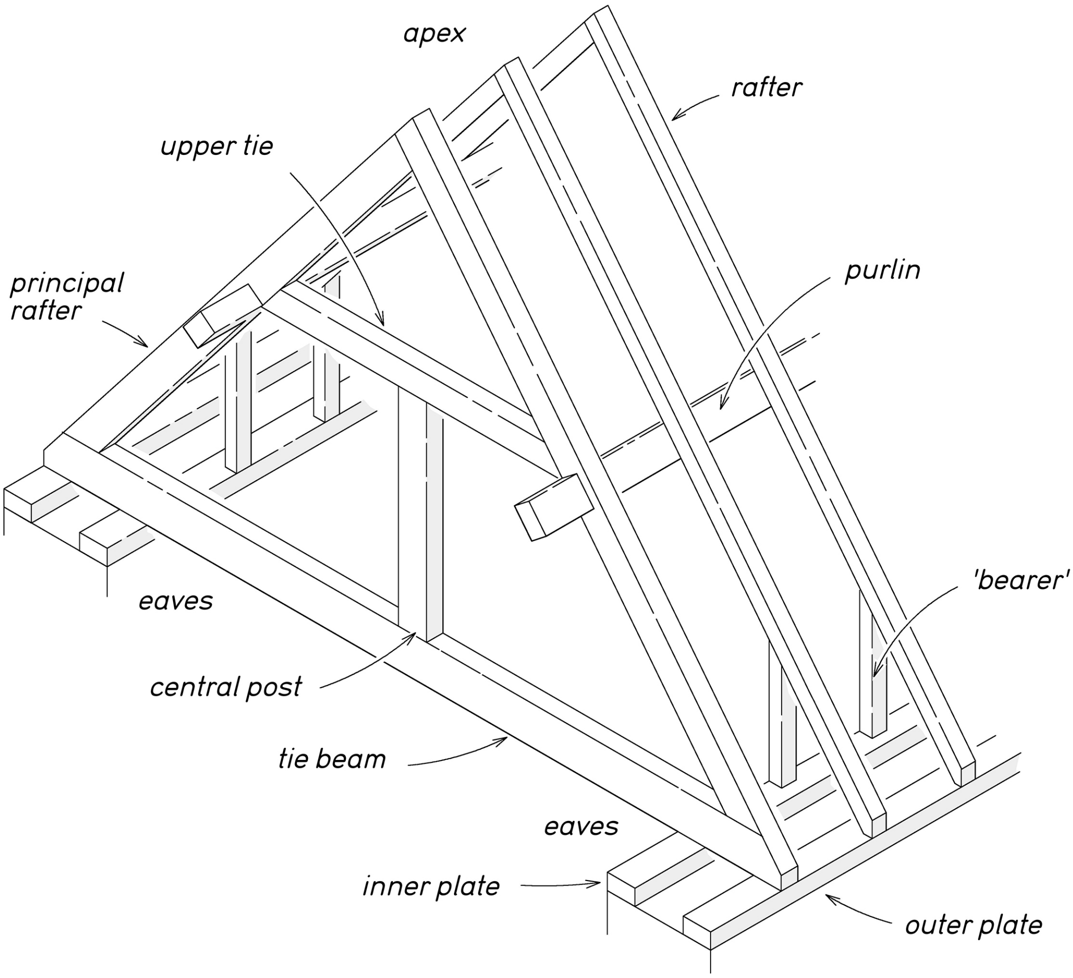



*Figure 1: Terms used in this report to describe roofing timbers*

## 2) STUDY 1 – THE CONSISTORY COURT AND RINGERS' CHAPEL ROOF SPACES AT LINCOLN CATHEDRAL

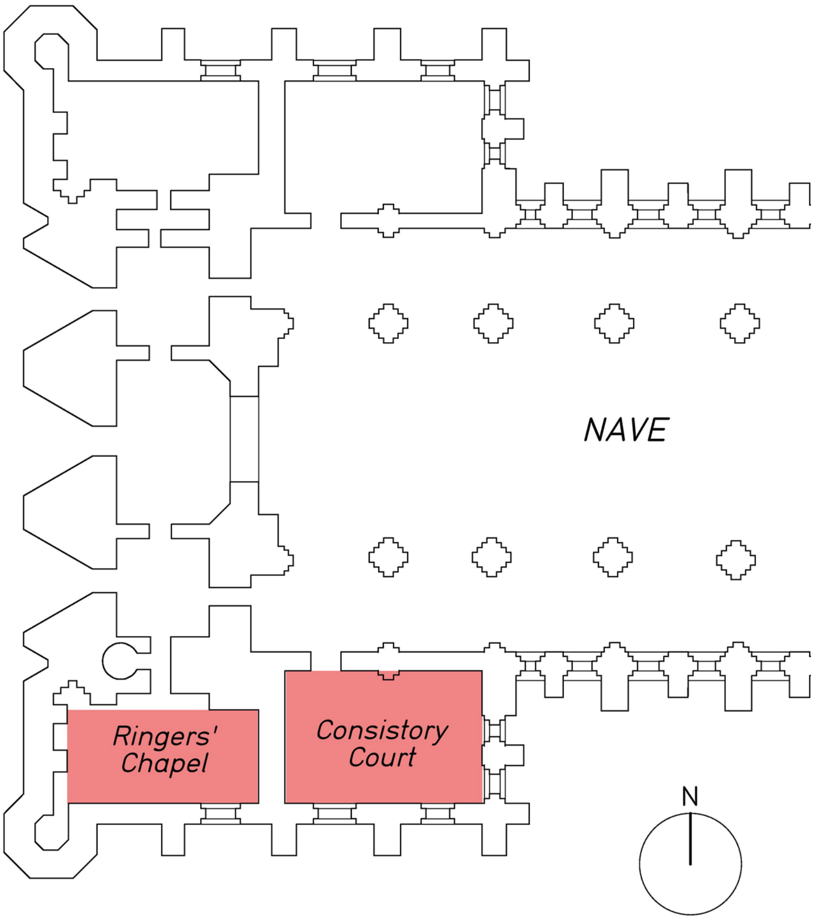



*Figure 2: Location plan of roof space above the chapels in Lincoln Cathedral*

## 2.1 The Monitoring System

Sensors were mostly installed between 25th and 27th January 1995 and the system was completed on 3rd February of that year.

Four MP100 relative humidity/temperature sensors were connected to a Campbell Scientific 21X data logger. These were installed in the following locations:

1. at high level in the centre of the roof space (temp/RH 1)
2. in the eaves on the South side (temp/RH 2)
3. in the centre of the roof space at eaves level (temp/RH 3)
4. in the eaves on the North side (temp/RH 4)

Six temperature sensors (thermocouples) were also installed as follows:

1. North (N) eaves on the surface of a bearer (Surftemp 1)
2. N eaves 75mm depth in the bearer (Deeptemp 2)
3. South (S) eaves rafter on surface 1.25m above plate (Surftemp 3)
4. same location but at 75mm depth (Deeptemp 4)
5. S eaves, surface of an oak bearer (Surftemp 5)
6. same location but at 75mm depth (Deeptemp 6)

The deep thermocouples were installed at the bottom of 6mm diameter holes, which were then backfilled with electrical component grease. However, the deep temperature readings obtained are suspiciously similar to the surface temperatures and most grease is thermally conductive. Unfortunately the site notes, which would have given the type of grease used, have not survived and the data is thus unreliable. We are therefore only using the surface temperatures recorded by sensors 1, 3 and 5.

64 resistance sensors were used for moisture monitoring. These were installed in 32 locations as surface and depth pairs. Each surface sensor consisted of two screws. The depth sensors were nails that were insulated with polythene tubing, except at the tips, and forced into pre-drilled holes to a depth of 100mm.

These sensors may be placed in five categories:

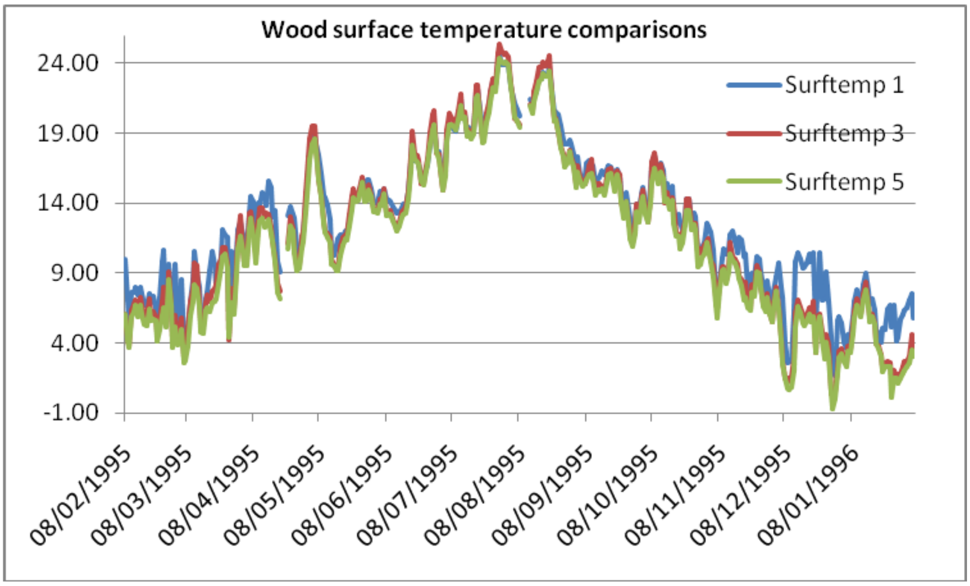
1. 12 pairs in original 1230 rafters
2. 4 pairs in original 1230 bearers
3. 8 pairs in 1984 oak bearers (all in the interconnecting Ringing Chapel roof)
4. 4 pairs in old pine plate (age not known)
5. 4 pairs in 1993 pine bearers

## 2.2 Results

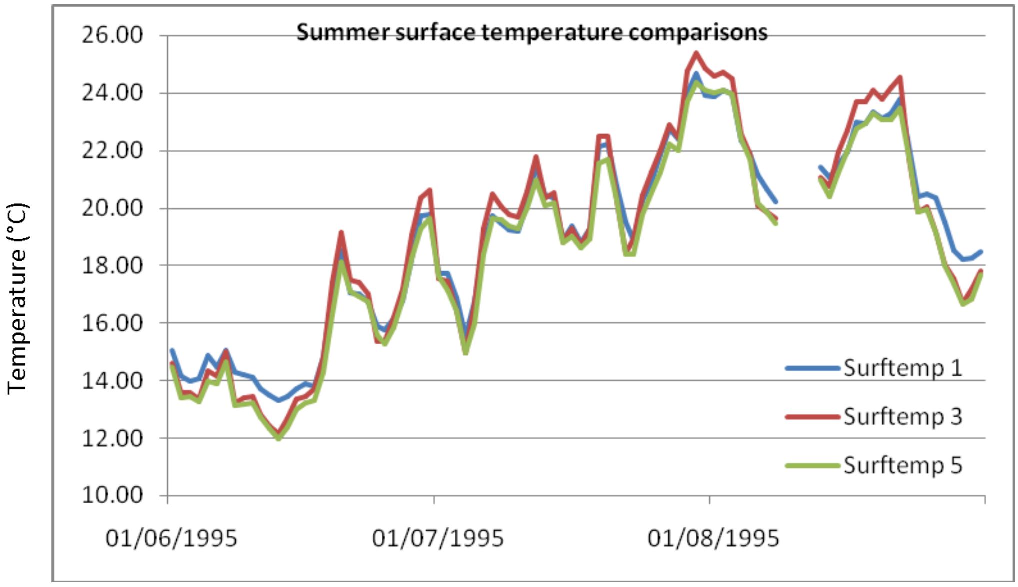
### 2.2.1 Wood temperature comparisons

These are shown in Graph 1. The results from the three temperature sensors (Surftemp 1, 3 and 5) are very similar. However, Surftemp 1 (N eaves, blue trace) seems to be the warmest during the winter months whilst Surftemp 5 (S eaves, green trace) is the coldest. The S side rafter 1.25m above plate level (Surftemp 3, red trace) is the warmest in summer.

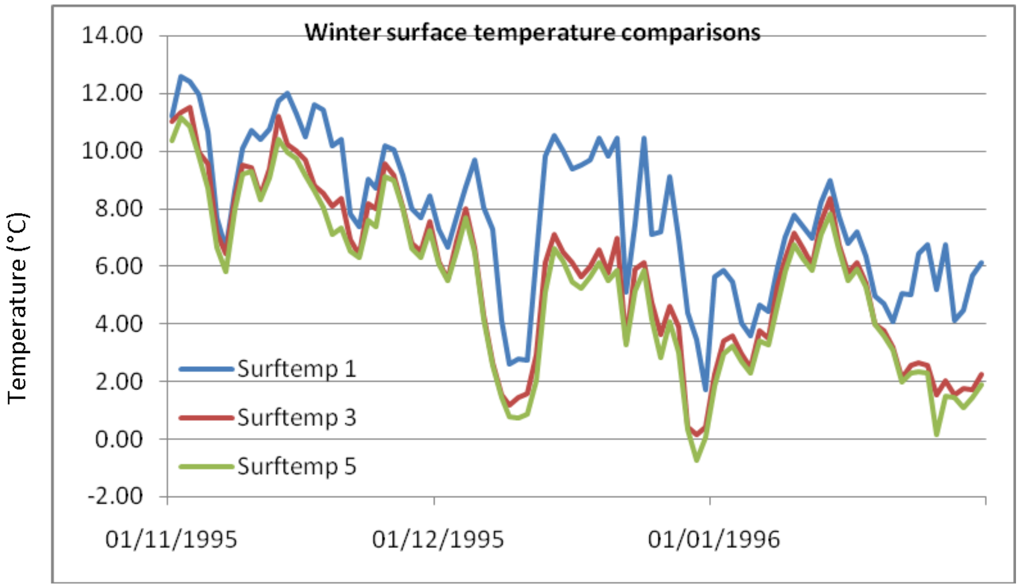
Data from July to September and from November to January are presented as Graphs 2 and 3 to provide more detail.




*Graph 1: Comparison of wood surface temperatures*




*Graph 2: Data from three temperature sensors from June to September*




*Graph 3: Data from three temperature sensors from November to January*

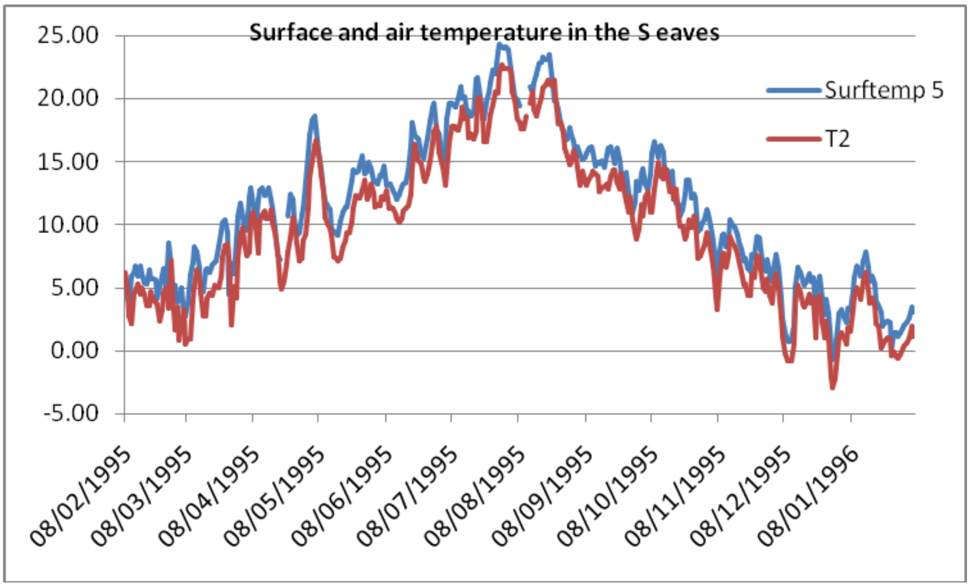
### 2.2.2 Surface and air temperature comparisons

Results in table 1 for the entire monitoring period reveal that in each case the wood surface temperature is warmer than the air temperature.

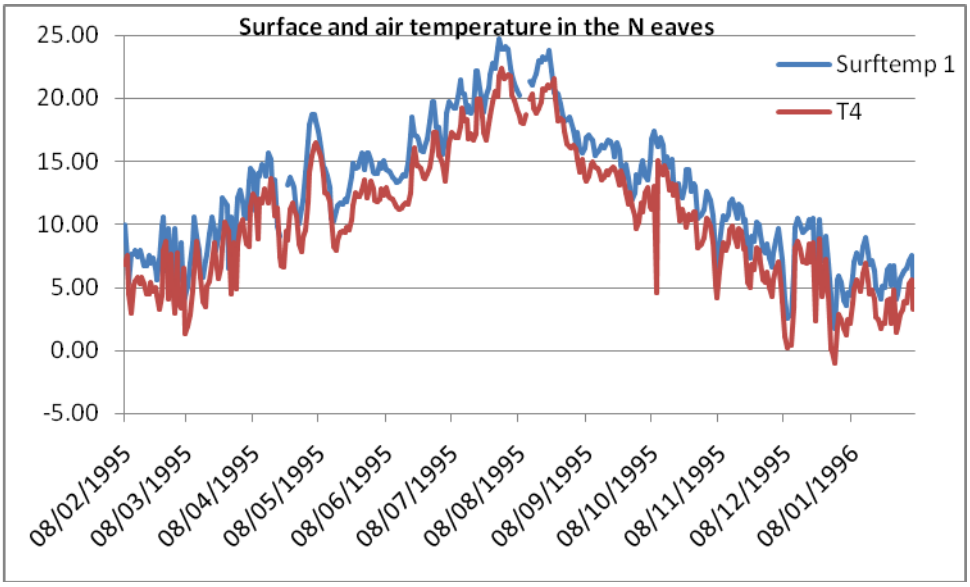
This is shown in Graphs 4 and 5 (T2 and T4).

| | Wood temperature | | | Air temperature | | |
|---|---|---|---|---|---|---|
| | Average | Max | Min | Average | Max | Min |
| Centre of roof, high level | 10.3 | 24.5 | 0.2 | 7.3 | 22.3 | -3.5 |
| South eaves | 9.9 | 23.5 | -0.7 | 8.2 | 21.5 | -2.9 |
| North eaves | 11.6 | 23.8 | 1.7 | 9.3 | 21.5 | -1.0 |

*Table 1: Wood surface and air temperatures at eaves level and high level*




*Graph 4: Wood surface and air temperatures in the S eaves*

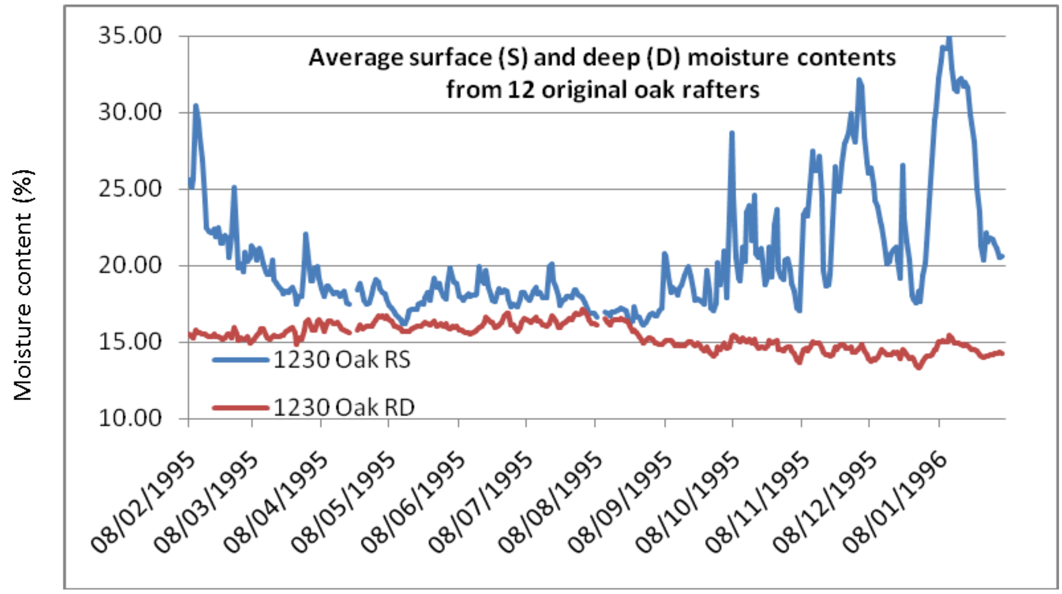



*Graph 5: Wood surface and air temperatures in the N eaves*

2.2.3 Timber moisture contents

Within-group moisture content variation for our five categories of timber was small and it is reasonable to create an average graph for each category.

a) Original 1230 rafters




*Graph 6: Average surface and deep moisture content readings from the original 1230 rafters*

Timbers are considered to be damp and at risk from decay if the moisture content exceeds 20%. A surveyor with a moisture meter would be likely to conclude that the timbers were dry if the roof was investigated during the summer months, but that there was a serious damp problem if the survey was undertaken during winter. However, the deep readings show that the timber is dry.

However, the potential confusion becomes worse because electrical resistance in wood decreases as the surface temperature increases. Meter manufacturers state that readings can be approximately corrected by adding 0.5% for every 5° below 20°C and subtracting 0.5% for every 5°C above. This is wood surface temperature and not air temperature.

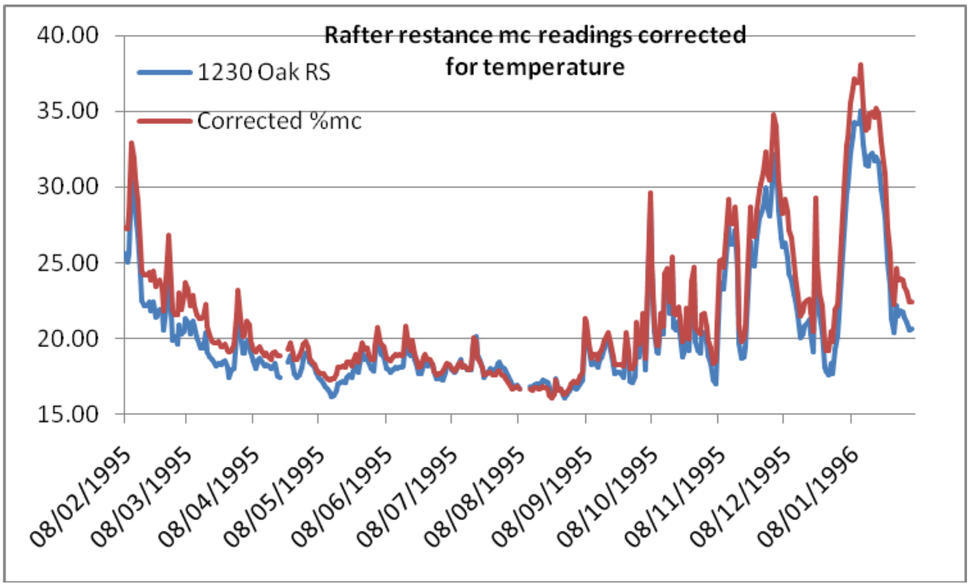
We can correct the surface rafter readings used in Graph 6 because surface temperatures were recorded (Surftemp 1). This correction is performed more precisely than the meter manufacturers suggest by using the Pfaff and Garrahan equation as modified to set the calibration point at +20°C by Samuelson (1992).

The result is shown in Graph 7.

Equation 1 – Pfaff and Garrahan (modified):

$$u_k = \frac{u + 0.567 - 0.0260x + 0.000051x^2}{0.881\ (1.0056)^x}$$

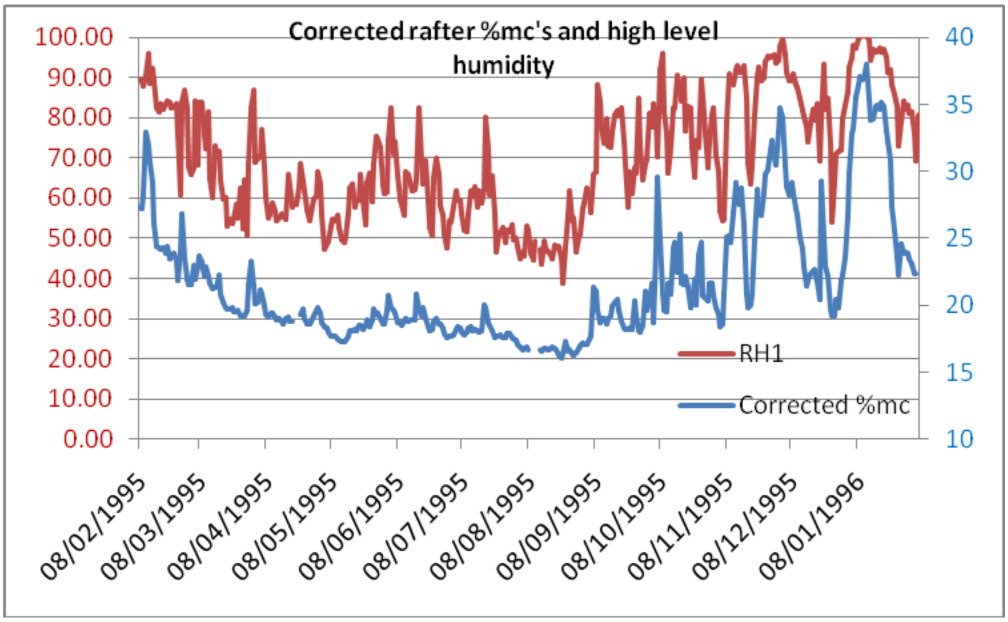
u = moisture meter reading
$u_k$= temperature corrected %MC
x= surface temp + 2.8°




*Graph 7: Comparison of surface moisture meter readings and temperature-corrected readings*

The temperature correction has little effect during the summer months but if the correction is not used then the meter reading is an underestimation during the winter months. However, this does not have any practical significance in this case because the accuracy of resistance moisture meters decreases above about 18%MC and very high readings, as in Graph 7, are impossible to evaluate accurately. Graph 6 also shows that the fluctuations in moisture content in an unheated roof are considerable so that improved accuracy would only have relevance for that particular section of timber at that particular time.

Wood moisture contents equilibrate with relative humidity and temperature has only a small effect. Equilibrium moisture contents may be calculated using the Hailwood Horrobin equation (Equation 2). Results are demonstrated in Graph 8, which shows, as expected, that the outline of the %RH peaks and troughs is similar to the corrected moisture content trace. Equilibrium moisture contents are not greatly affected by temperature, but relative humidity is. In a cold but dry building the winter temperature will drop causing the relative humidity to rise. This, in turn, causes the wood moisture content to rise, but if the building is dry this does not matter. Few organisms would thrive at the low temperatures required to produce the high humidities. The popular concept that decay is inevitable at wood moisture contents above 20% is completely erroneous in this situation.




*Graph 8: Corrected moisture content readings from rafters compared with relative humidity at high level within the roof*

Equation 2 – Hailwood Horrobin:

Further information on how the wood is behaving, and perhaps the inaccuracy of the high readings, may be gleaned from calculating the predicted moisture content from the recorded humidities.

This can be done using the Hailwood Horrobin equation (US Forest Products Laboratory version):

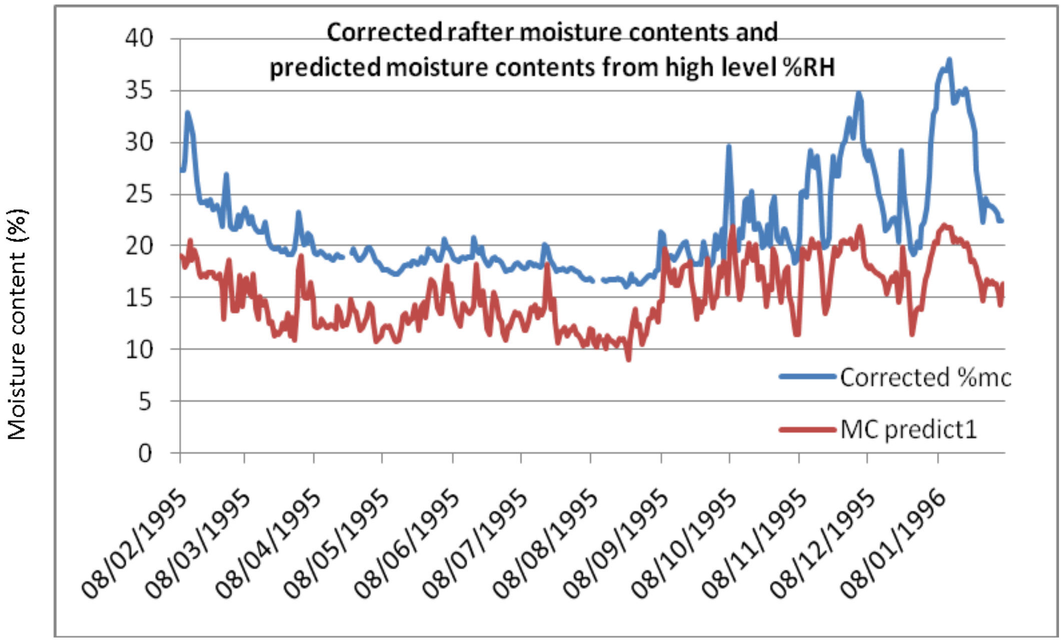
$$M = 1800 / W\,(KH / (1 - KH) + (K_1KH + 2K_1K_2K^2H^2) / (1 + K_1KH + K_1K_2K^2H^2))$$

$M$ = *moisture content* (%)
$T$ = *temperature* (°F)
$H$ = *relative humidity* / 100

$W = 330 + 0.452T + 0.00415T^2$
$K = 0.791 + 0.000463T - 0.000000844T^2$
$K_1 = 6.34 + 0.000775T - 0.0000935\ T^2$
$K_2 = 1.09 + 0.0284\mathrm{T} - 0.0000904T^2$

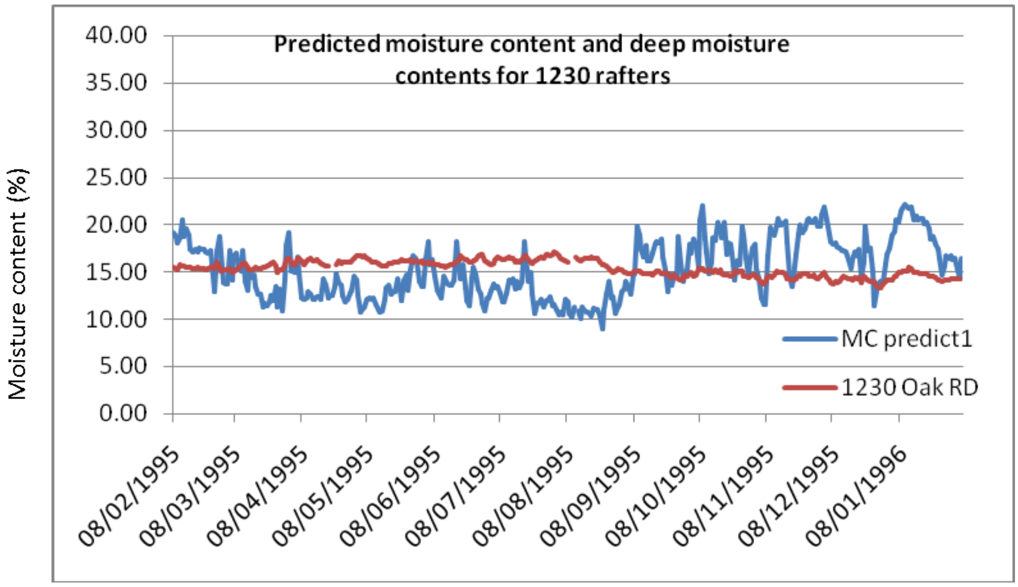
Predicted and measured (corrected) surface moisture contents are shown in Graph 9 and there is generally good agreement between the peaks and troughs. The predicted moisture contents must always be more variable because they are calculated from daily readings (in this case daily averages) and there is not time for the wood to equilibrate properly.

Nevertheless, Graph 9 suggests that very high surface readings in winter are a rapid response to high relative humidities and not caused by some form of surface contamination or salt migration over the past 800 years. Equilibrium moisture contents behave as predicted but the surface of the timber is much more absorbent than the model expects.




*Graph 9: Corrected moisture content readings from rafters compared with moisture contents predicted using the Hailwood Horrobin equation (Equation 2)*

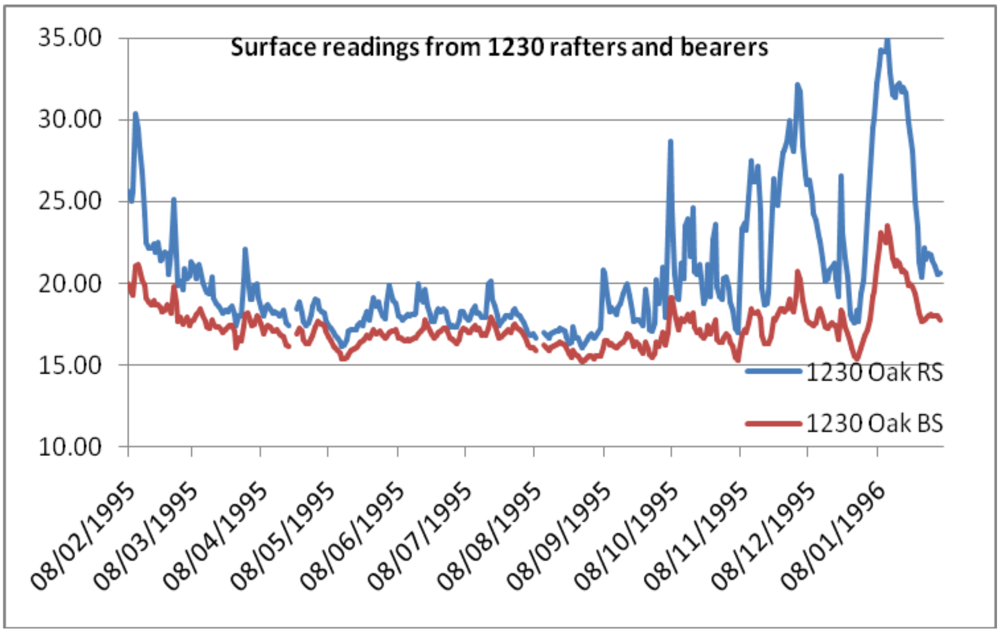
Graph 10 shows the predicted and measured (temperature corrected) moisture contents at depth, which seem to average the predicted moisture distribution throughout the year.



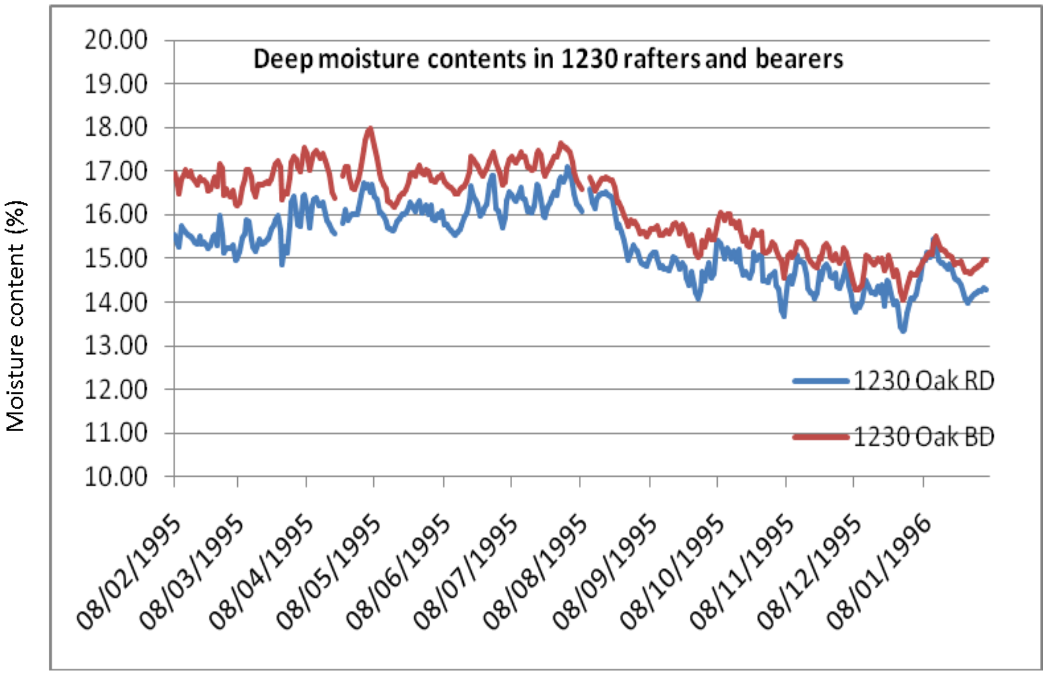

*Graph 10: Deep moisture content readings for 1230 rafters compared with predicted moisture contents*

b) Original 1230 bearers

Surface readings in the eaves timbers (bearers) are similar to those from the rafters, but are much more muted (Graph 11). Deep readings from both locations are comparable, with eaves moisture contents being slightly higher (Graph 12).




*Graph 11: Surface moisture content readings from the original 1230 rafters and bearers*

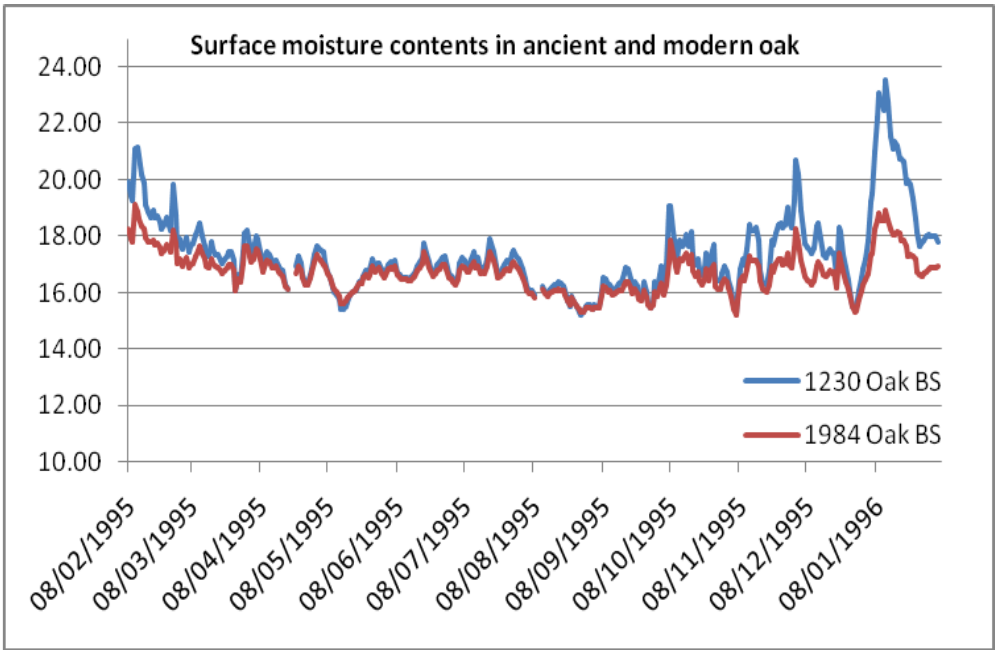



*Graph 12: Deep moisture content readings from the original 1230 rafters and bearers*

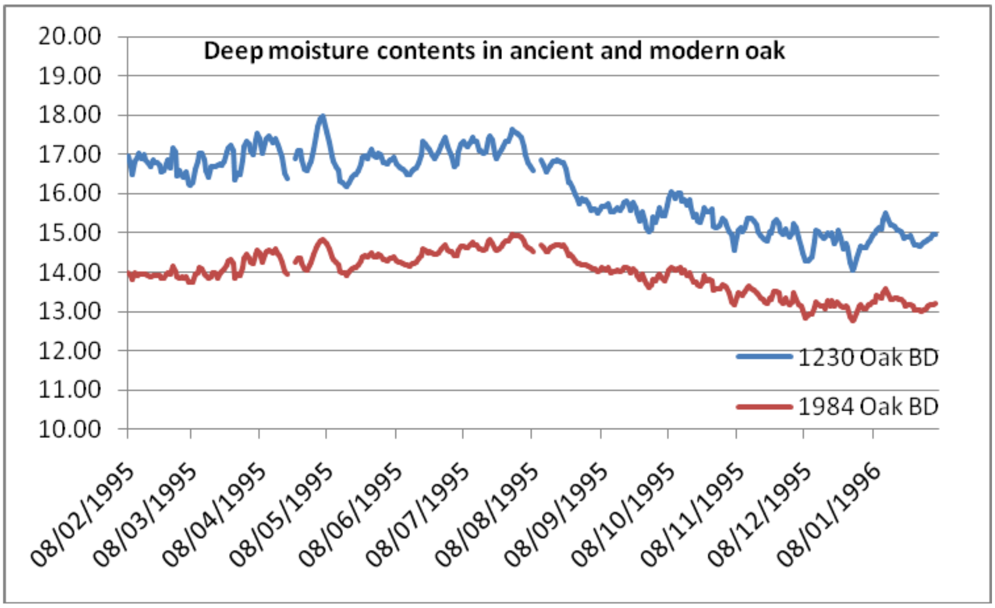
c) 1984 Oak bearers

Surface moisture contents in the recent oak are compared with the original oak bearers in Graph 13, whilst deep readings are compared in Graph 14. The surface of the ancient oak seems to be more hygroscopic, absorbing more moisture at high humidities than the modern oak.

Deep traces are similar but the moisture content in the old oak is 2 – 3% higher.




*Graph 13: Surface moisture content readings in original and modern oak bearers*



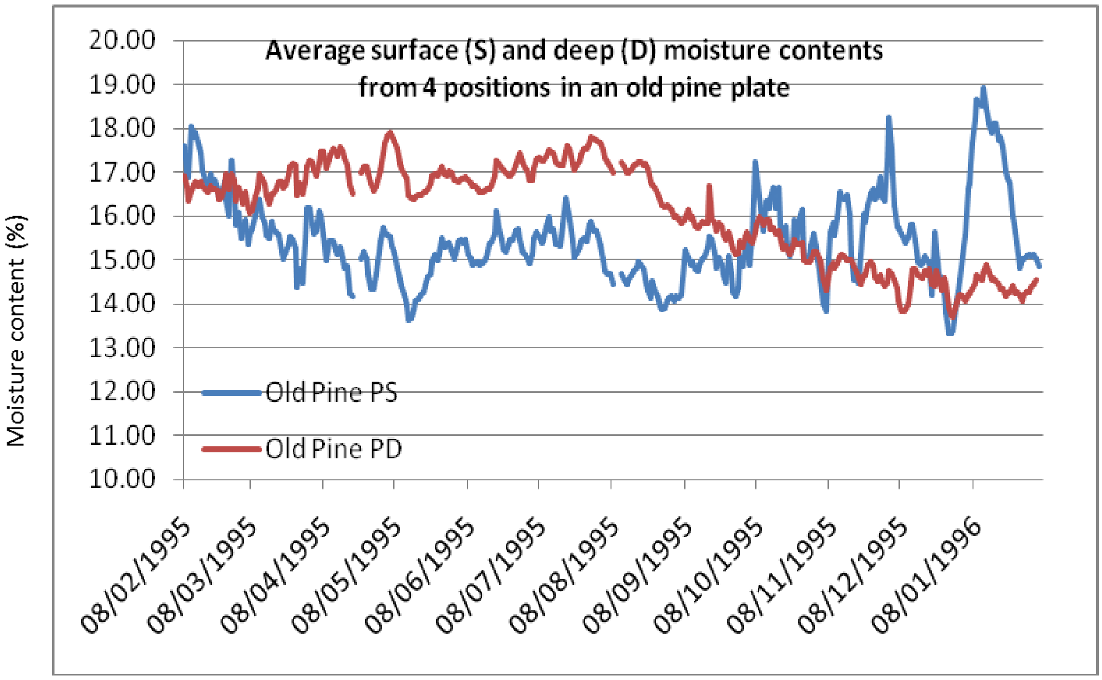

*Graph 14: Deep moisture content readings in original and modern oak bearers*

d) Old pine plate

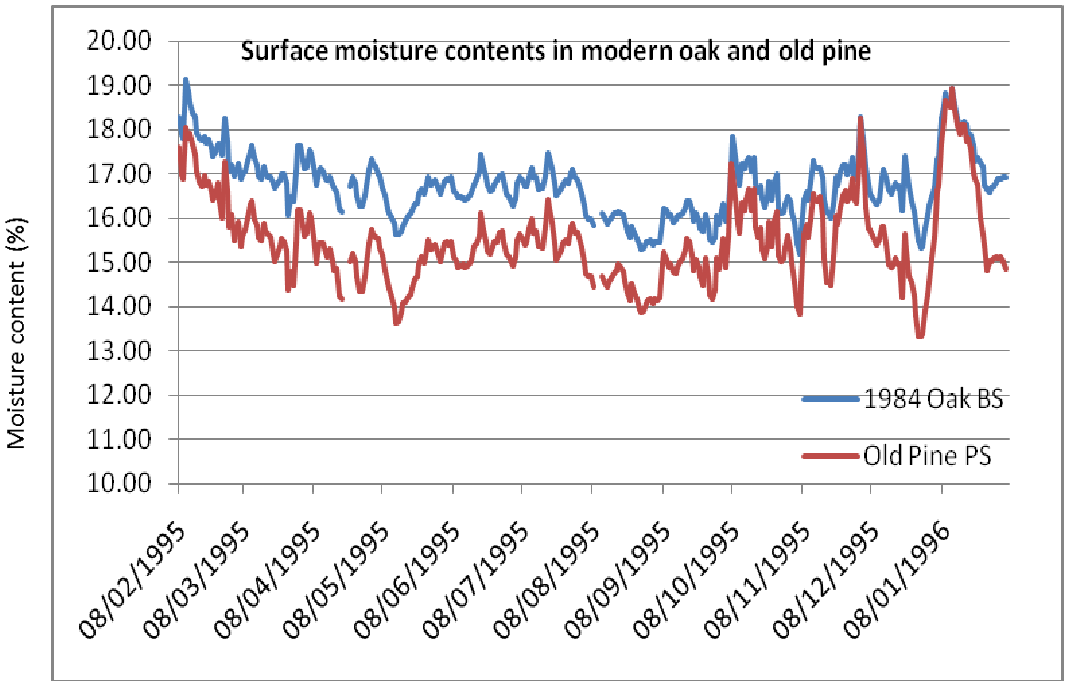
The moisture distribution seems to be different in the pine because deep readings are higher than shallow ones during the summer months, as seen in Graph 15.

Graph 16, which averages data from 4 sensors, shows that surface absorption in softwood follows a similar pattern to surface absorption in oak. The oak seems to be 1 – 2% damper during the summer months.

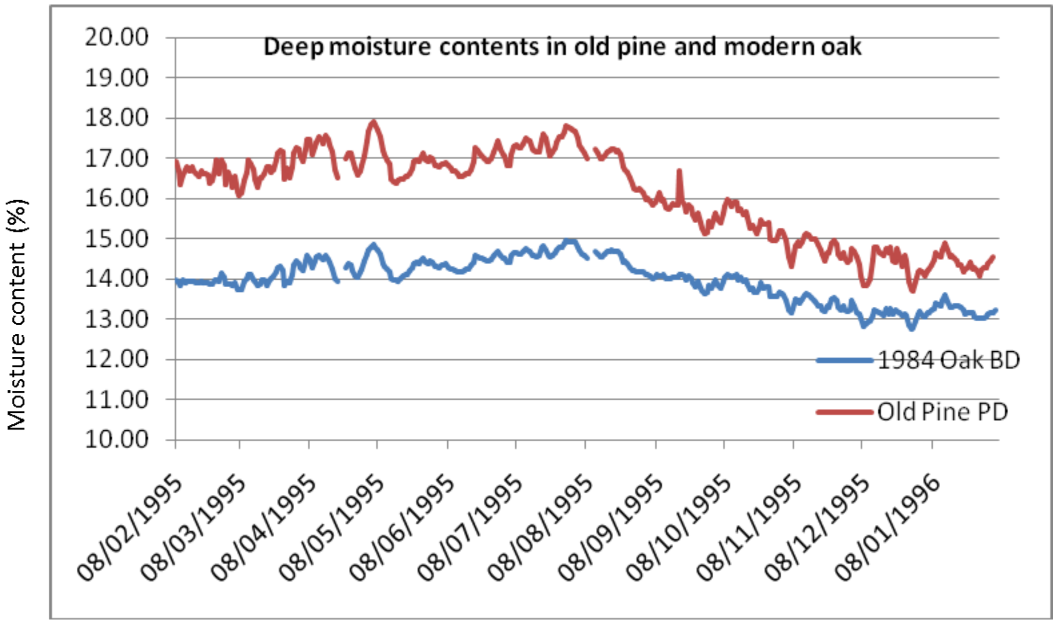
Graph 17 compares deep readings in old pine with those in modern oak. It would seem that the pine shows a stronger reaction to humidity change at depth.




*Graph 15: Average moisture content readings from surface and deep readings in an old pine plate*




*Graph 16: Comparison of surface moisture content readings in old oak and old pine*




*Graph 17: Comparison of deep moisture content readings in old pine and modern oak*

e) 1993 Pine bearers

Surface and depth readings are shown in Graph 18.

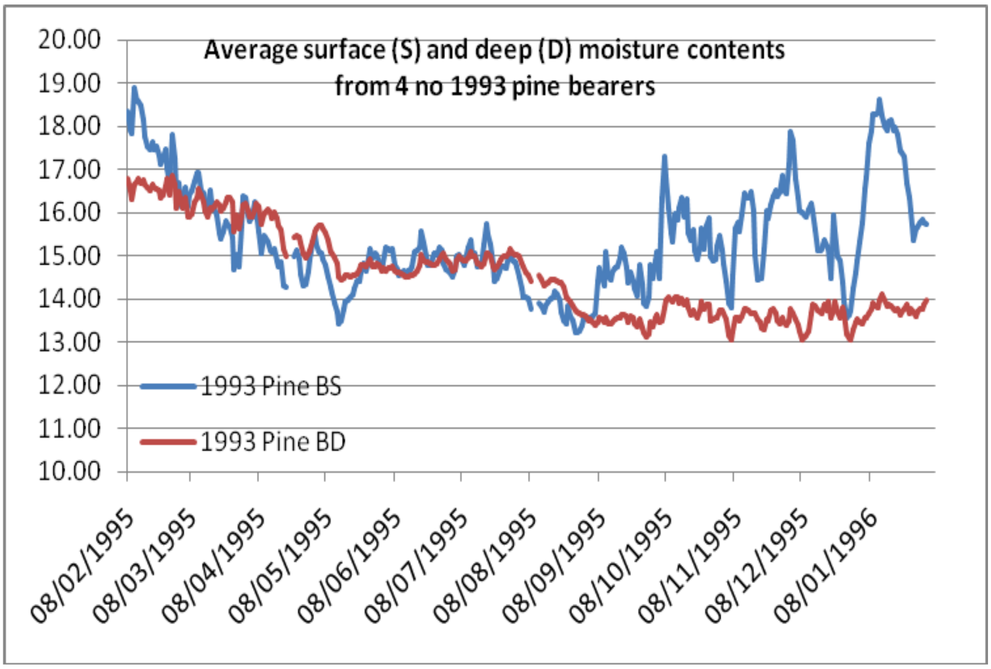
Graph 19 compares surface readings for modern oak and modern/old softwood. The modern oak has a higher moisture content than pine in summer when humidities are lower.

Graph 20 compares moisture contents at depth.

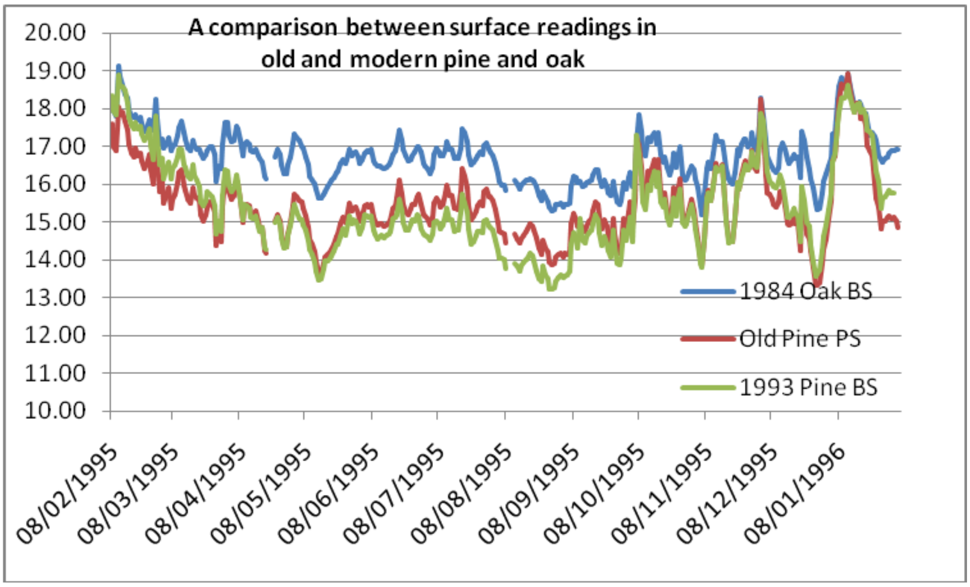
These results suggest that the old pine retained more moisture at depth.

Graph 21 compares modern pine with predicted moisture contents (based on humidity). It shows that wood moisture contents, surface and depth remain above those predicted during the summer months when humidities are low.

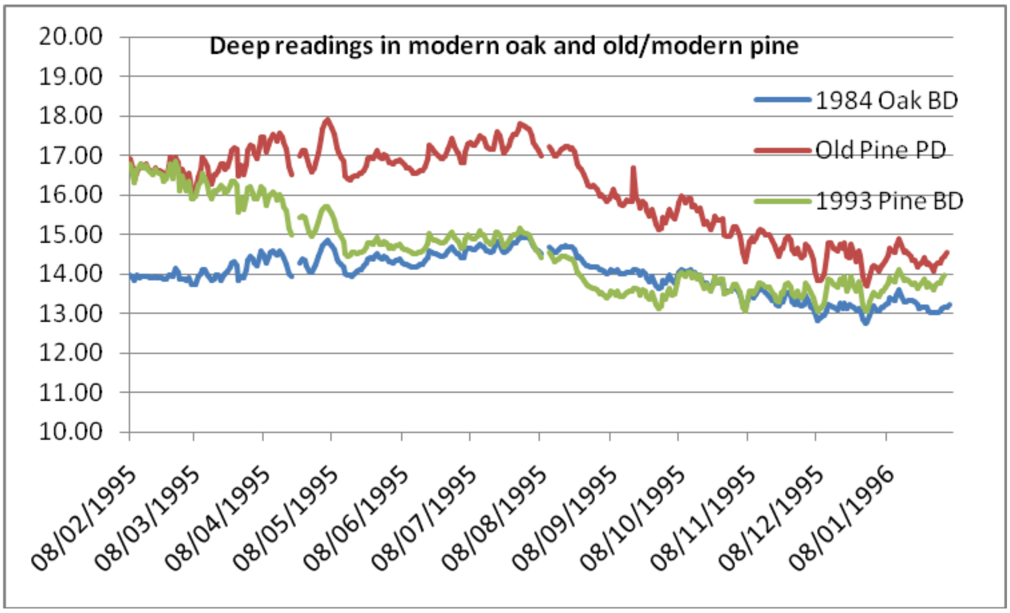
However surface readings increase in line with humidity increases as temperatures drop in winter and are much closer to predicted values. Deep readings remain rather consistent within a narrow range of moisture contents.



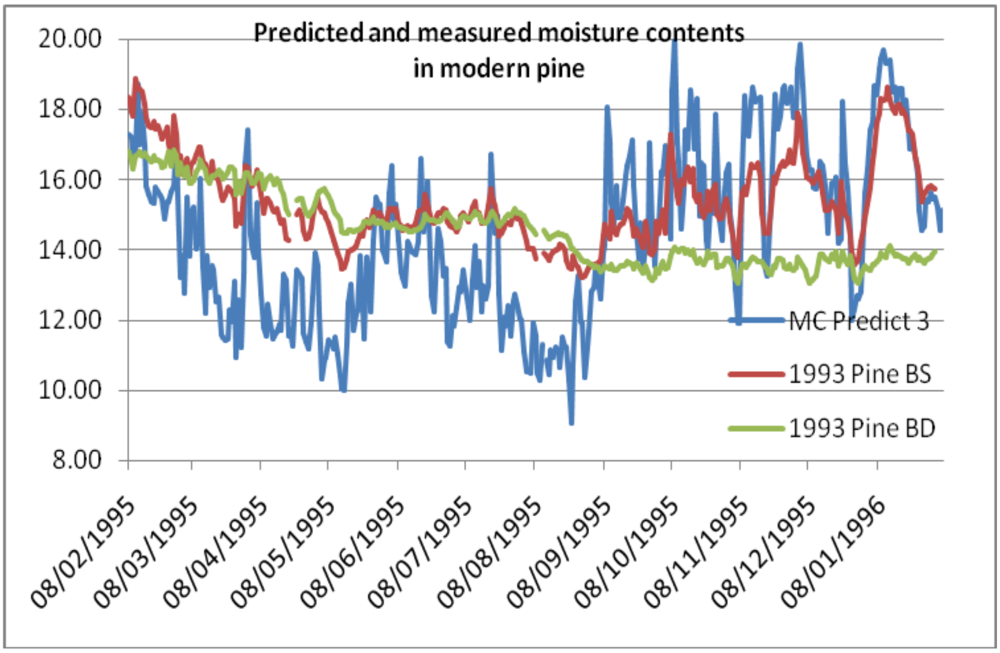

*Graph 18: Average surface and deep moisture content readings from 1993 pine bearers*




*Graph 19: Comparison of surface moisture content readings in old and modern pine and oak*




*Graph 20: Comparison of deep moisture content readings in modern oak and old and modern pine*




*Graph 21: Comparison of predicted and measured moisture contents in modern pine*

# 3) STUDY 2 – WINCHESTER CATHEDRAL NAVE ROOF

## 3.1 The Monitoring System

Sensors were installed mostly on 27th and 28th February 1995 and the system was completed on 1st March of that year.

Four MP100 relative humidity/temperature sensors were connected to a Campbell Scientific 21X data logger. These were installed in the following locations:

1. eaves on the N side of the roof space (temp/RH 1)
2. centre of roof at eaves level (temp/RH 2)
3. eaves on the S side (temp/RH 3)
4. apex of the roof space at eaves level (temp/RH 4)

None of these sensors functioned continuously and there are long periods of missing data.

Six temperature sensors (thermocouples) were also installed but, as at Lincoln, data from the deep sensors were unreliable and not used:

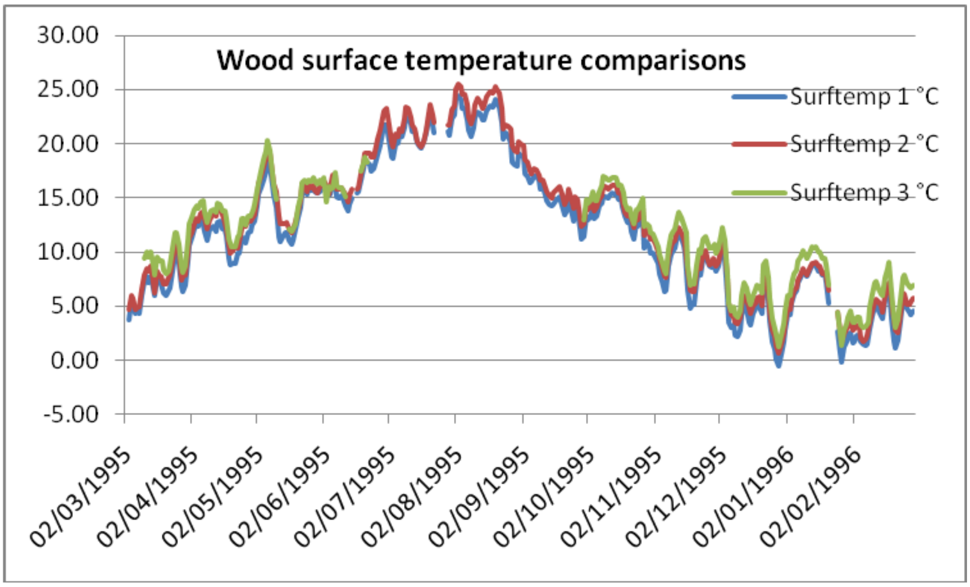
1. N eaves (Surftemp 1)
2. S eaves (Surftemp 2)
3. centre of roof space (Surftemp 3)

As at Lincoln, 64 resistance sensors were used for moisture monitoring. These were installed in 32 locations as surface and depth pairs. Each surface sensor consisted of two screws. The depth sensors were nails insulated with polythene tubing, except at the tips, and forced into pre-drilled holes to a depth of 100mm.

## 3.2 Results

### 3.2.1 Wood temperature comparisons

Graph 22 shows, as might be expected, that the S eaves (Surftemp 2) are the warmest during the summer months and timbers at the centre of the roof space (Surftemp 3) retain the highest temperature during the winter.

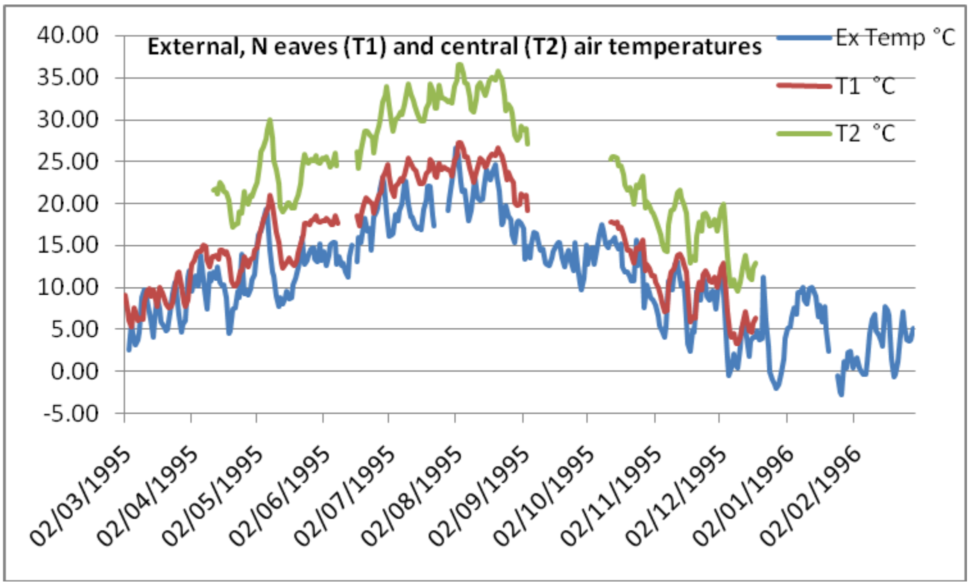



*Graph 22: Comparison of wood surface temperatures at the N eaves (Surftemp 1), S eaves (Surftemp 2) and centre (Surftemp 3) of the roof*

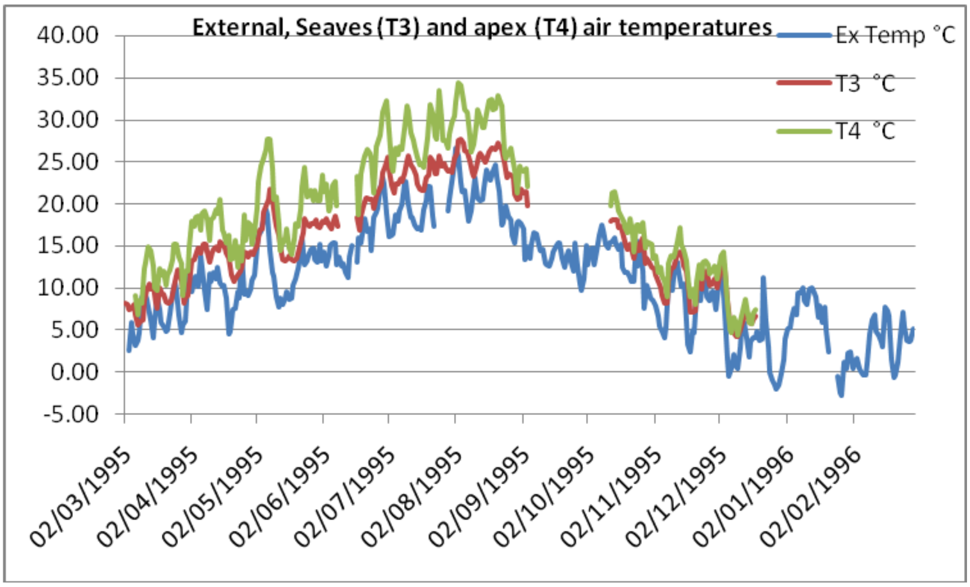
3.2.2 Wood and air temperatures compared with external temperature

The Nave roof at Winchester is huge. Graphs 23 and 24 show that the centre of the roof, at both ceiling and apex levels, is much warmer than the eaves and exterior during the summer months.

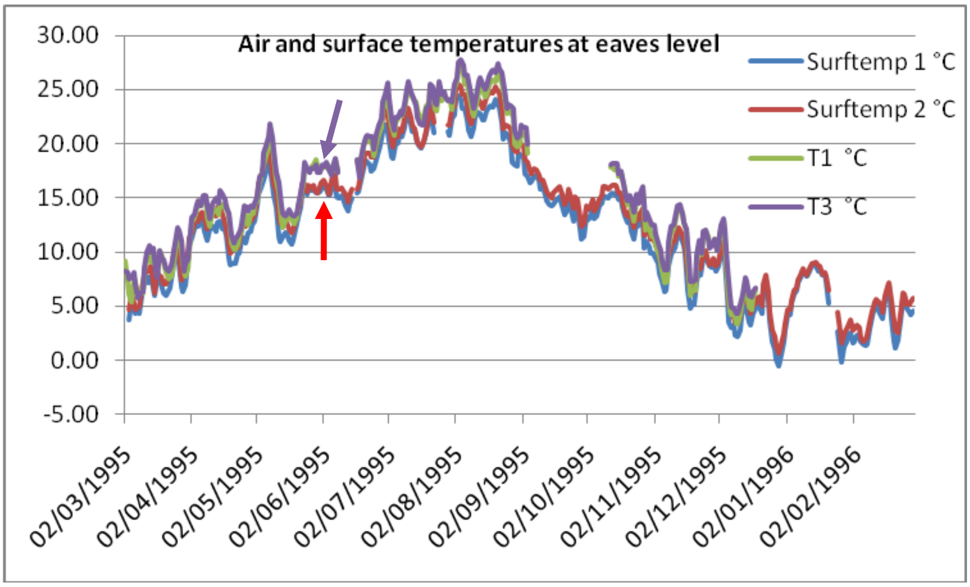
Graph 25 is a comparison between air and wood surface temperatures in the N eaves (T1 and Surftemp 1) and the S eaves (T3 and Surftemp 2). The air temperatures traces are now slightly higher than surface temperatures (arrows in Graph 25).




*Graph 23: Comparison of air temperatures from the centre of the roof at ceiling level, N eaves and exterior*




*Graph 24: Comparison of air temperatures from the apex, S eaves and exterior*




*Graph 25: Comparison of air and wood surface temperatures in the N eaves (T1 and Surftemp 1) and the S eaves (T3 and Surftemp 2)*

### 3.2.3 Timber moisture contents

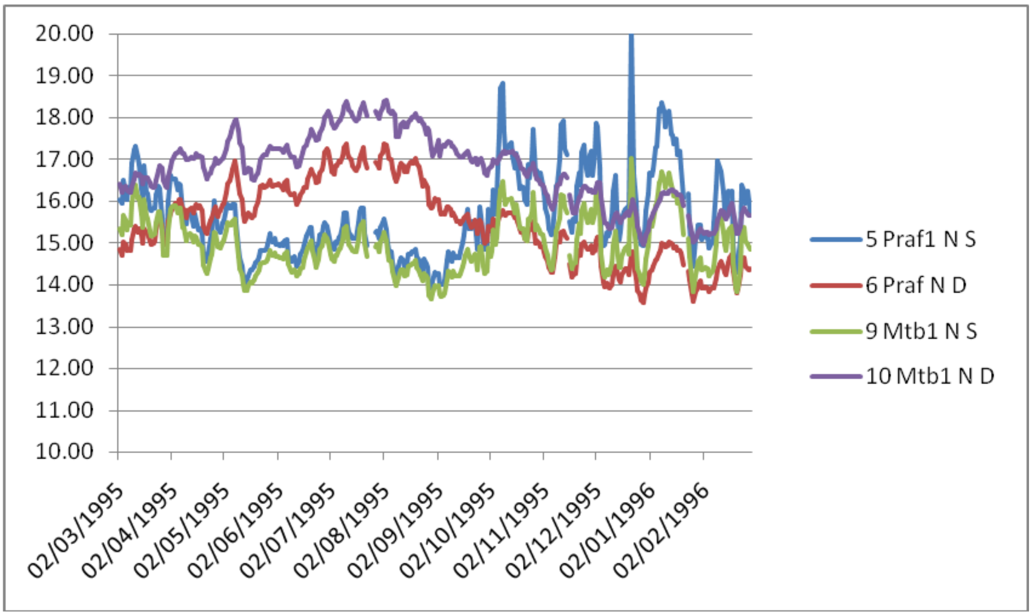
The roofs at Lincoln Cathedral were rather small and contained timbers of different ages and species. It was therefore convenient to average the results from the various groups. In contrast, the Nave roof at Winchester is vast and predominantly oak, which is either original (late 14th century) or of some later but still ancient period.

We have therefore categorised the following results into medieval or old (identified by the clerk of the works at the time) and location. There were also a few modern oak and softwood timbers to provide data for comparison.

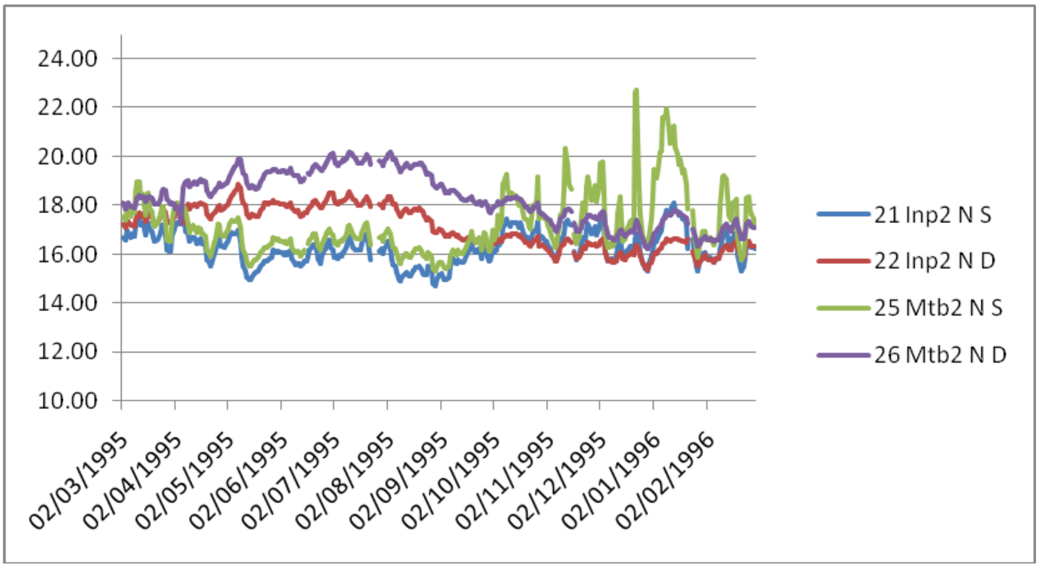
#### a) Medieval: N eaves

Deep moisture contents are higher than surface moisture contents during the summer months. The surface tie beam and principal rafter moisture contents become much more erratic in winter (Graphs 26 and 27).

*Key: Praf1 N = Principal rafter 1 at N eaves, shallow (S) or deep (D)*
*Mtb 1 N = Mid line of tie beam at N eaves*
*Mtb2 N = Mid line of tie beam 2 at N eaves*
*Inp2 N = Inner plate at the same location*




*Graph 26: Surface and deep moisture content readings from timbers at N eaves*

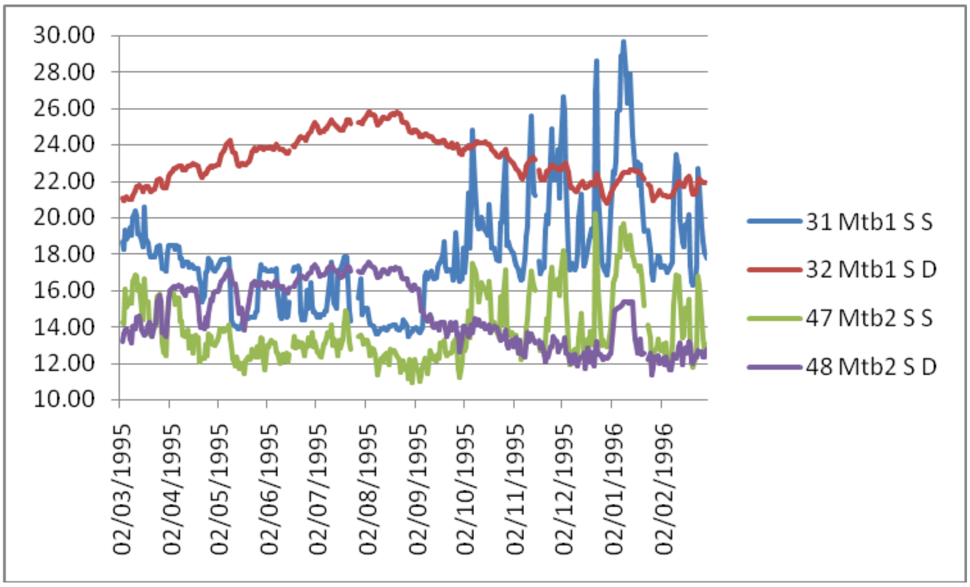



*Graph 27: Surface and deep moisture content readings from timbers at N eaves*

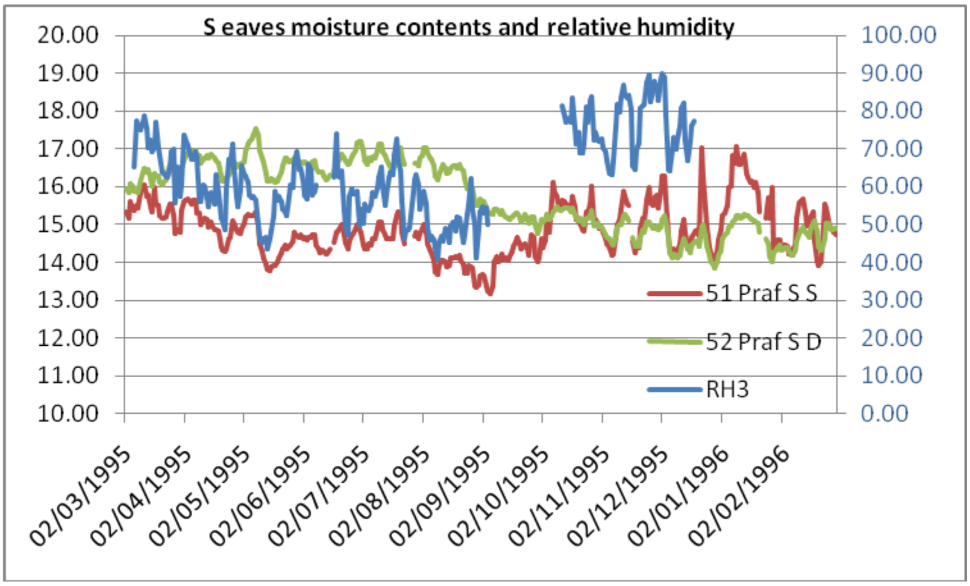
b) Medieval: S eaves

Tie beam 1 behaves much more erratically than tie beam 2 (Graph 28) and the higher deep moisture content (green) suggests that the wall below is wet – perhaps because of a faulty parapet gutter. Graph 29 shows the moisture variation in the principle rafter compared with relative humidity. Equilibrium moisture responses are greater at higher humidities.

*Key: Mtb 1 and 2 S = Mid line of tie beams 1 and 2, S eaves*
*Praf S = Principal rafter at S eaves*




*Graph 28: Surface and deep moisture content readings from tie beams at S eaves*

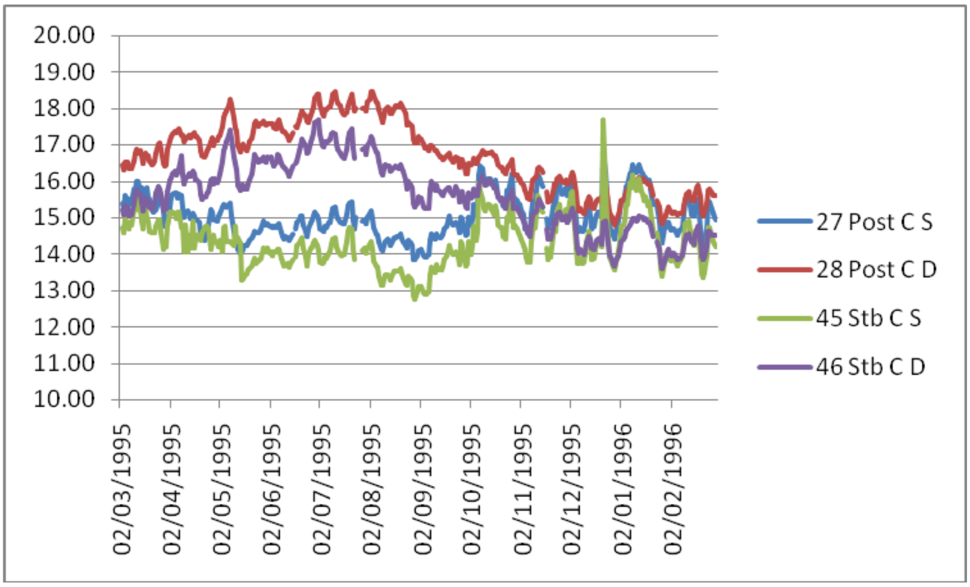



*Graph 29: Surface and deep moisture content readings from principal rafter compared with relative humidity at S eaves*

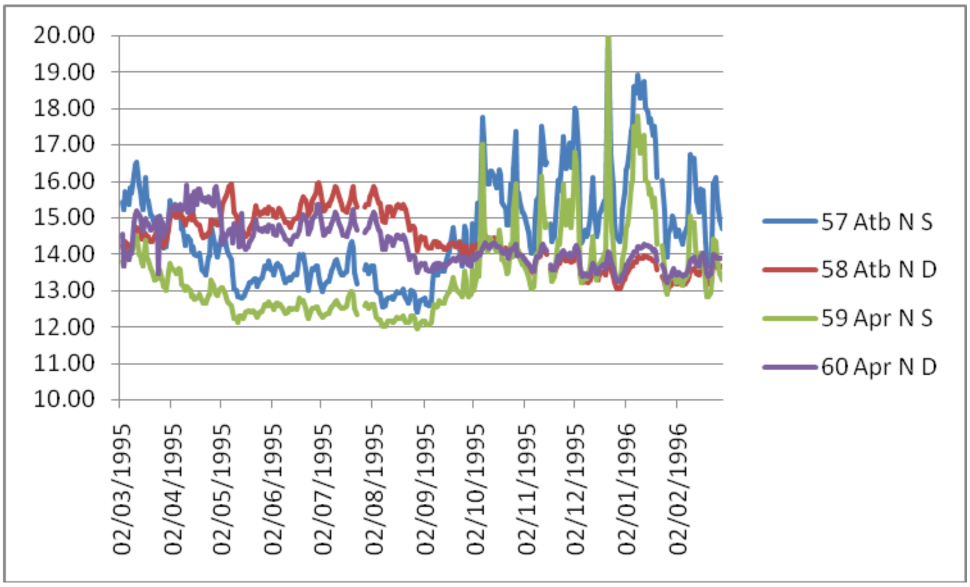
c) Medieval: Central

Graph 30 suggests that timbers in the centre of the roof at floor level have higher deep moisture contents during the winter than timbers at the apex (Graph 31). However timbers at the apex are more variable during the winter and this is in response to variable relative humidity (Graph 32). All of the timbers remain dry. The reason for this variability will be discussed in section 7.

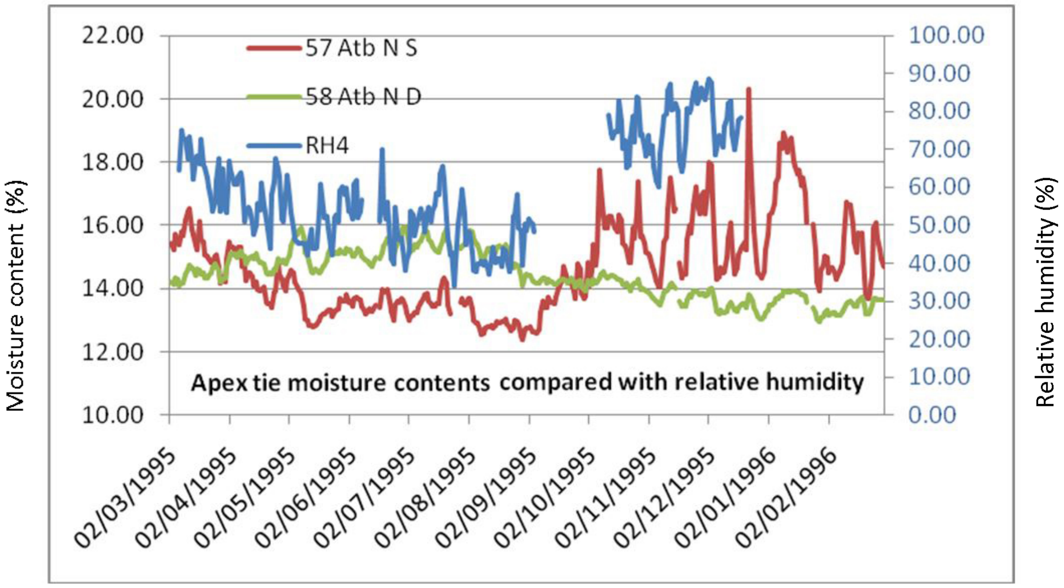
*Key: Post C = Post at centre of roof space*
*Stb C = Second height tie at centre of roof*
*Atb N = North side of upper tie at apex*
*Apr N = North side of principal rafter at apex*




*Graph 30: Surface and deep moisture content readings from timbers in the centre of the roof*




*Graph 31: Surface and deep moisture content readings from timbers of the roof*

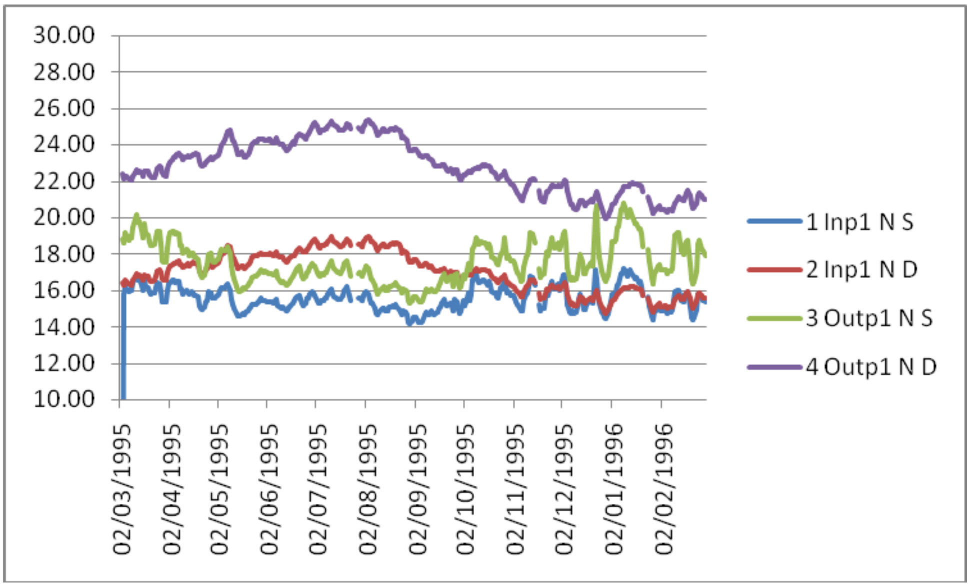



*Graph 32: Surface and deep moisture content readings at the apex compared with relative humidity*

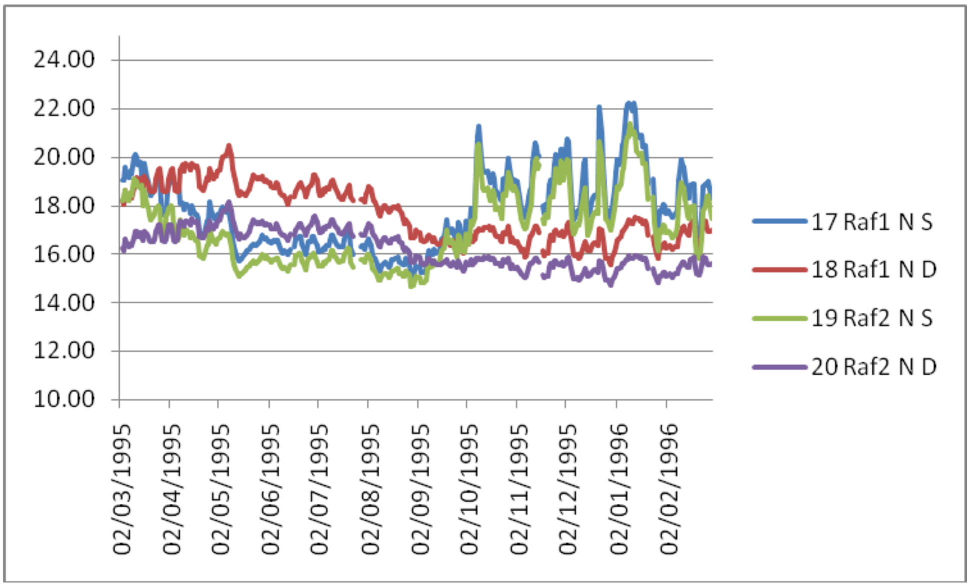
d) Old: North eaves

Graph 33 shows that the outer plate is wet at depth (purple). Graph 34 shows that the rafter is a little damper at depth nearest to the plate, however the timber remains essentially dry.

*Key: Inp = Inner plate*
*Outp = Outer plate*
*Raf1 = Rafter near plate and in side close to lead*
*Raf2= Rafter close to lead at 4 feet above plate*




*Graph 33: Surface and deep moisture content readings from inner and outer plates at N eaves*

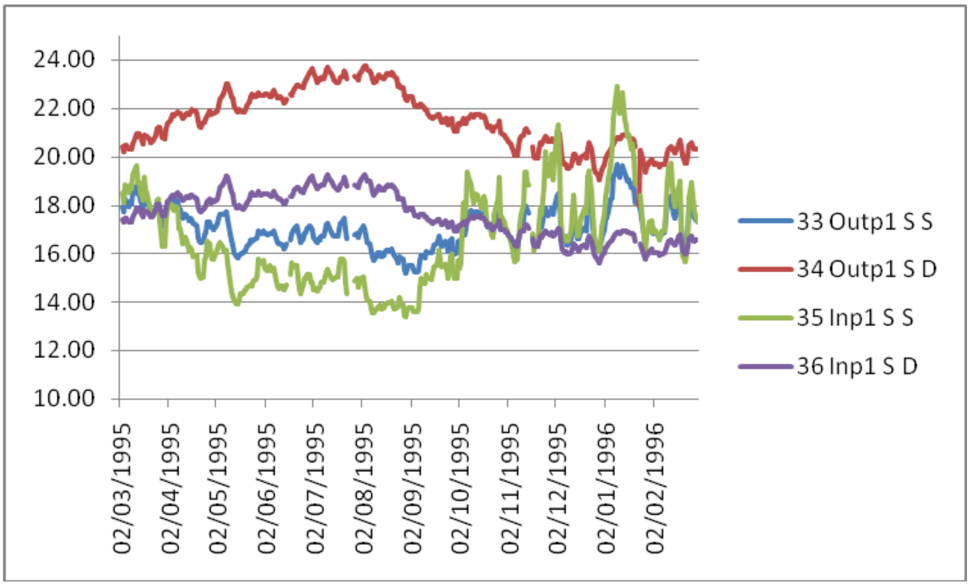



*Graph 34: Surface and deep moisture content readings from rafters at N eaves*

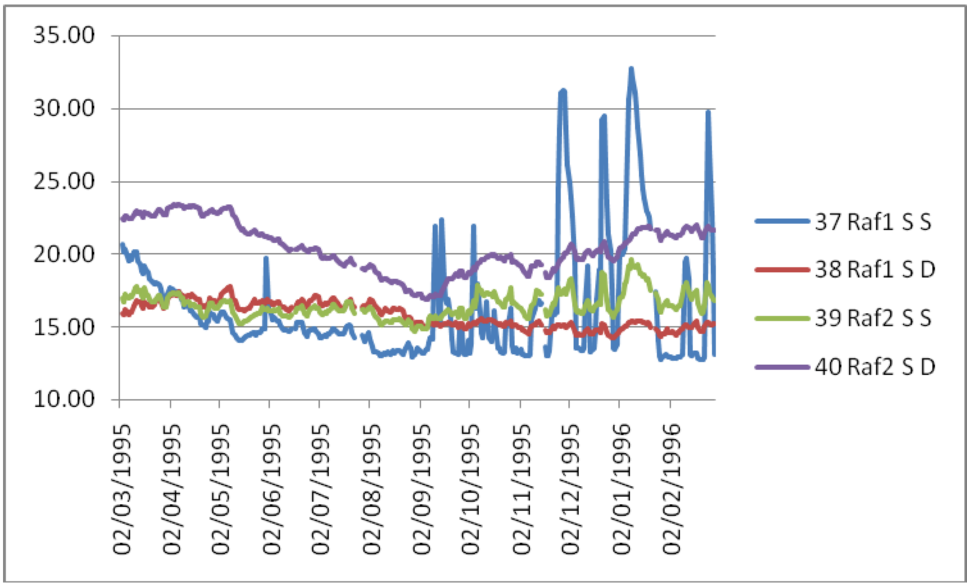
e) Old: South eaves

Graphs 35 and 37 show that the outer plate is wet at depth (red). Graph 36 shows a rafter that is damper nearer to the plate, but also very responsive to humidity variation higher up in winter.

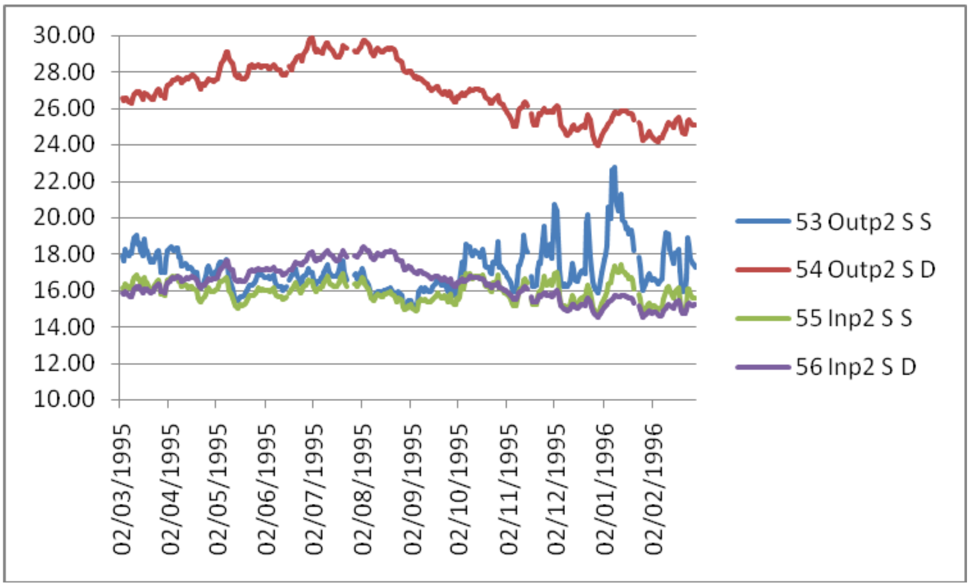
*Key: Outp 1 = Outer plate 1*
*Inp 1 = Inner plate 1*
*Raf 1 = Rafter, near lead and 4 feet above plate*
*Raf 2 = Rafter, near lead and near plate*
*Outp = Outer plate*
*Inp = Inner plate*




*Graph 35: Surface and deep moisture content readings from the outer and inner plates at S eaves*




*Graph 36: Surface and deep moisture content readings from the rafters at S eaves*

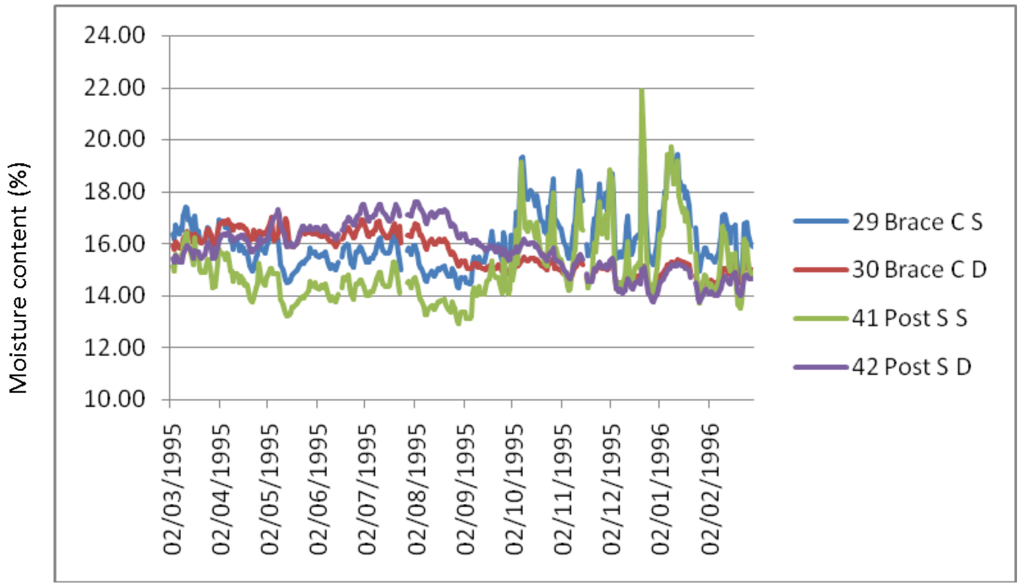



*Graph 37: Surface and deep moisture contents readings from the outer and inner plates at S eaves*

f) Old: Central

Timbers are dry, but Graph 38 shows the now familiar response of variable moisture content in winter.

*Key: Brace = central brace*
*Post = central post S side*

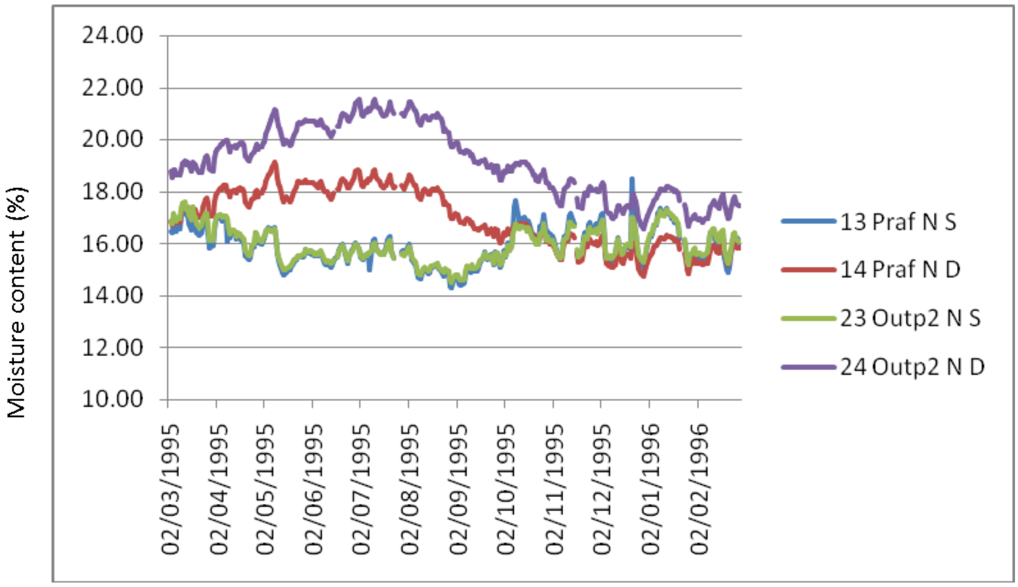



*Graph 38: Surface and deep moisture content readings in the central brace and central post*

g) New oak: North eaves

Graph 39 shows that the outer plate is damp at depth.

*Key: Praf = Principal rafter*
*Outp = Outer plate*

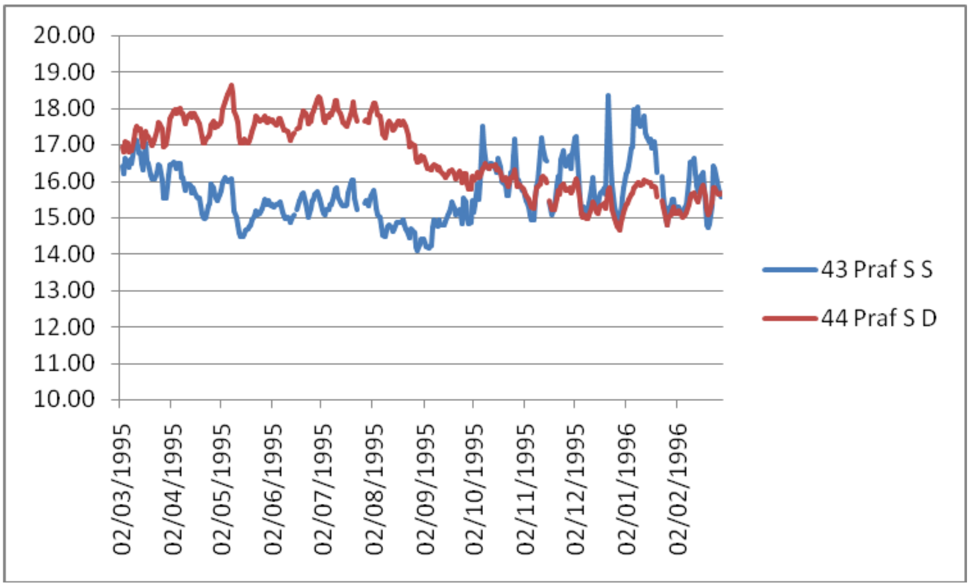



*Graph 39: Surface and deep moisture content readings from the principal rafter and outer plate at N eaves*

h) New oak: South eaves

Graph 40 shows the familiar effect of higher moisture contents at depth in the summer and more erratic and frequently damper surface moisture contents during the winter months.

*Key: Praf = Principal rafter*

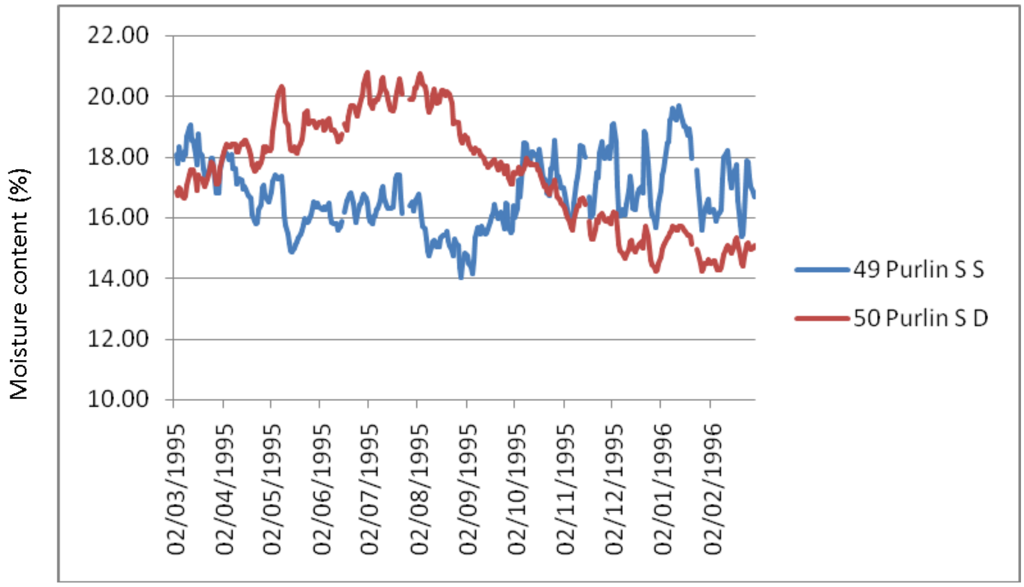



*Graph 40: Surface and deep moisture content readings in the new oak principal rafter at S eaves*

i) New softwood: S eaves

The softwood trace in Graph 41 is similar to the new oak trace in Graph 40, except that deep readings in summer are a little higher.

*Key: 49 Purlin S S = Purlin South eaves surface*
*50 Purlin S D = Purlin South eaves depth*




*Graph 41: Surface and deep moisture content readings from new softwood purlin at S eaves*

# 4) STUDY 3 – ST JOHN'S CHURCH, BISHOPSTONE, NAVE AND CHANCEL ROOFS

This is a small church dating from the 13th century in the village of Bishopstone near Salisbury.

## 4.1 The Monitoring System

Sensors were installed mostly on 2nd and 3rd April 1996 but the system was not completed until 7th May of that year.

Four MP100 relative humidity/temperature sensors were connected to a Campbell Scientific 21X data logger:

1. Chancel – N eaves (temp/RH 1)
2. Chancel – high level (temp/RH 2)
3. Nave – high level (temp/RH 3)
4. Nave – N eaves (temp/RH 4)

Six temperature sensors (thermocouples) were also installed. Only the three surface readings are used in this study because the attempt to obtain deep readings was unsuccessful. The surface sensors were installed in the following locations:

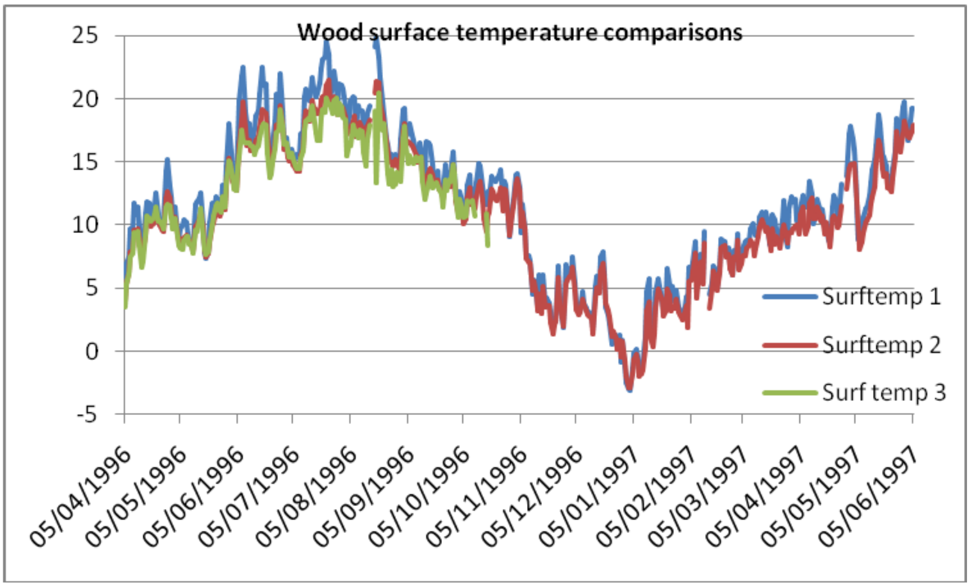
1. Nave – high level (Surftemp 1)
2. Nave – N eaves (Surftemp 2)
3. Chancel – N eaves (Suftemp 3)

50 moisture content sensors were installed in shallow and deep pairs. 24 were in the Nave roof and 26 in the Chancel roof. All of the timbers appeared to be medieval.

## 4.2 Results

### 4.2.1 Wood temperature comparisons

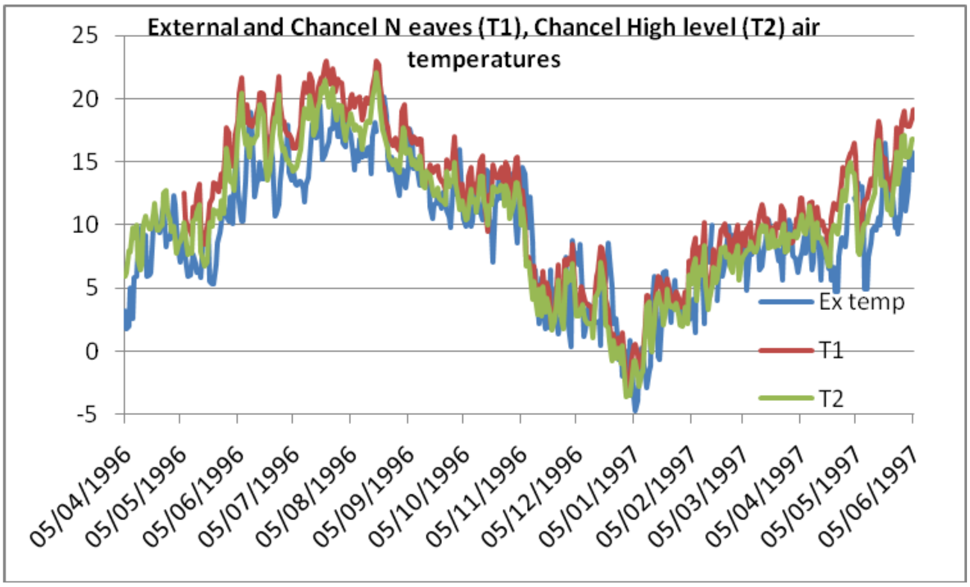
Graph 42 shows that Surftemp 3 (Chancel – N eaves) failed at the end of October. There are no major differences between the monitoring locations. The Nave at high level has the highest surface temperature.



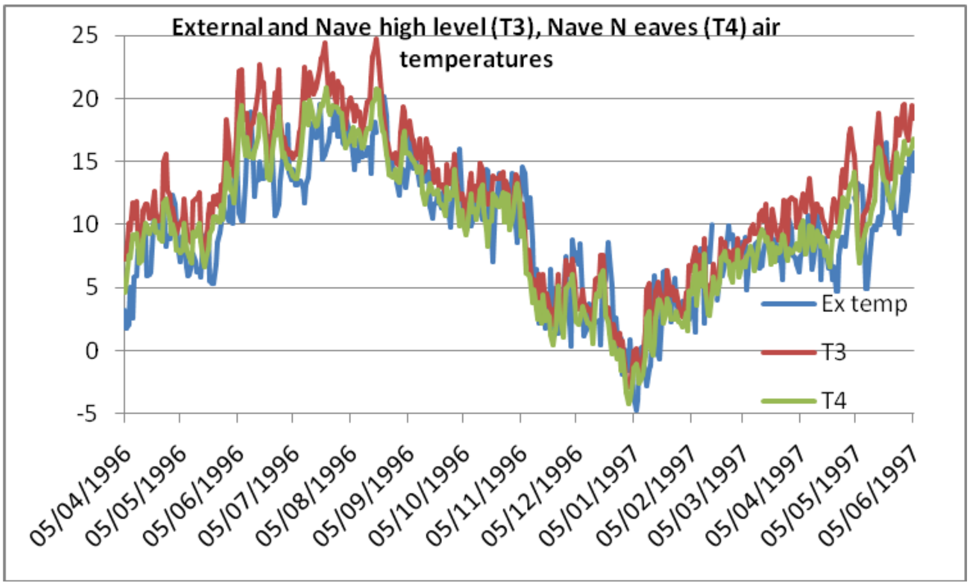

*Graph 42: Comparison of wood surface temperatures at N eaves in Chancel*

4.2.2 Interior air temperatures compared with external temperature

Graphs 43 and 44 show that the external temperature is generally the lowest.




*Graph 43: External and internal air temperatures in the Chancel*




*Graph 44: External and internal air temperatures in the Nave*

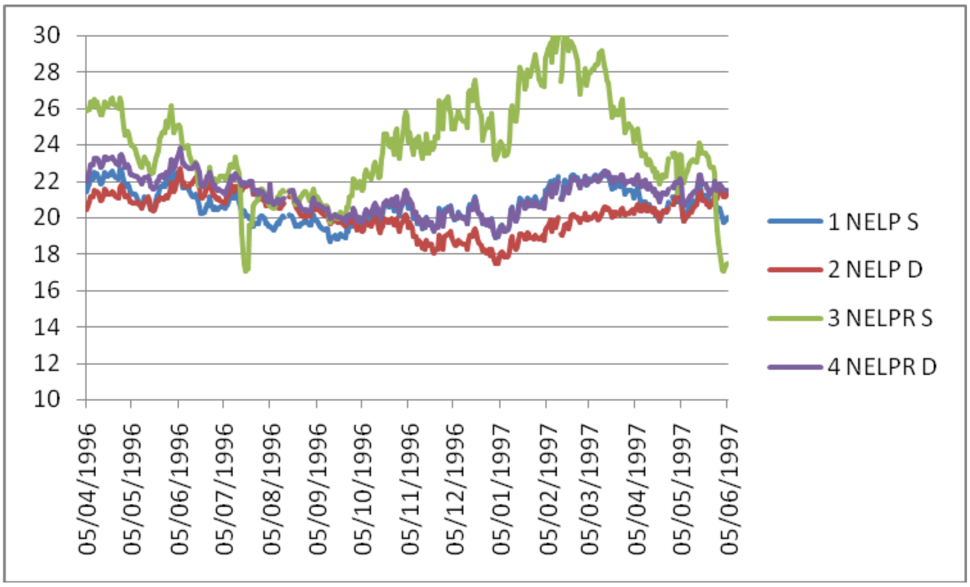
### 4.2.3 Timber moisture contents

As with Case Study 2 the focus here is on different orientations and components because all of the timber appeared to be of a similar age.

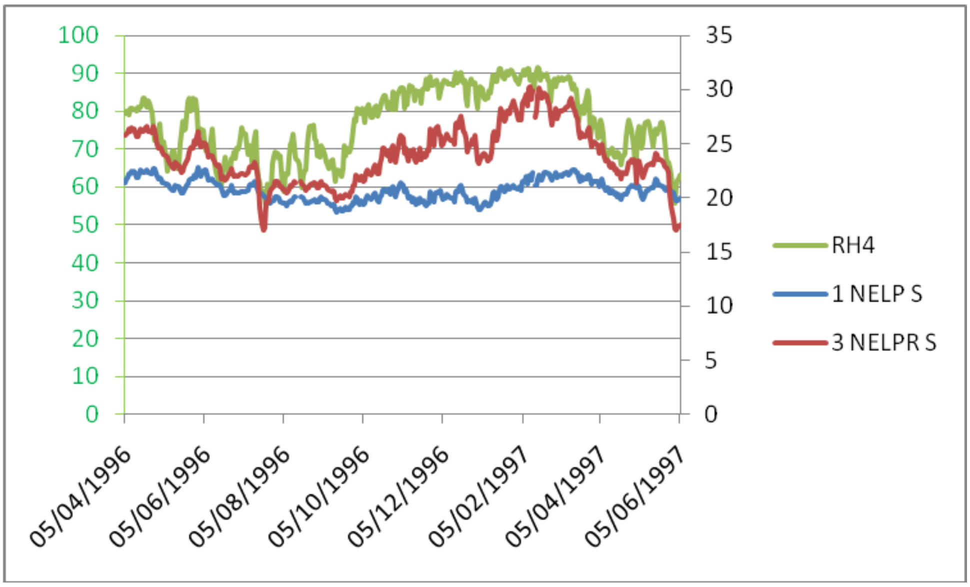
a) Nave: North side eaves level

The surface of the principal rafter seems to be particularly susceptible to humidity change and is wet (Graph 45). The response to humidity is demonstrated in Graph 46, where the humidity at eaves level is compared with moisture contents in the plate and rafter.

*Key: NELP = N eaves low level plate*
*NELPR = N eaves low level principal rafter*




*Graph 45: Surface and deep moisture content readings from timbers at N eaves in Nave*

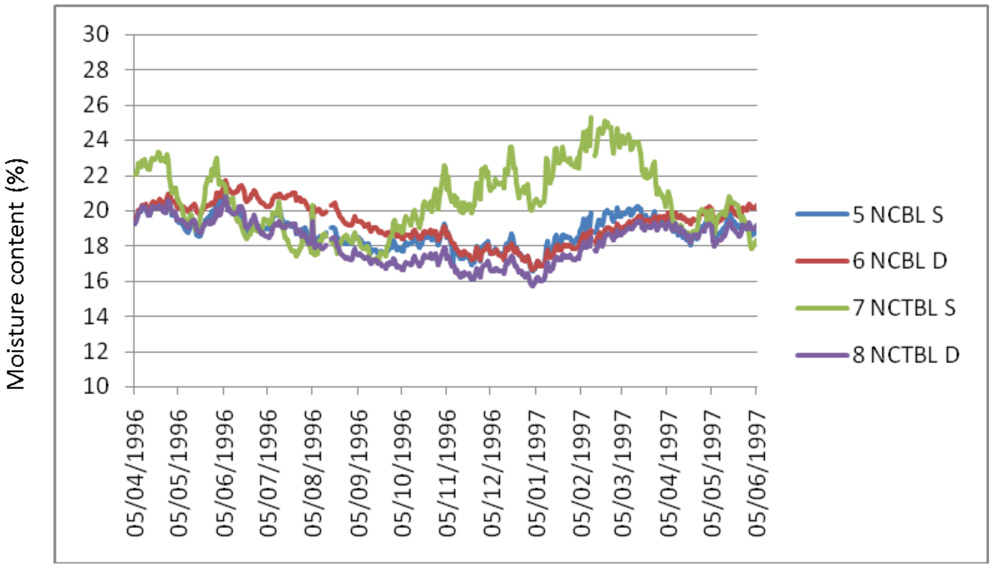



*Graph 46: Surface moisture content readings from plate and rafter at N eaves compared with relative humidity*

b) Nave: Centre ceiling level

Unfortunately, it is not possible after 20 years to ascertain the precise location of these timbers. Nevertheless, Graph 47 shows that the central beam (5, 6) had a similar moisture content at its surface and at depth. The surface of the tie beam was much more erratic, but at depth it was within the range of the other two.

*Key: NCBL = Nave central beam low level*
*NCTBL = Nave central tie beam low level*
*S = Surface*
*D = Depth*

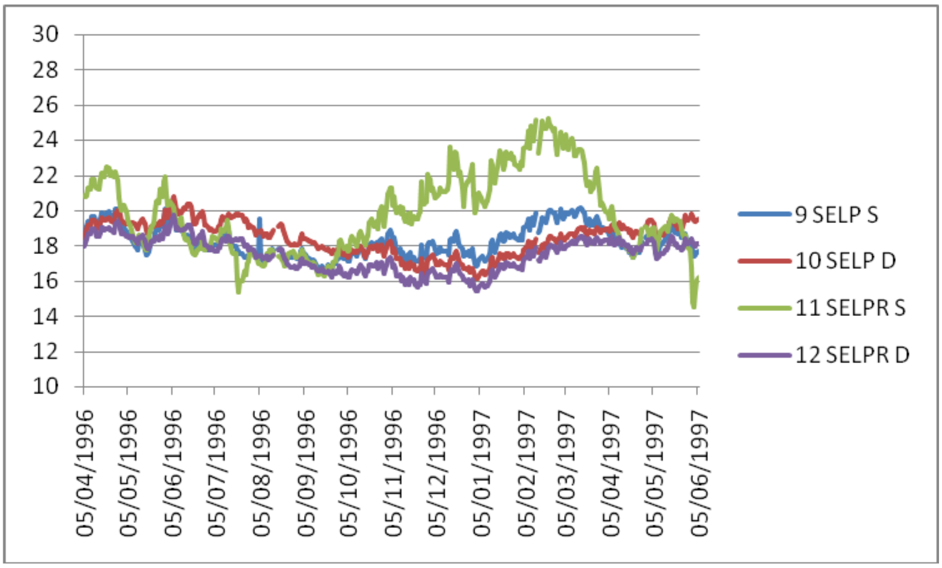



*Graph 47: Surface and deep moisture content readings from the Nave central beam and tie beam*

c) Nave: South side eaves level

Graph 48 is similar to Graph 47.

*Key: SELP = S eaves level plate*
*SELPR = S eaves level principal rafter*



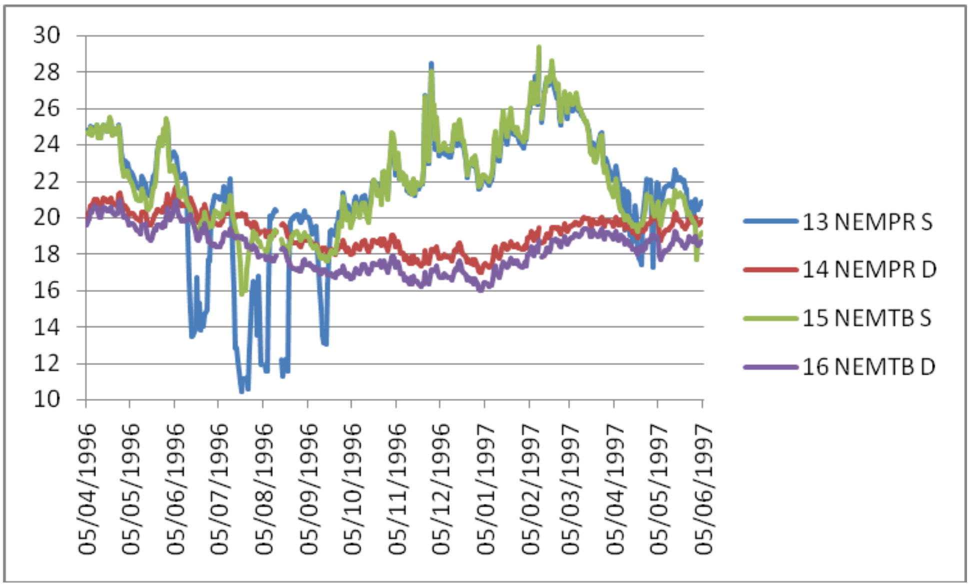

*Graph 48: Surface and deep moisture content readings from plate and principal rafter at S eaves*

d) Nave: North side mid-height

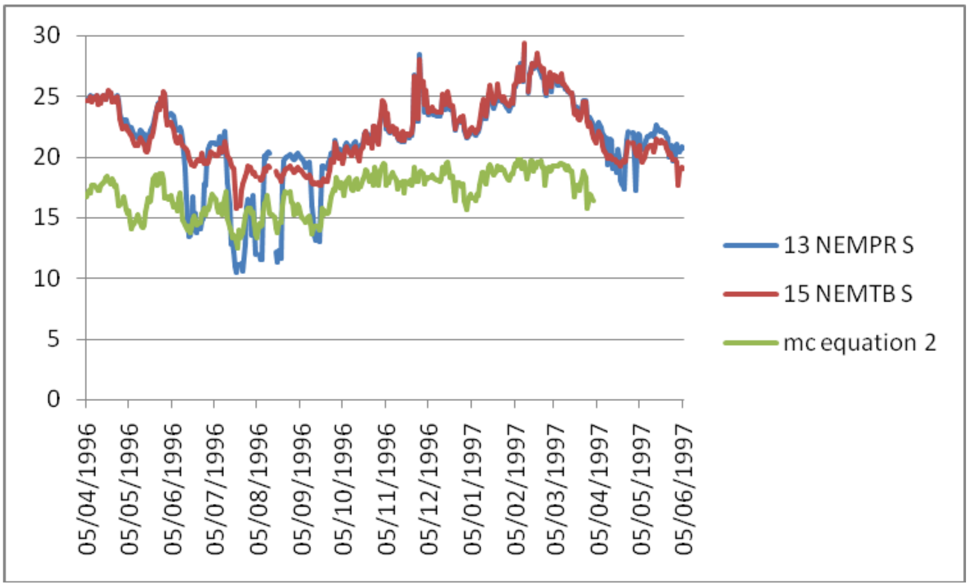
Surface readings shown in Graph 49 seem particularly responsive to humidity fluctuations, particularly the principal rafter (13) which responds to low humidities.

The responses of 13 and 15 are demonstrated in Graph 50 by comparing the peaks and troughs with the calculated equilibrium moisture content from the Hailwood Horrobin equation (MC Equation 2), which predicts the erratic lower summer values for 13 but considerably underestimates the winter surface moisture readings for both 13 and 15 shown in Graph 46. This seems to be because surface changes in the timber over time make it more responsive to humidity fluctuations than the equilibrium model predicts, but the difference may also be compounded by increasing inaccuracies with meter readings over about 18%.

*Key: NEMPR = N eaves [side] mid height principal rafter*
*NEMTB = N eaves [side] mid height tie beam*




*Graph 49: Surface and deep moisture content readings from principal rafter and tie beam at N eaves*

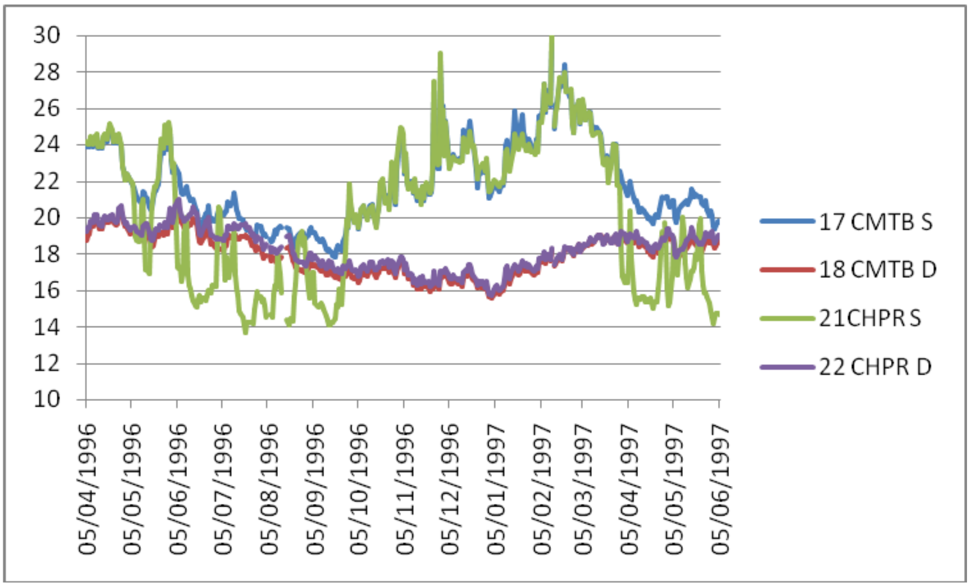



*Graph 50: Surface and deep moisture content readings from tie beam and principal rafter at N eaves compared with calculated equilibrium moisture content using the Hailwood Horrobin equation (Equation 2)*

e) Nave: Central

The principal rafter (green trace on the graph) is equilibrating with erratic lower summer humidities shown in Graph 46.

*Key: CMTB = Central mid-level tie*
*CHPR = Central high principal rafter*

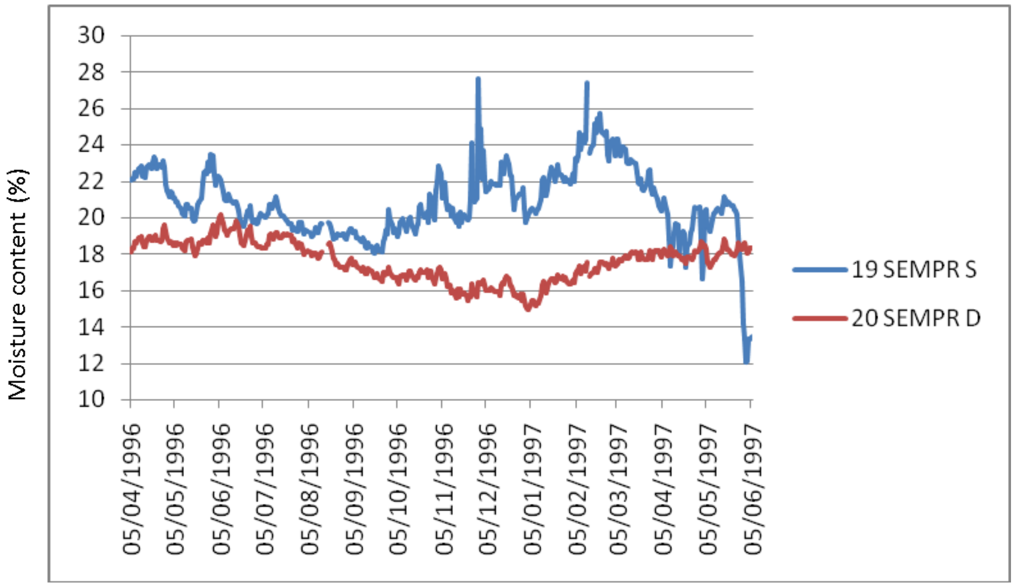



*Graph 51: Surface and deep moisture content readings from tie beam and principal rafter*

f) Nave: South side mid-height

Summer moisture fluctuations are similar at the surface and at depth, but the surface moisture content increases with the rise in winter relative humidity while the moisture content at depth drops a little.

*Key: SEMPR = S eaves mid-height principal rafter*

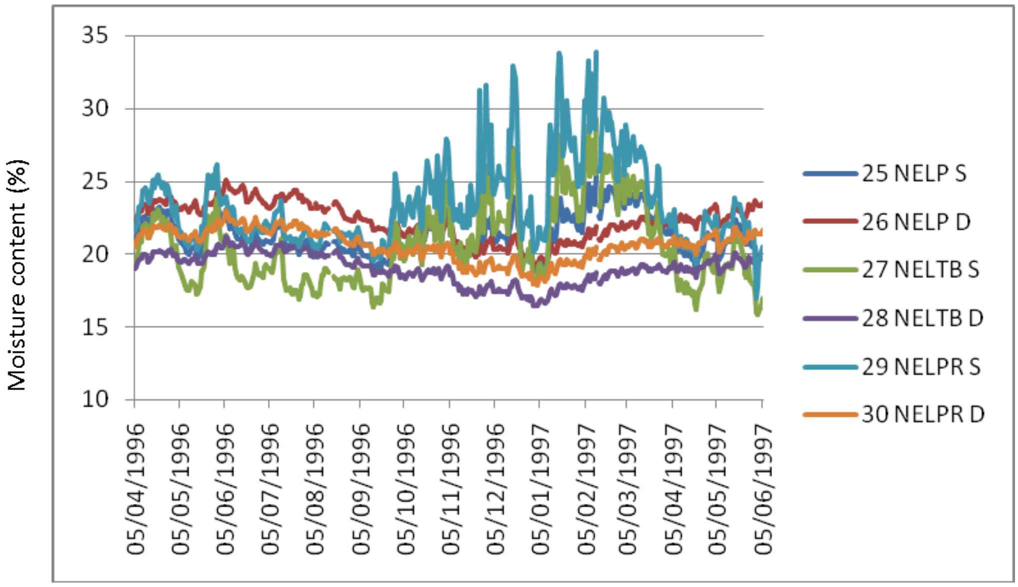



*Graph 52: Surface and deep moisture content readings from the principal rafter at mid height in the S eaves*

g) Chancel: North eaves low level

Surfaces equilibrate rapidly at high humidities. The elevated deep readings show that the eaves are damp (Graph 53).

*Key: NELP = N eaves low level plate*
*NELTB = N eaves low level tie beam*
*NELPR = N eaves low level principal rafter*

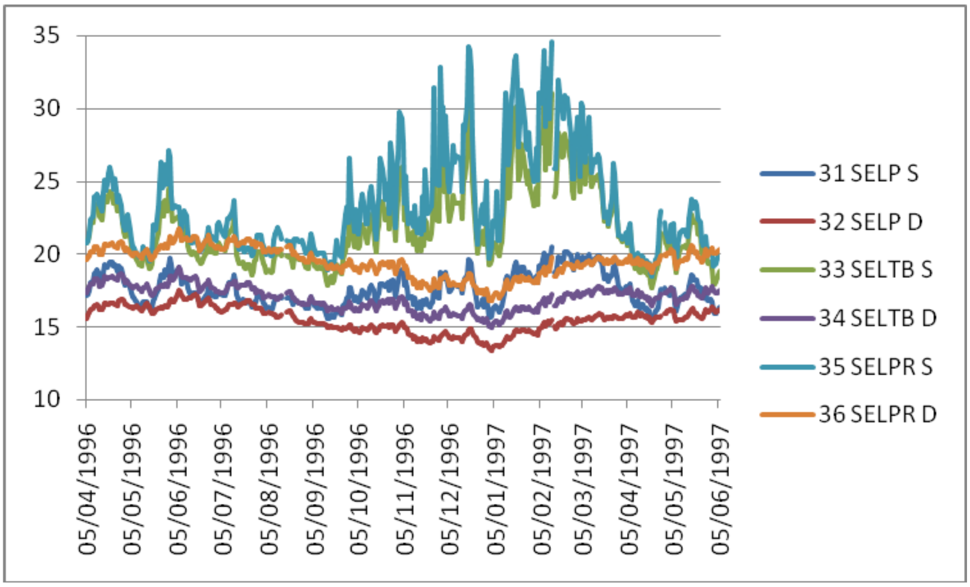



*Graph 53: Surface and deep moisture content readings from plate, tie beam and principal rafter at N eaves*

h) Chancel: South eaves low level

Moisture distribution in the S eaves (Graph 54) is similar to the N eaves (Graph 53).

*Key: SELP = S eaves low level plate*
*SELTB = S eaves low level tie beam*
*SELPR = S eaves low level principal rafter*

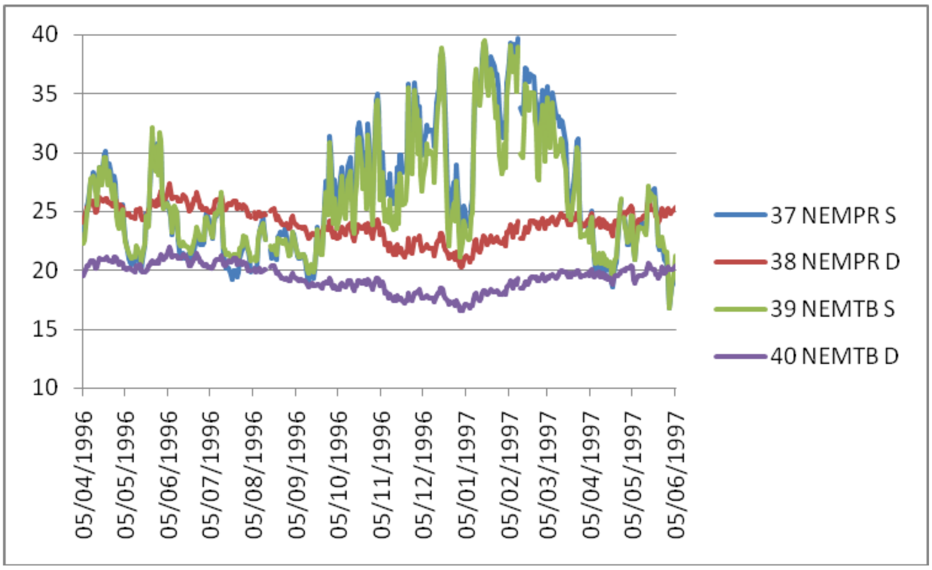



*Graph 54: Surface and deep moisture content readings from plate, tie beam and principal rafter at S eaves*

i) Chancel: North eaves mid-level

The chancel is damp and surface readings react strongly to high humidities (Graph 55).

*Key: NEMPR = N eaves mid height principal rafter*
*NEMTB = N eaves mid height tie*

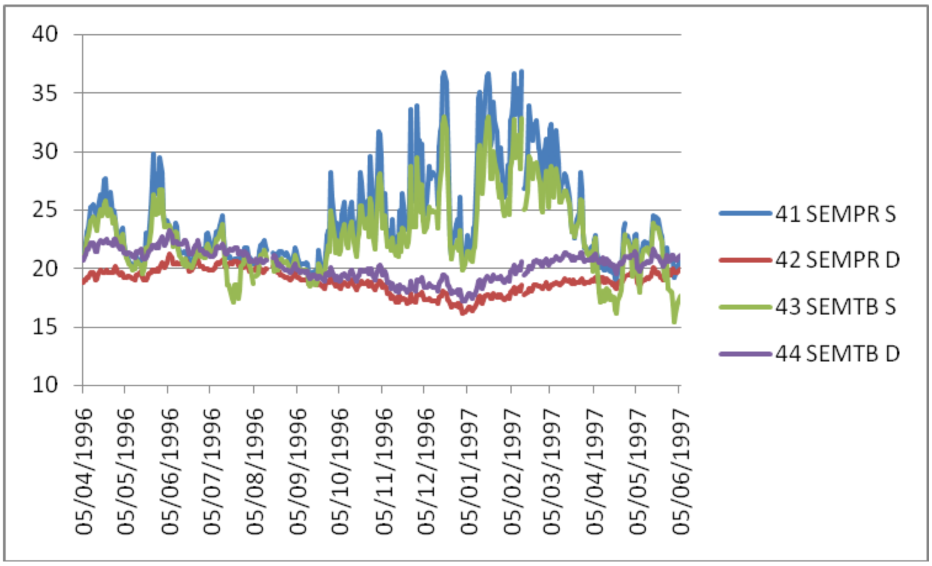



*Graph 55: Surface and deep moisture content readings from tie beam and principal rafter at mid height N eaves*

j) Chancel: South eaves mid-level

Moisture distribution in the S eaves (Graph 56) is similar to the N eaves (Graph 55).

*Key: SEMPR = S eaves mid height principal rafter*
*SEMTB = S eaves mid height tie*

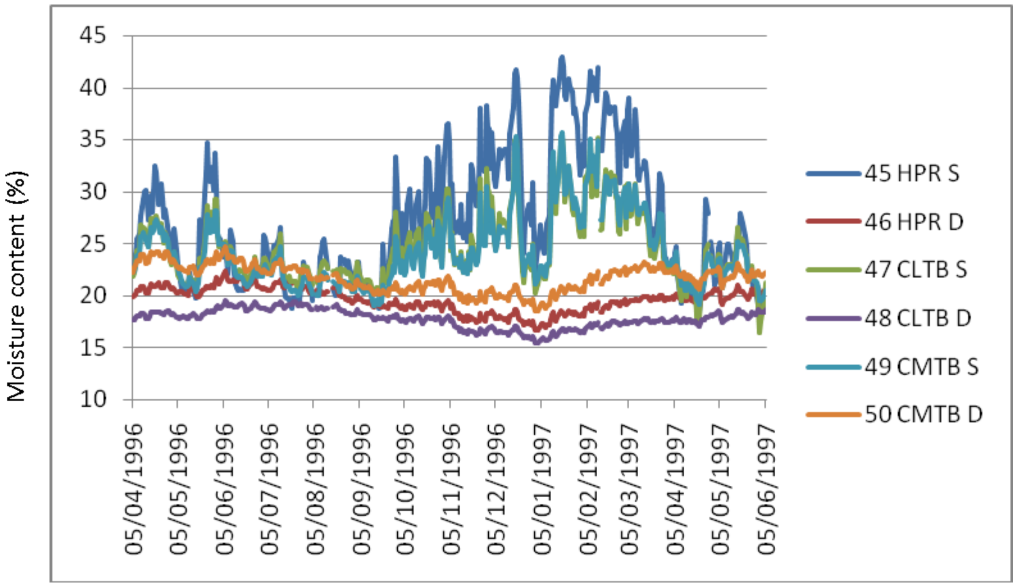



*Graph 56: Surface and deep moisture content readings from tie beam and principal rafter at mid height S eaves*

k) Chancel: Centre

The chancel is humid with very high surface and deep readings. Surface equilibrium moisture contents, and presumably humidity, increase with height (Graph 57).

*Key: HPR = High level principal rafter*
*CLTB = Centre low level tie beam*
*CLMB = Centre mid-level tie*




*Graph 57: Surface and deep moisture content principal rafter, tie beam and mid-level tie*

# 5) VARIATIONS IN MOISTURE CONTENT WITH AGE

We now have a large number of timber moisture contents from different timbers of various ages. A direct comparison is difficult, but the Hailwood Horrobin equation provides a calculated moisture content based on relative humidity and is therefore independent of any age effects. This produces a useful baseline from which to make comparisons.

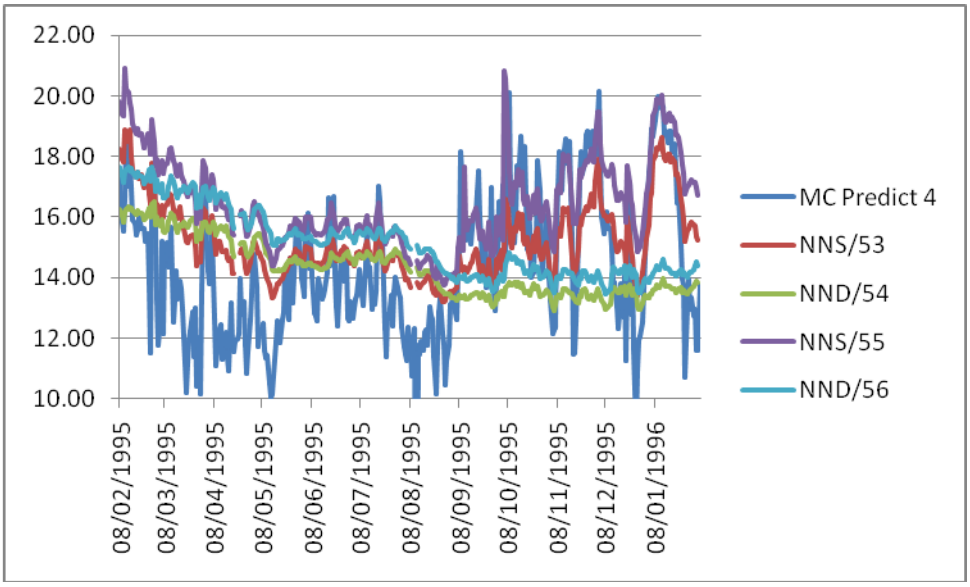
## 5.1 Modern softwood

The Hailwood Horrobin equation was derived from modern softwood. There is not much of this material in our data set, but it makes a starting point to see how well the equation might be expected to predict moisture fluctuations. Also, the calibration of the sensors is obtained from electrical resistance and the results may vary a little between the two models. It must also be remembered that the relative humidity readings, from which the predicted moisture contents are obtained, are daily averages and the relationship between these and hourly surface moisture measurements may be variable. An exact correspondence between predicted and recorded moisture contents cannot, therefore, be expected.

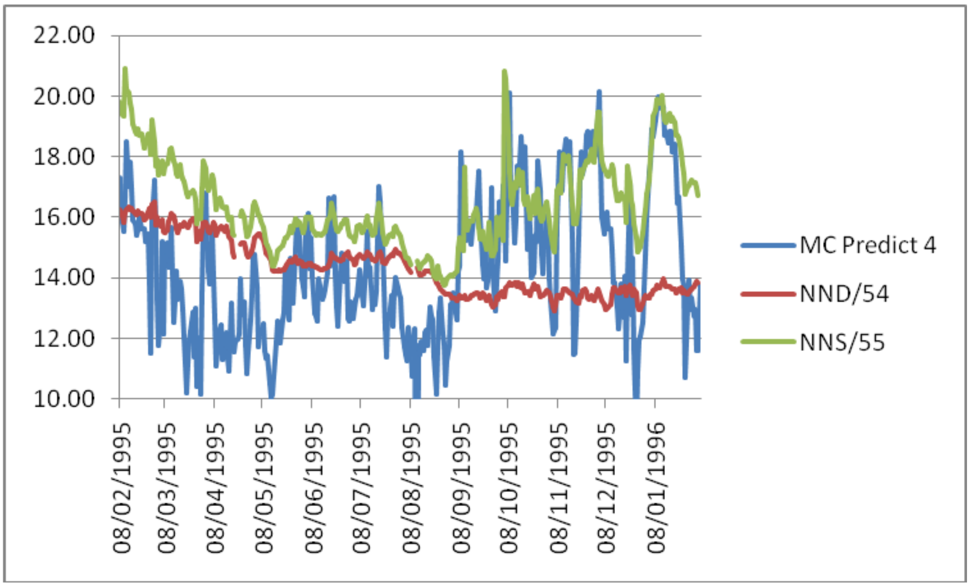
a) Lincoln – Modern softwood (1993)

Graph 58 shows moisture contents from two modern softwood bearers on the N side of the Consistory Court roof at Lincoln Cathedral and compares them with the predicted moisture content calculated from adjacent relative humidity readings using the Hailwood Horrobin equation.

Graph 59 simplifies the graph by just using data from NND/ 54 and 55. The graph shows that the equation reasonably predicts higher (damp) surface moisture content levels and fluctuations in winter, but the timber seems to be slower to dry in summer when humidities are lower and do not decline to the predicted values (very dry).




*Graph 58: Lincoln Cathedral: Surface and deep moisture content readings from modern softwood compared with predicted moisture content*

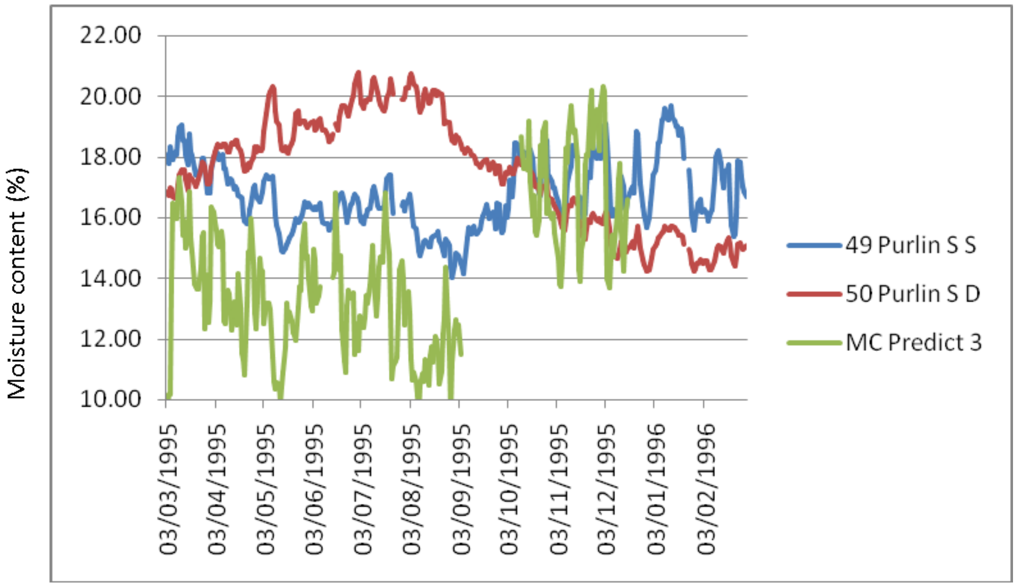



*Graph 59: A simplified representation of the data from NND/ 54 and 55 in Graph 58*

b) Winchester – Modern softwood

The relative humidity data from Winchester (and therefore the predicted moisture contents based upon it) is much more sporadic because of equipment problems. Nevertheless, Graph 60 shows that measured surface values (49 Purlin) follow predicted values in winter and are a little higher than predicted values during the summer months. The deep trace (50 Purlin) follows the same outline as the surface trace, but is damper during the summer months.

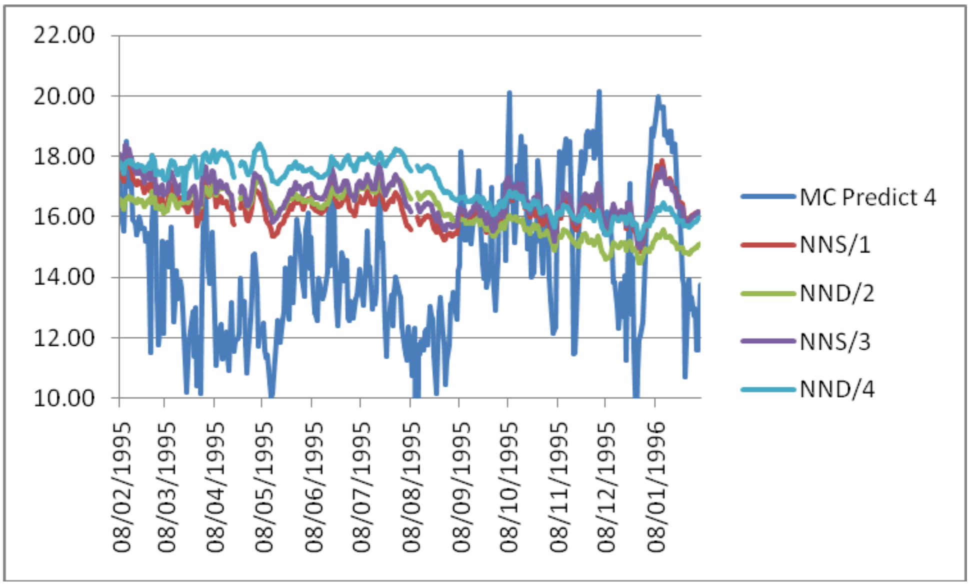
The results from Winchester are similar to those from Lincoln and indicate that the predicted moisture contents provide a useful comparison model for assessing timber age effects using the data analysed in this report.




*Graph 60: Winchester Cathedral: Surface and deep moisture content readings from modern softwood compared with predicted moisture content*

c) Lincoln – Modern oak (1984)

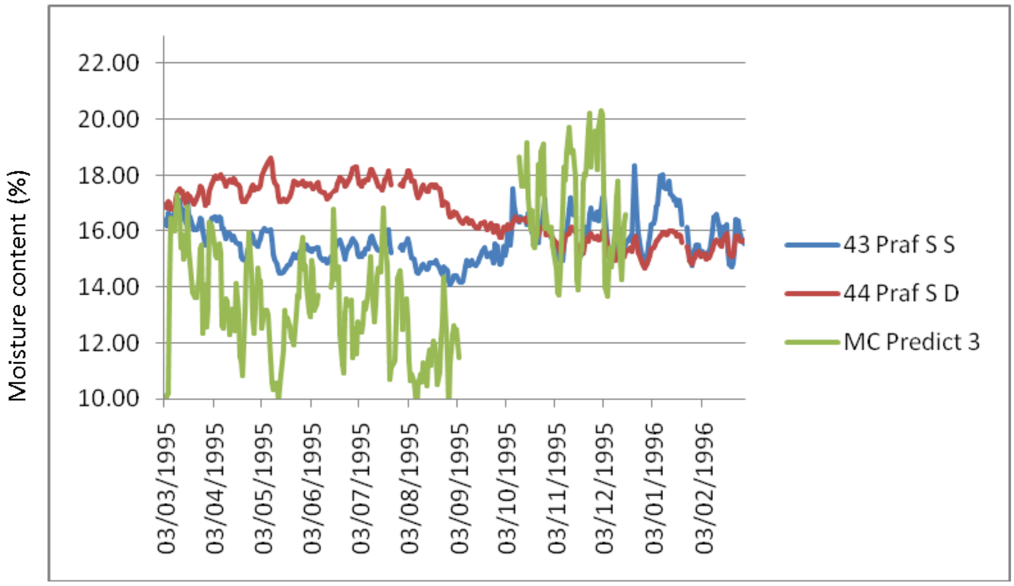
The modern oak from the Ringers' Chapel roof space at Lincoln has peaks and troughs of moisture content in the same positions as the calculated moisture contents (Graph 61) but the response is much more muted than shown by softwood in the preceding graphs.




*Graph 61: Lincoln Cathedral, Ringers' Chapel: Surface and deep moisture content readings from modern oak compared with predicted moisture content*

d) Winchester – Modern oak (no date for repair)

The oak traces in Graph 62 are similar in outline, though more muted, to the softwood traces in Graph 60. The surface of the modern oak only responds slowly to humidity fluctuations.

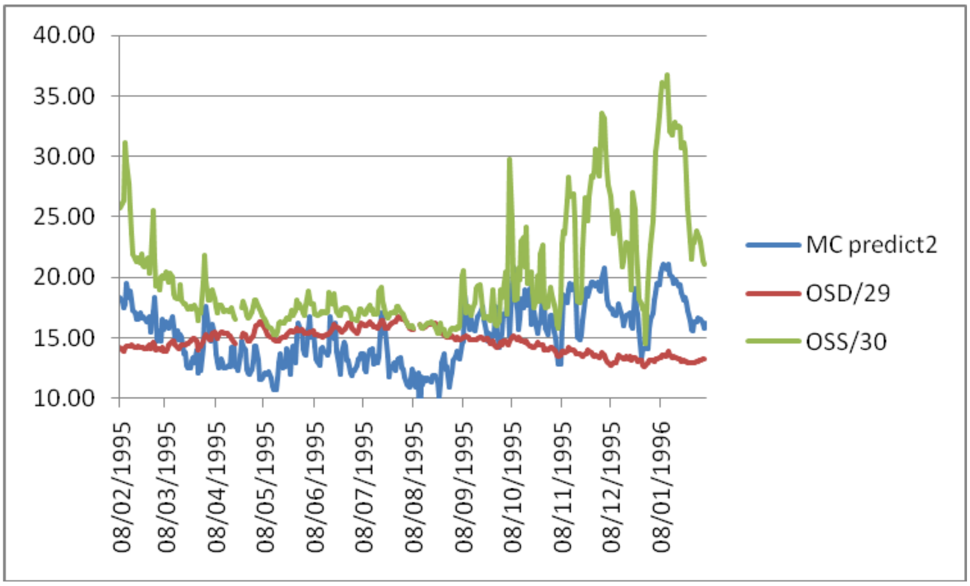



*Graph 62: Winchester Cathedral: Surface and deep moisture content readings from modern oak compared with predicted moisture content*

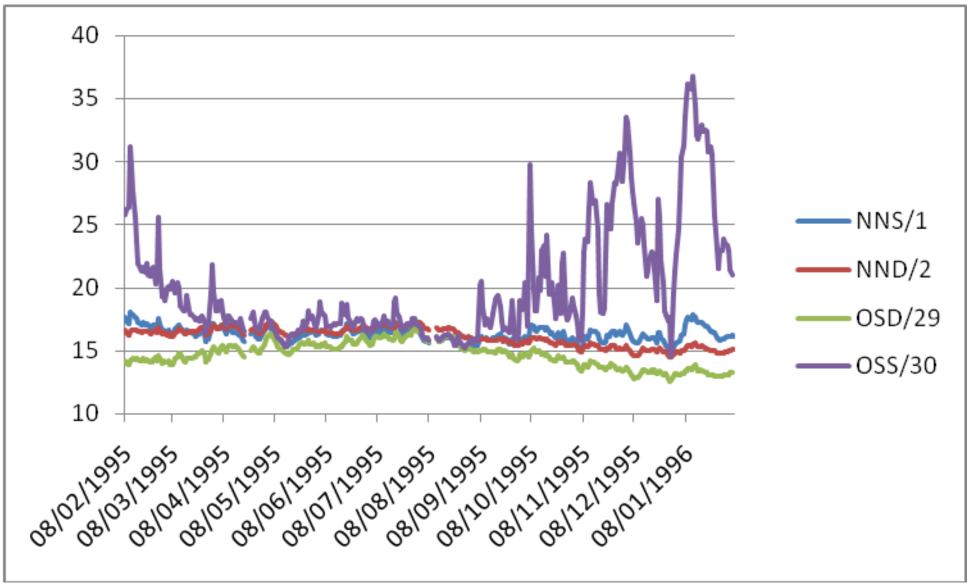
e) Lincoln – Medieval oak (1230)

Graph 63 shows typical results from a rafter on the S side of the Consistory Court roof at Lincoln. Timbers during the summer months are essentially dry. There is some variation at the surface compared with depth and the average would be a few per cent higher than predicted. In winter, however, when the humidity rises, the surface of the timber seems to become much wetter (green trace compared with dark blue). This is following the shape of the predicted trace and so is a surface effect rather than contamination. The magnitude of this wetting cannot be deduced because it is beyond the accurate upper limit of the model.

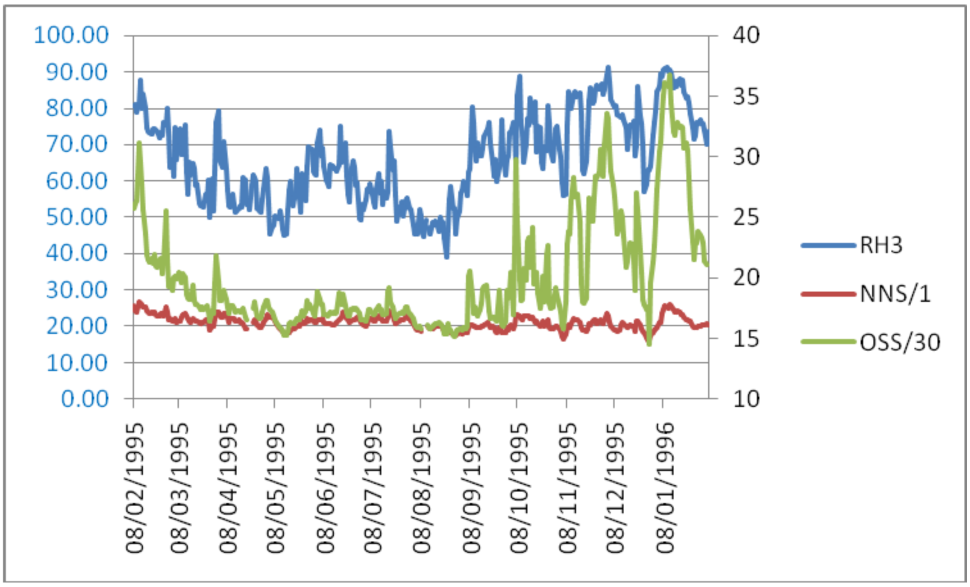
Graph 64 compares the moisture distribution in a 1984 oak bearer (NNS/D) with the 1230 medieval rafter in Graph 63. Moisture contents during the summer months are fairly similar and dry, but in winter, when humidities are high (Graph 65), the surface of the medieval rafter seems to become much more hygroscopic. This is a change in the wood surface properties; there is no extra water entering the building.




*Graph 63: Lincoln Cathedral, Consistory Court: Surface and deep moisture content readings from medieval oak compared with predicted moisture content*




*Graph 64: Lincoln Cathedral, Consistory Court: Comparison of surface and deep moisture content readings from medieval and modern oak*

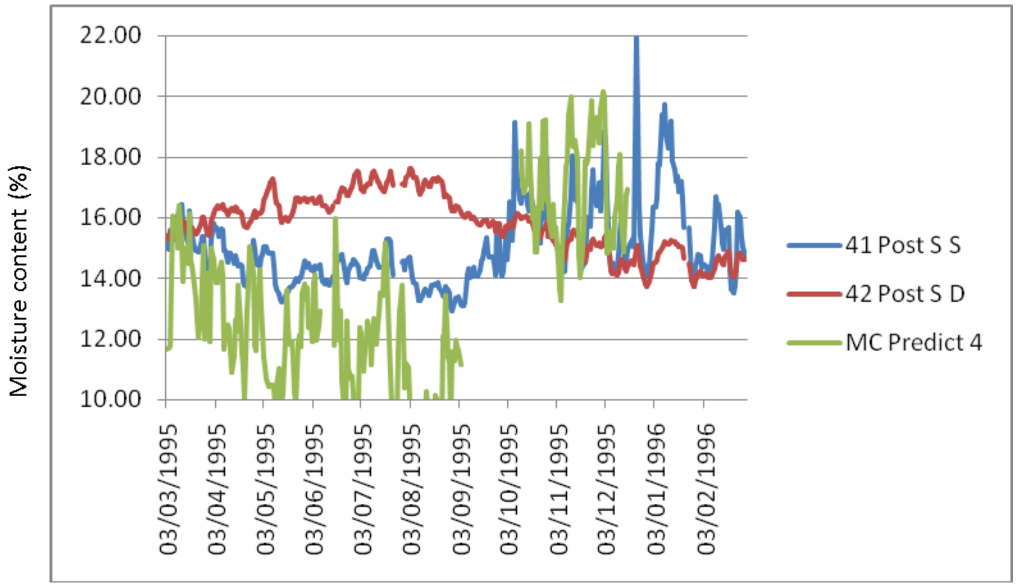



*Graph 65: Lincoln Cathedral, Consistory Court: Surface moisture content readings from medieval and modern oak compared with relative humidity*

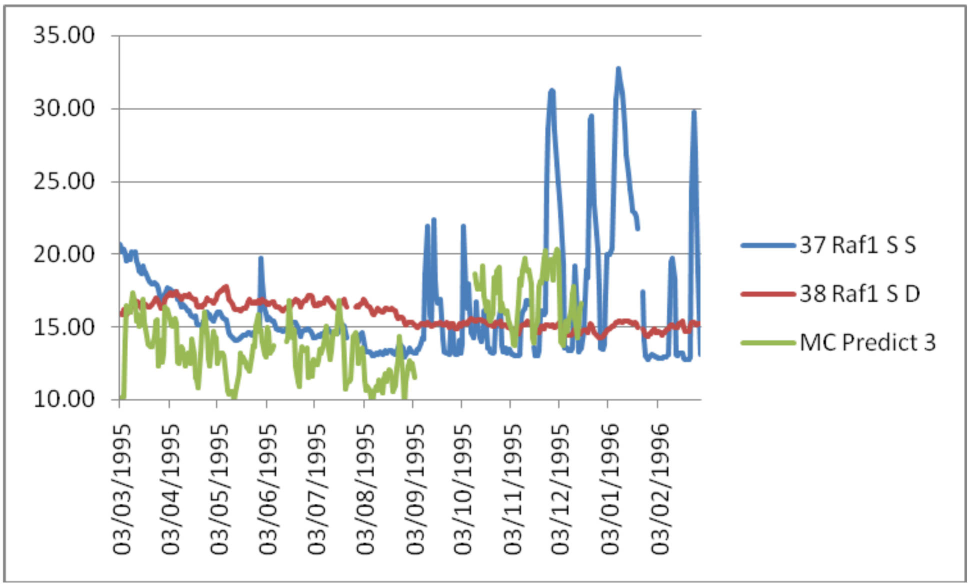
f) Winchester – Old Oak (date unknown)

Graph 66 is data from a post in the centre of the roof space. Predicted values during the winter are similar to measured values. Near the eaves, however, (Graph 67) the surface readings from a rafter seem to become much higher.

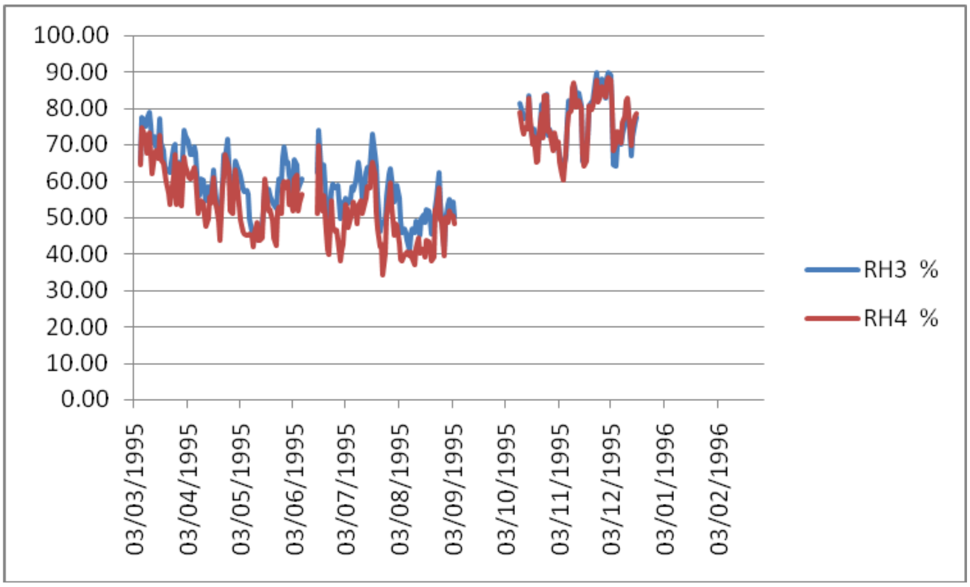
If we compare relative humidities at the eaves and at high level (Graph 68), however, then they are similar and the differences between Graph 66 and 67 seem to be due to timber variation.




*Graph 66: Winchester Cathedral: Surface and deep moisture content readings from old oak post in centre of roof compared with predicted moisture content*



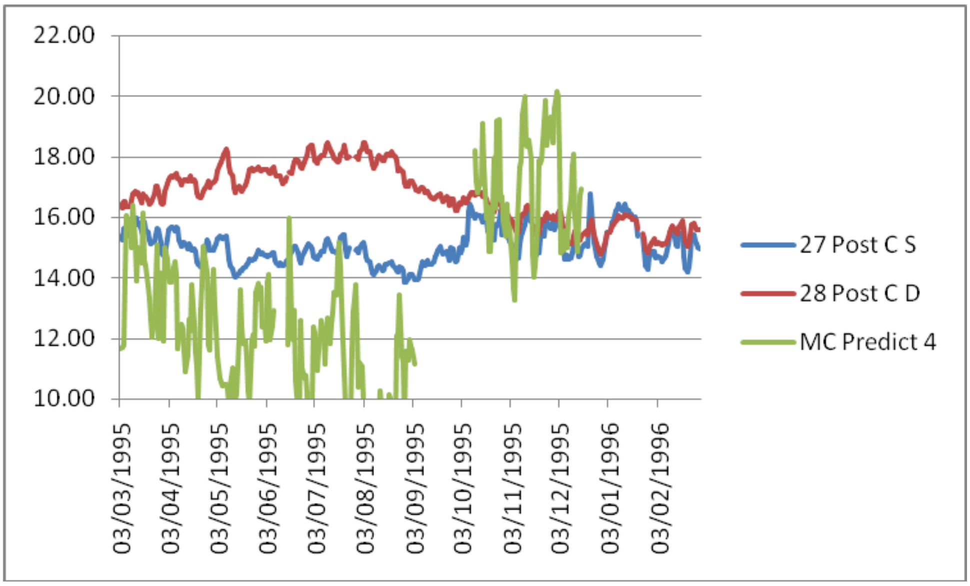

*Graph 67: Winchester Cathedral: Surface and deep moisture content readings from old oak rafter at eaves level compared with predicted moisture content*



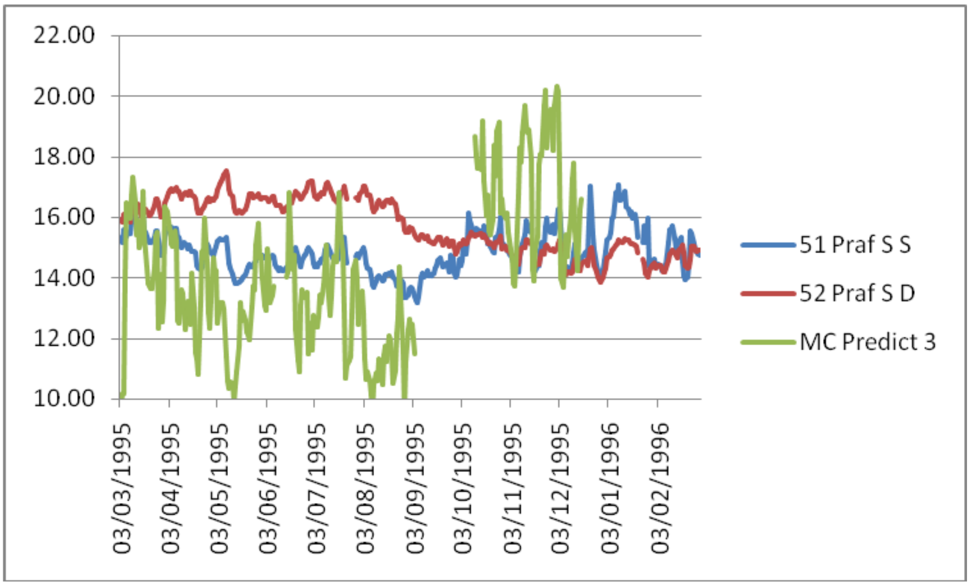

*Graph 68: Winchester Cathedral: Comparison of relative humidities at the eaves and at high level*

g) Winchester – Medieval (14th century)

Graph 69 is a central post and is directly comparable to Graph 66. This seems to suggest that great age does not necessarily mean great hygroscopicity but that the environment at the centre of the roofspace is likely to be the most stable. Graph 70 is data from a principal rafter on the S side and this also shows a dry environment and a reasonably stable response in winter.



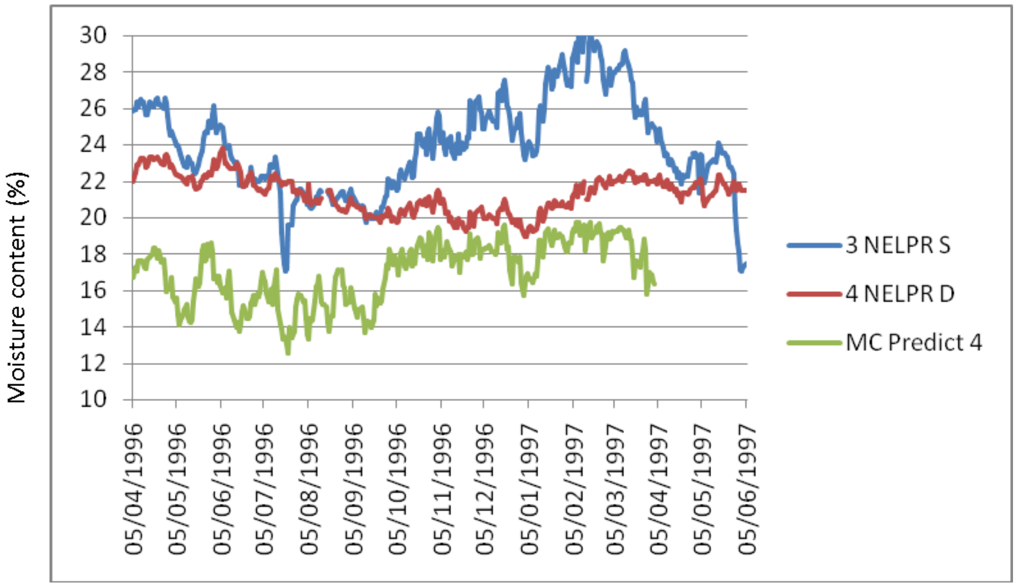

*Graph 69: Winchester Cathedral: Surface and deep moisture content readings from medieval oak in centre of roof compared with predicted moisture content*



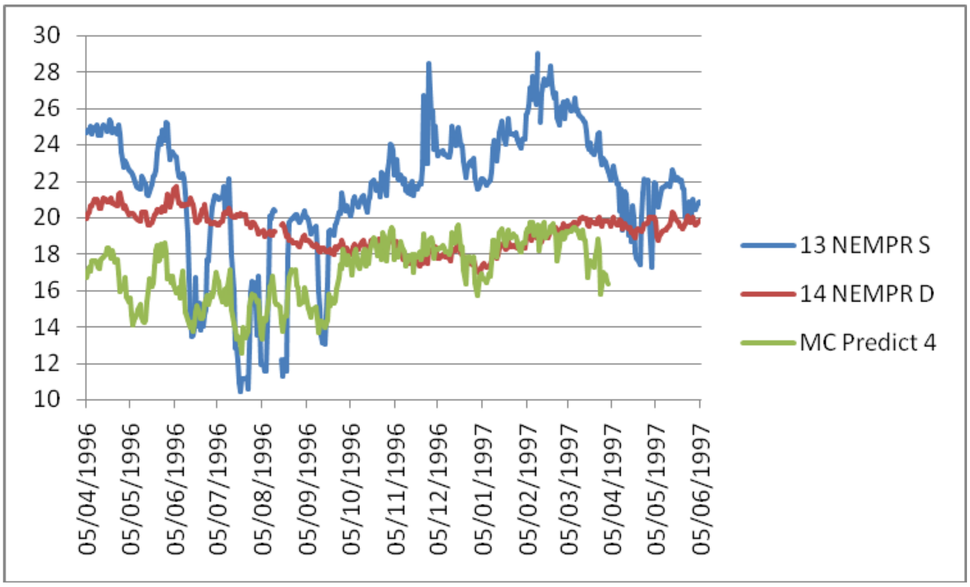

*Graph 70: Winchester Cathedral: Surface and deep moisture content readings from medieval oak principal rafter on S side of roof compared with predicted moisture content*

h) Bishopstone Church – Medieval (13th century)

Graphs 71 and 72 are from a principal rafter at eaves level and at mid-roof height. Both show an exaggerated hygroscopic response. Graph 72 shows that the timber can lose moisture as swiftly as it gains it, but this has not been a common response within the data sets. Again, it is worth noting that the timber moisture contents seem to be responding to shorter-term humidity fluctuations than the daily humidity averages would predict.




*Graph 71: Bishopstone Church: Surface and deep moisture content readings from medieval oak principal rafter at eaves level compared with predicted moisture content*




*Graph 72: Bishopstone Church: Surface and deep moisture content readings from medieval oak principal rafter at mid-roof level compared with predicted moisture content*

# 6) WITHIN-TIMBER VARIATION

The data presented above indicates that there is considerable variation in surface moisture content between timbers in the same roof. The research project also looked at within timber variation.

## 6.1 Method

We eventually assembled a reference collection of 68 dendro-dated components (mostly rafters) from 50 buildings. These dated from the 13th to the 20th century. Each component was cut into 5cm x 5cm x 2.5cm slices of sapwood, transition wood, heartwood and juvenile wood. Samples were further subdivided into $2.5cm^3$. The number of cubes obtained varied according to how much sapwood or core timber was present in each component.

## 6.2 Experiment 1

Samples from 10 components were selected for investigation and stored at 100% RH until a constant weight was obtained. The age distribution and number of samples used is provided in Table 2; the results are presented in Table 3 and illustrated in Graphs 73 and 74.

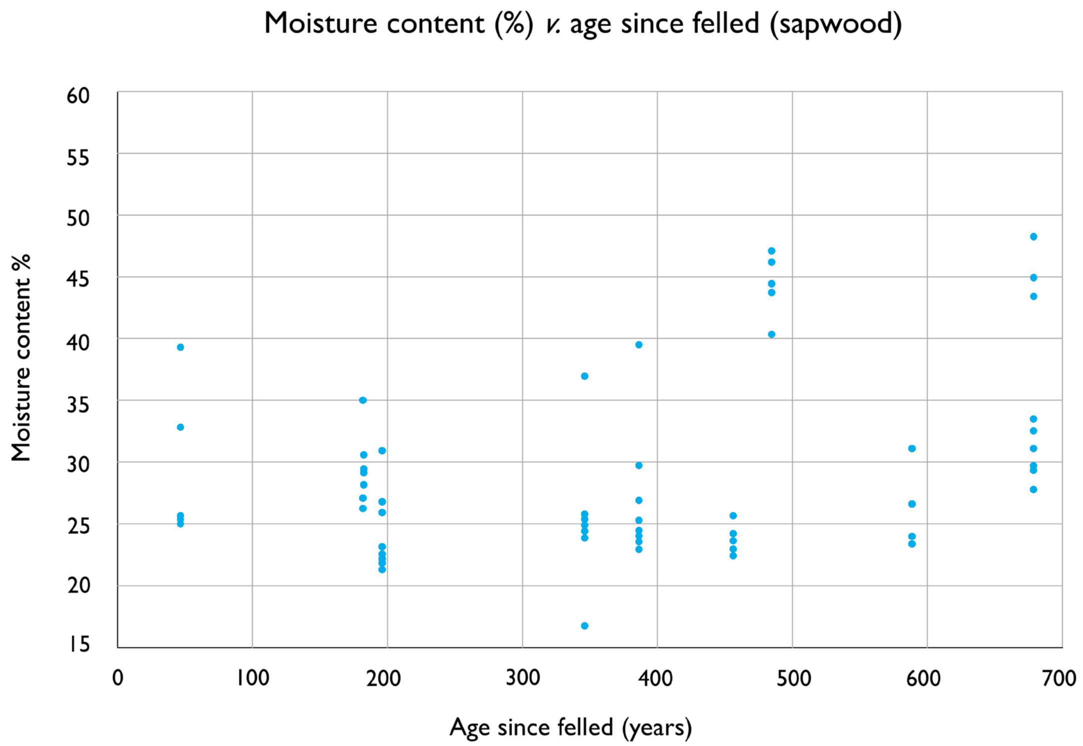
| **Table 2: Number of samples and age distribution** | | | | |
|---|---|---|---|---|
| **No** | **Age** | **Sapwood** | **Heartwood** | **Juvenile wood** |
| 1 | 1222-1317 | 9 | 9 | 9 |
| 2 | 1318-1406 | 4 | 12 | 12 |
| 3 | 1382-1495 | 2 | 8 | 9 |
| 4 | 1364-1511 | 6 | 6 | 6 |
| 5 | 1435-1539 | 12 | 12 | 9 |
| 6 | 1555-1610 | 11 | 12 | 12 |
| 7 | 1650-? | 12 | 12 | 12 |
| 8 | 1710-1801 | 12 | 12 | - |
| 9 | 1720-1815 | 12 | 12 | 3 |
| 10 | 1859-1950 | 9 | 9 | 0 |

*Table 2: The age distribution and number of samples used in Experiment 1*

Equilibrium moisture contents are shown in table 3:

| Table 3: Equilibrium moisture contents @ 100% RH | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Sapwood | | | Heartwood | | | Juvenile wood | | |
| No | Max | Min | Av | Max | Min | Av | Max | Min | Av |
| 1 | 48.0 | 27.7 | 34.4 ± 7.69 | 47.4 | 23.9 | 30.9 ± 8.31 | 36.3 | 23.9 | 29.4 ± 4.43 |
| 2 | 30.9 | 23.2 | 26.0 ± 3.51 | 26.1 | 17.5 | 22.9 ± 2.35 | 24.3 | 20.4 | 22.6 ± 1.15 |
| 3 | 69.4 | 60.8 | 65.1 ± 6.01 | 36.3 | 29.2 | 32.2 ± 2.23 | 29.2 | 23.6 | 25.7± 1.55 |
| 4 | 69.9 | 40.1 | 48.4 ± 10.79 | 26.4 | 22.6 | 24.1 ± 1.48 | 47.4 | 21.9 | 27.0 ± 10.04 |
| 5 | 25.6 | 22.3 | 23.7 ± 0.92 | 28.3 | 19.6 | 21.6 ± 2.32 | 23.9 | 22.0 | 22.9 ± 0.67 |
| 6 | 39.3 | 22.9 | 26.2 ± 4.73 | 31.9 | 22.4 | 25.2 ± 2.72 | 39.4 | 24.0 | 27.2 ± 5.24 |
| 7 | 36.9 | 16.5 | 25.0 ± 4.44 | 39.2 | 20.2 | 23.7 ± 5.01 | 23.7 | 21.1 | 22.4 ± 0.84 |
| 8 | 30.9 | 21.3 | 24.4 ± 3.05 | 24.3 | 21.3 | 23.1 ± 0.99 | - | - | - |
| 9 | 34.9 | 26.1 | 28.8 ± 2.68 | 30.8 | 23.5 | 26.8 ± 2.07 | 29.7 | 22.9 | 25.7 ± 3.56 |
| 10 | 39.1 | 24.8 | 27.9 ± 5.26 | 28.8 | 25.6 | 27.3 ± 1.06 | 30.2 | 24.5 | 26.8 ± 1.56 |

*Table 3: Results of the equilibrium moisture contents of Experiment 1*




*Graph 73: Results from sapwood samples in Experiment 1*


*Graph 74: Results from heartwood samples in Experiment 1*

6.3 Experiment 2

A different set of six samples from each age range was allowed to equilibrate for 4 weeks at 22°C and at relative humidities controlled by saturated salt solutions. Moisture contents were then measured with a resistance-type moisture meter (Protimeter) to establish the range of readings for each age group. Absolute moisture contents were obtained by the oven/balance method (dried for 8 hours at 100°C +/- 5). Results are presented in the following tables. The set of readings on the left half are absolute moisture contents, while meter readings are shown on the right. The wood moisture content calculated for that humidity by Equation 2 is provided below each table.

*Table 4: Measured and absolute moisture contents of blocks after 4 weeks at constant humidity*

| Moisture content range (gravimetric and meter) | | | | | | | |
|---|---|---|---|---|---|---|---|
| **No** | **Date range** | **Sapwood** | **Heartwood** | **Juvenile wood** | **Meter Sapwood** | **Meter Heart-wood** | **Meter Juvenile** |
| 1 | 1318 - 1406 | 18.0 - 18.7 | 16.3 - 19.5 | 17.4 - 19.0 | 19.0 - 20.0 | 16.6 - 20.0 | 16.6 - 17.3 |
| 2 | 1395 - 1450 | 18.6 - 18.9 | 17.0 - 18.1 | 21.1 - 22.2 | 22.3 - 22.8 | 23.0 - 25.0 | 24.1 -26.2 |
| 3 | 1435 - 1539 | 18.4 - 19.0 | 15.5 - 22.1 | 17.2 -20.0 | 18.3 - 18.6 | 19.2 - 27.3 | 20.0 -21.0 |
| 4 | 15th century | 17.0 - 20.6 | 13.4 - 16.1 | 12.7 - 14.5 | 20.3 - 24.2 | 20.3 - 23.9 | 18.1 - 19.8 |
| 5 | 1553 - 1610 | 17.0 - 23.3 | 12.6 - 14.6 | 13.0 - 16.0 | 17.2 - 19.3 | 19.8 - 20.9 | 19.8 -20.5 |
| 6 | 1670 - 1723 | 24.3 - 27.7 | 14.4 - 15.0 | 15.8 - 16.3 | 27.8 - 28.3 | 21.9 - 26.4 | 25.5 -26.3 |
| 7 | 1710 - 1801 | 17.5 - 19.3 | 14.3 - 17.2 | 15.3 - 16.1 | 18.1 - 20.4 | 17.6 - 19.7 | 19.1 - 21.8 |
| 8 | 1730 - 1815 | 17.4 - 17.9 | 11.1 - 15.0 | 11.1 - 14.5 | 17.5 - 18.6 | 17.4 - 18.4 | 17.5 - 18.3 |

*4.1 Potassium nitrate ($KNO_3$) = 95.5% Relative humidity – Calculated equilibrium moisture content = 22%*

| Moisture content range (gravimetric and meter) | | | | | | | |
|---|---|---|---|---|---|---|---|
| **No** | **Date range** | **Sapwood** | **Heartwood** | **Juvenile wood** | **Meter Sapwood** | **Meter Heart-wood** | **Meter Juvenile** |
| 1 | 1318 - 1406 | 11.7 - 12.9 | 10.5 - 11.9 | 11.3 - 12.1 | 15.1 - 15.7 | 14.0 - 14.4 | 14.1 - 14.4 |
| 2 | 1395 - 1450 | 12.2 - 12.7 | 10.0 - 11.4 | 13.1 - 13.9 | 15.7 - 16.8 | 17.2 - 18.4 | 16.8 - 17.8 |
| 3 | 1435 - 1539 | 10.9 - 11.5 | 10.1 - 10.7 | 10.0 - 10.8 | 12.9 - 13.2 | 14.1 - 14.3 | 14.3 - 14.5 |
| 4 | 15th century | 10.4 - 13.6 | 10.1 - 10.4 | 8.1 - 9.6 | 14.1 - 17.2 | 14.8 - 15.7 | 15.0 - 15.3 |
| 5 | 1553 - 1610 | 9.2 - 10.6 | 8.2 - 8.6 | 8.5 - 13.3 | 12.4 - 14.1 | 13.8 - 14.2 | 14.9 - 15.1 |
| 6 | 1670 - 1723 | 13.0 - 13.3 | 7.9 - 10.0 | 9.1 - 10.6 | 21.5 - 22.4 | 19.1 - 19.2 | 19.3 - 19.8 |
| 7 | 1710 - 1801 | 11.5 - 15.6 | 11.2 - 12.1 | 8.8 - 9,9 | 15.8 - 17.0 | 13.5 - 14.1 | 14.3 - 16.2 |
| 8 | 1730 - 1815 | 12.2 - 13.2 | 8.9 - 9.4 | 7.3 - 8.1 | 12.9 - 13.6 | 14.0 - 15.1 | 14.0 - 15.2 |

*4.2 Potassium bromide (KBr) = 80.7 % Relative humidity – Calculated equilibrium moisture content = 16.2%*

| Moisture content range (gravimetric and meter) | | | | | | | |
|---|---|---|---|---|---|---|---|
| **No** | **Date range** | **Sapwood** | **Heartwood** | **Juvenile wood** | **Meter Sapwood** | **Meter Heart-wood** | **Meter Juvenile** |
| 1 | 1318 - 1406 | 10.1 - 10.5 | 8.9 - 9.9 | 8.6 - 9.0 | 14.2 - 14.6 | 12.3 - 12.6 | 12.5 - 12.8 |
| 2 | 1395 - 1450 | 8.4 - 10.0 | 9.9 - 10.4 | 10.8 - 11.0 | 13.2 - 15.5 | 15.6 - 16.9 | 14.6 - 15.7 |
| 3 | 1435 - 1539 | 9.1 - 9.8 | 9.1 - 9.5 | 8.8 - 9.3 | 11.9 - 12.7 | 12.8 - 13.2 | 13.8 - 15.4 |
| 4 | 15th century | 8.9 - 10.0 | 8.2 - 8.6 | - | 15.1 - 16.2 | 15.1 - 15.4 | - |
| 5 | 1553 - 1610 | 8.0 - 10.0 | 7.4 - 8.0 | 9.6 - 10.0 | 10.6 - 11.5 | 13.7 - 14.0 | 13.9 - 14.8 |
| 6 | 1670 - 1723 | 10.4 - 10.7 | 8.0 - 8.4 | 8.0 - 9.5 | 17.8 - 19.5 | 14.7 - 17.3 | 17.2 - 18.5 |
| 7 | 1710 - 1801 | 9.6 - 10.3 | 7.7 - 9.4 | - | 13.2 - 15.6 | 12.6 - 12.7 | - |
| 8 | 1730 - 1815 | 8.6 - 10.2 | 5.1 - 8.2 | - | 11.8 - 12.3 | 12.9 - 13.5 | - |

*4.3 Strontium chloride ($SrCl_2$) = 70.8 % Relative humidity – Calculated equilibrium moisture content = 13.3%*

## 6.4 Results

*Experiment 1:* Comparison of the maximum and minimum columns in Table 3 shows that there is considerable variation in equilibrium moisture content at high humidities, particularly in the sapwood.

*Experiment 2:* This looked at results from partial equilibrium moisture contents over a fixed period of time, compared with resistance meter readings. This was intended to give a better understanding of moisture distribution over a length of time which might reasonably be expected during the variation in humidity during the course of a year in an unheated roof.

The meter readings generally gave a reasonable approximation to the calculated equilibrium moisture content. This is commonly within the range ± 3% although there are exceptions (for example line 6 in 5.3).

The absolute moisture contents are lower than the meter readings, although the difference declines at high humidities (5.1) particularly in the sapwood. This will be because the meter is measuring the surface moisture content, which equilibrates first. At lower humidities the core of the timber, despite the large surface area of a 25mm$^3$, is slow to equilibrate.

# 7) THE DEPTH OF MOISTURE ADSORPTION IN MEDIEVAL TIMBERS

## 7.1 Introduction

Our moisture content monitoring in medieval timbers showed that surface hygroscopicity and moisture sorption could be very variable and related to humidity change. Deep readings were considerably more constant, but the deep probes were inserted to a depth of 100mm and did not provide any data on the potential depth of surface effects – so at what depth were moisture contents beginning to become constant?

## 7.2 Method

We investigated this problem during the winter of 1995 (when humidities would be high) at Lincoln Cathedral and Salisbury Cathedral, using a Protimeter fitted with a hammer probe and electrodes insulated except at the tip. The depth to which this instrument was driven into the timber was controlled by metal spacers of decreasing size placed between the electrodes. A surface reading was followed by a reading at the deepest spacer, which was then removed and the electrodes were hammered further in to the depth of the next. The maximum depth reached in each test was 37mm.

7.3 Results

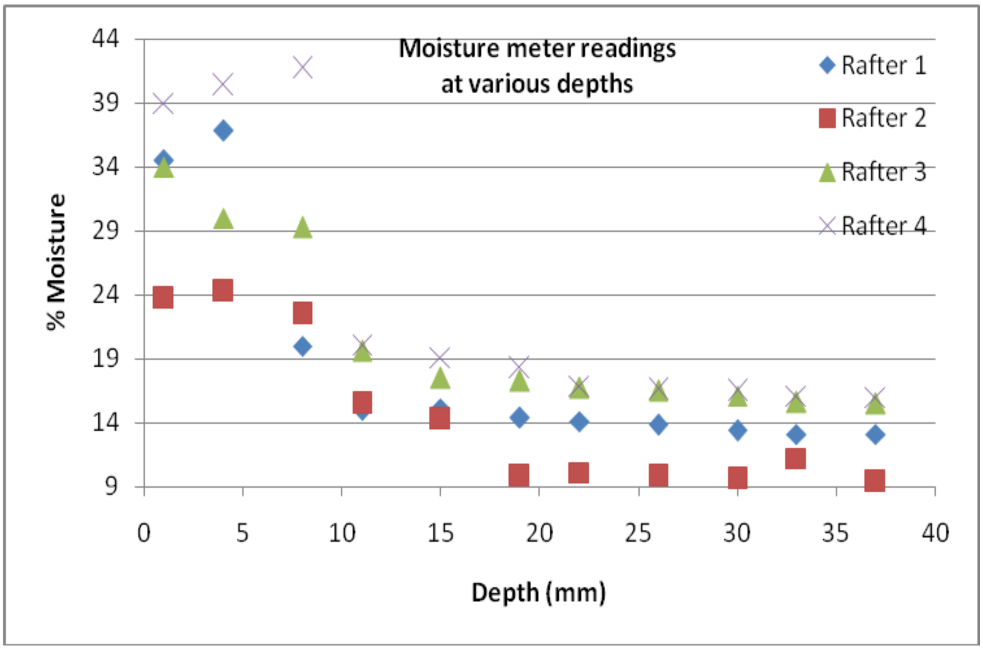
7.3.1 Salisbury Cathedral

*Table 5: Percentage moisture content readings at different depths*

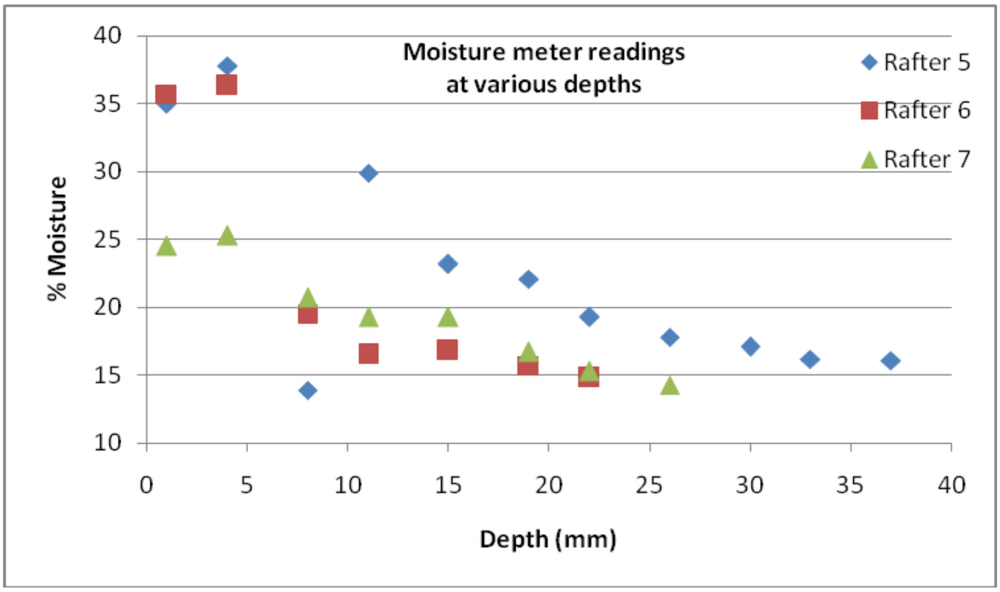
| | | % moisture content readings at different depths (mm) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Timber No** | **Size** | **2** | **4** | **8** | **11** | **15** | **19** | **22** | **26** | **30** | **33** | **37** |
| **1** | 124 radius | 14.7 | 15.6 | 16.3 | 16.6 | 16.5 | 16.7 | 16.6 | 16.6 | 16.2 | 15.9 | 15.9 |
| **2** | 340 x 200 | 16.1 | 16.7 | 16.7 | 15.4 | 15.0 | 14.6 | 14.4 | 14.1 | 14.1 | 14.0 | 14.1 |
| **3** | 300 x 300 | 13.9 | 14.8 | 15.3 | 15.1 | 15.0 | 16.9 | 14.5 | 14.5 | 14.3 | 14.2 | 14.3 |
| **4** | 255 x 170 | 14.0 | 15.2 | 15.9 | 16.2 | 16.3 | 16.0 | 15.8 | 15.7 | 15.6 | 15.6 | 15.8 |
| **5** | 255 x 170 | 13.9 | 14.4 | 14.1 | 15.1 | 15.5 | 15.5 | 15.8 | 16.0 | 16.0 | 16.0 | 16.1 |
| **6** | 124 radius | 12.8 | 14.2 | 15.1 | 15.9 | 16.2 | 16.5 | 16.6 | 16.6 | 16.5 | 16.5 | 16.4 |
| **7** | 300 x 200 | 13.9 | 14.3 | 13.7 | 14.0 | 13.8 | 13.9 | 13.9 | 14.0 | 14.1 | 14.0 | 14.2 |
| **8** | 280 x 300 | 14.2 | 15.0 | 15.5 | 15.8 | 15.8 | 16.1 | 16.1 | 16.0 | 15.7 | 15.3 | 15.2 |
| **9** | 250 x 170 | 12.4 | 12.4 | 13.7 | 14.7 | 15.2 | 15.7 | 16.2 | 16.4 | 16.6 | 16.8 | 17.4 |
| **10** | 220 x 125 | 14.0 | 15.1 | 15.9 | 16.2 | 16.3 | 16.5 | 16.6 | 16.5 | 16.4 | 16.3 | 16.5 |
| **11** | 145 x 140 | 13.4 | 13.9 | 14.4 | 15.2 | 15.8 | 16.2 | 16.3 | 16.5 | 16.7 | 16.9 | 17.0 |
| **12** | 190 x 145 | 12.5 | 13.9 | 14.7 | 15.5 | 16.2 | 16.5 | 17.0 | 17.3 | 17.4 | 17.4 | * |
| **13** | 300 x 250 | 10.8 | 12.7 | 13.5 | 13.7 | 14.0 | 14.3 | 14.5 | 14.7 | 14.8 | 14.6 | 14.9 |
| **14** | 170 x 140 | 15.8 | 16.3 | 16.3 | 16.4 | 16.7 | 16.8 | 16.9 | 16.3 | 16.0 | 15.9 | 15.8 |

* timber too hard for electrodes

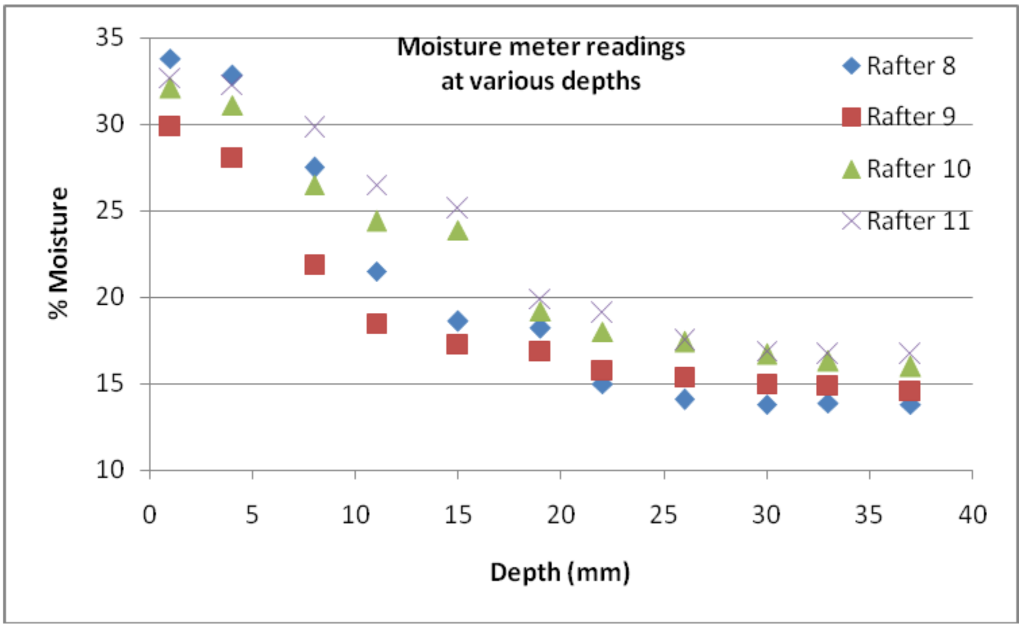
These results are displayed in Graphs 75 to 78.




*Graph 75: Moisture content readings at various depths in rafters 1 to 4*




*Graph 76: Moisture content readings at various depths in rafters 5 to 7*




*Graph 77: Moisture content readings at various depths in rafters 8 to 11*

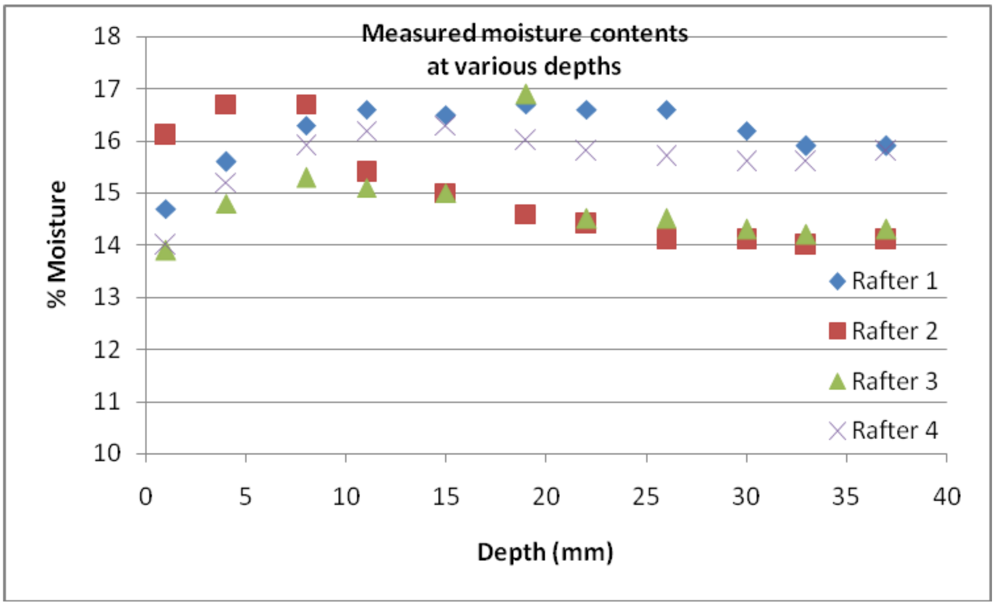
7.3.2 Lincoln Cathedral

*Table 6: Percentage moisture content readings at different depths*

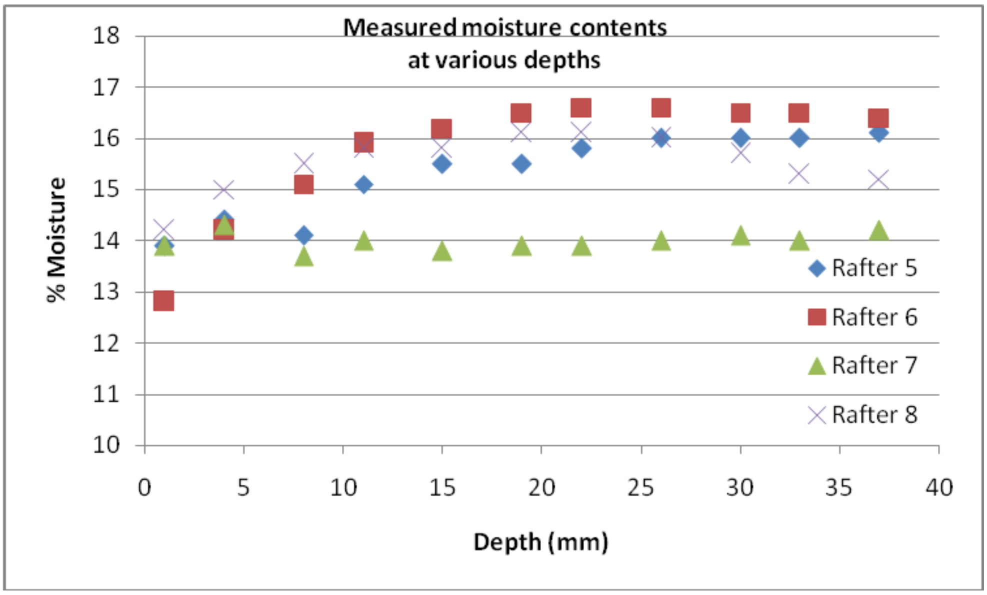
| | | **% moisture readings at different depths (mm)** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Timber No** | **Size** | **2** | **4** | **8** | **11** | **15** | **19** | **22** | **26** | **30** | **33** | **37** |
| **1** | 165 x 160 | 34.5 | 36.8 | 20.0 | 16.0 | 15.1 | 14.4 | 14.1 | 13.8 | 13.4 | 13.1 | 13.1 |
| **2** | 120 x 120 | 23.7 | 24.3 | 22.5 | 15.5 | 14.3 | 9.8 | 10.1 | 9.8 | 9.6 | 11.2 | 9.4 |
| **3** | 170 x 165 | 34.0 | 30.0 | 29.3 | 19.6 | 17.5 | 17.3 | 16.7 | 16.5 | 16.1 | 15.6 | 15.5 |
| **4** | 170 x 165 | 39.0 | 49.4 | 41.7 | 20.1 | 19.1 | 18.3 | 16.9 | 16.6 | 16.5 | 16.1 | 16.0 |
| **5** | 170 x 165 | 35.0 | 37.8 | 13.9 | 29.9 | 23.2 | 22.1 | 19.3 | 17.8 | 17.1 | 16.2 | 16.1 |
| **6** | 120 x 120 | 35.7 | 36.3 | 19.5 | 16.5 | 16.8 | 15.7 | 14.8 | * | * | * | * |
| **7** | 130 x 115 | 24.5 | 25.3 | 20.7 | 19.3 | 19.3 | 16.7 | 15.3 | 14.3 | * | * | * |
| **8** | 150 x 140 | 33.8 | 32.8 | 27.5 | 21.5 | 18.6 | 18.2 | 15.0 | 14.1 | 13.8 | 13.9 | 13.8 |
| **9** | 140 x 100 | 29.9 | 28.1 | 21.9 | 18.5 | 17.3 | 16.9 | 15.8 | 15.4 | 15.0 | 14.9 | 14.6 |
| **10** | 250 x 185 | 32.1 | 31.1 | 26.5 | 24.4 | 23.9 | 19.2 | 18.0 | 17.4 | 16.7 | 16.3 | 16.0 |
| **11** | 235 x 195 | 32.7 | 32.3 | 29.8 | 26.5 | 25.1 | 19.9 | 19.1 | 17.5 | 16.9 | 16.7 | 16.7 |

* timber too hard for electrodes

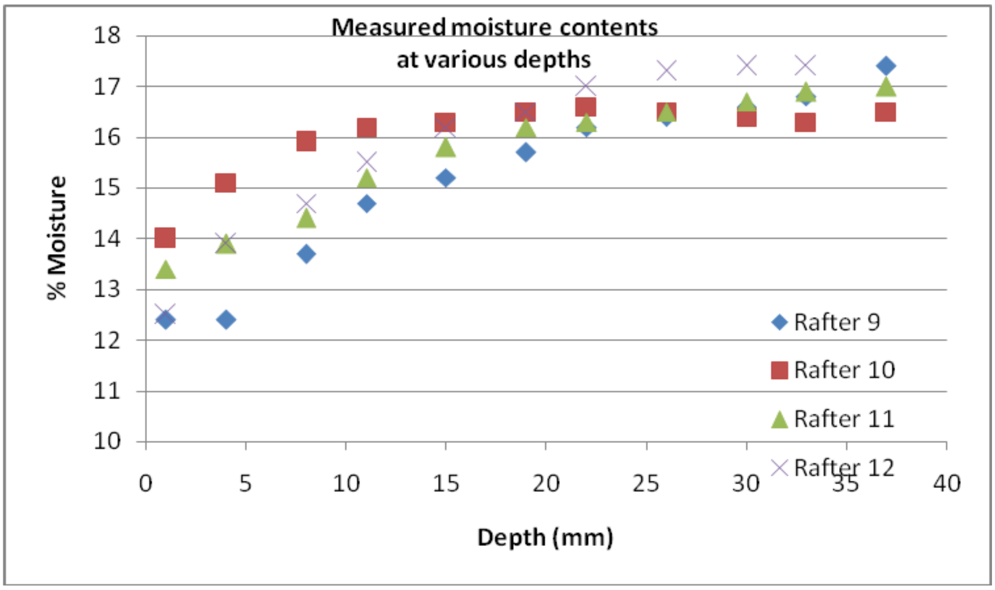
These results are displayed in Graphs 78 to 80.



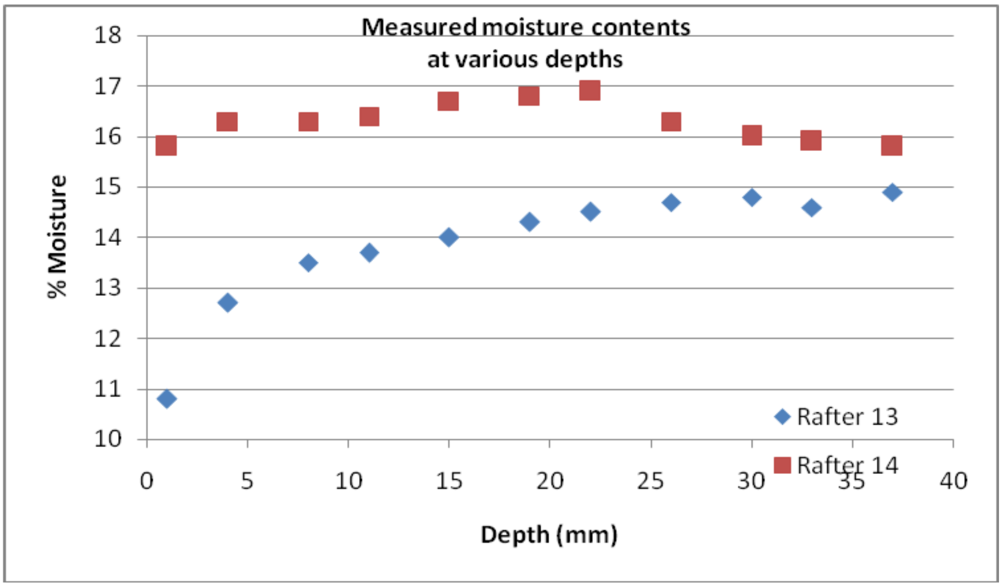

*Graph 78: Moisture content readings at various depths in rafters 1 to 4*




*Graph 78a: Moisture content readings at various depths in rafters 5 to 8*




*Graph 79: Moisture content readings at various depths in rafters 9 to 12*




*Graph 80: Moisture content readings at various depths in rafters 13 and 14*

The results are rather variable, but it does seem that a stable reading is not reached until a depth of around 20mm. This is a significant depth to insert and remove a hammer electrode in hard oak.

Timbers from both buildings are basically dry, but the Lincoln data would not demonstrate that without deep probing.

If a dry reading is generally considered to be below about 15% moisture content then the Salisbury data would not suggest the need for depth measurements. However, there is still variation and rafter 12 for example is damper at depth than the surface suggests.

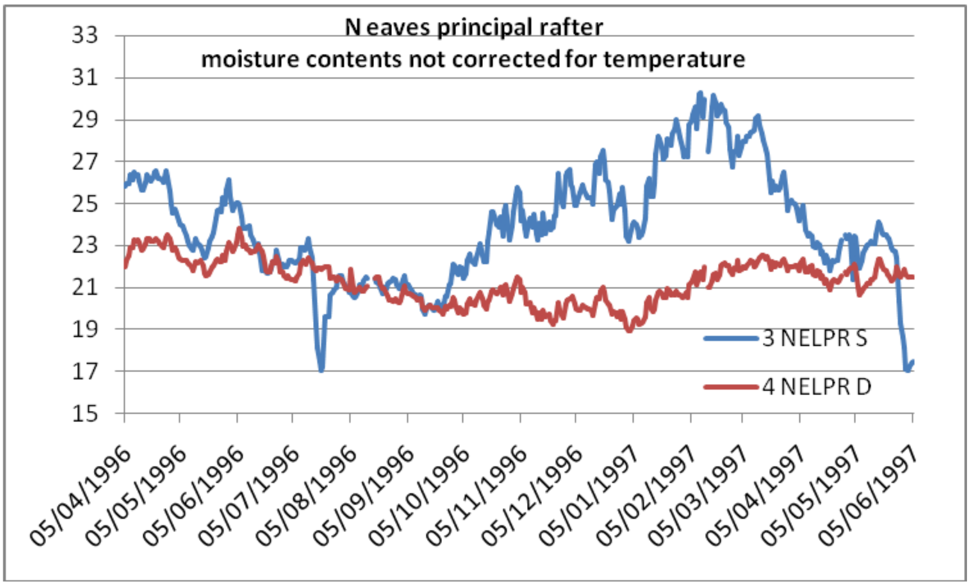
It is evident that conclusions from one rafter would not necessarily be the same as for the next and numerous readings are needed if a roof is to be evaluated. The potential use of this evaluation, however, is unclear.

## 8) CONCLUSIONS

Timber surface moisture contents increase in winter in an unheated roof when lower temperatures raise relative humidity. This, despite popular wisdom and the literature supplied by moisture meter manufacturers, does not mean that the timber is at risk from deterioration. The actual moisture content of the timber may be even higher than measured because the electrical resistance of wood is influenced by temperature change, but there is not necessarily any extra moisture involved.

Many of the mediaeval timbers at Lincoln Cathedral and Bishopstone Church produce very high surface readings in winter. Winchester Cathedral is dryer (except for the outer wall plate) but still shows erratic surface readings in some timbers during the winter months. Comparisons between the patterns of readings in the different categories of timber suggest that high readings are caused by variability in wood hygroscopicity and not by surface contamination or salt migration. It seems likely that surface porosity has changed, or that extractives have been lost over many centuries, so that the cellulose molecules can attach more moisture. This does not seem to be an inevitable consequence of great age, however, or to apply to all timbers of the same age in a roof. This, together with the depth to which surface modification extends, suggests that old oak timbers would have a considerable buffering effect on the environment.

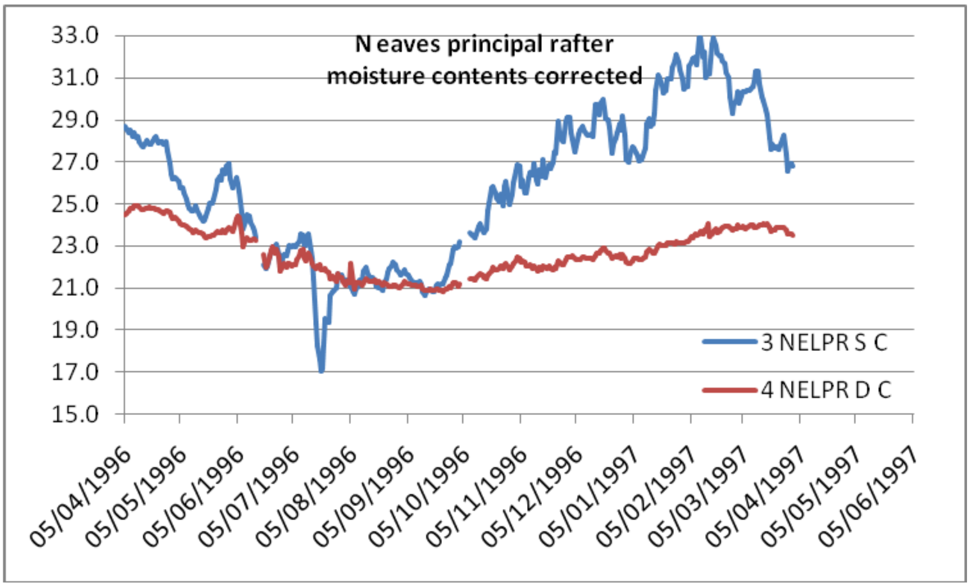
Deep readings are more stable, but even these show some fluctuation in moisture content throughout the year. Graph 81 shows shallow and deep readings from a principal rafter (low level) in the N eaves at Bishopstone.




*Graph 81: Bishopstone Church: Surface and deep moisture content readings from principal rafter at N eaves level*

The trace for the deep moisture contents seems to be somewhat similar in outline (peaks and troughs) to the trace for the shallow and it appears that the deep readings dip at the end of 1996 as the surface moisture content rises. However, both sets of resistance readings are affected by temperature.

The exact difference between temperature at depth and at the surface is unknown and may be influenced by heat transfer via the nail electrodes, but Graph 82 demonstrates what would happen if they were taken as reasonably similar and both data were corrected for temperature using the Pfaff and Garrahan equation (section 2.2.3). The deep readings now become more stable and any similarity with the surface readings mostly disappears.

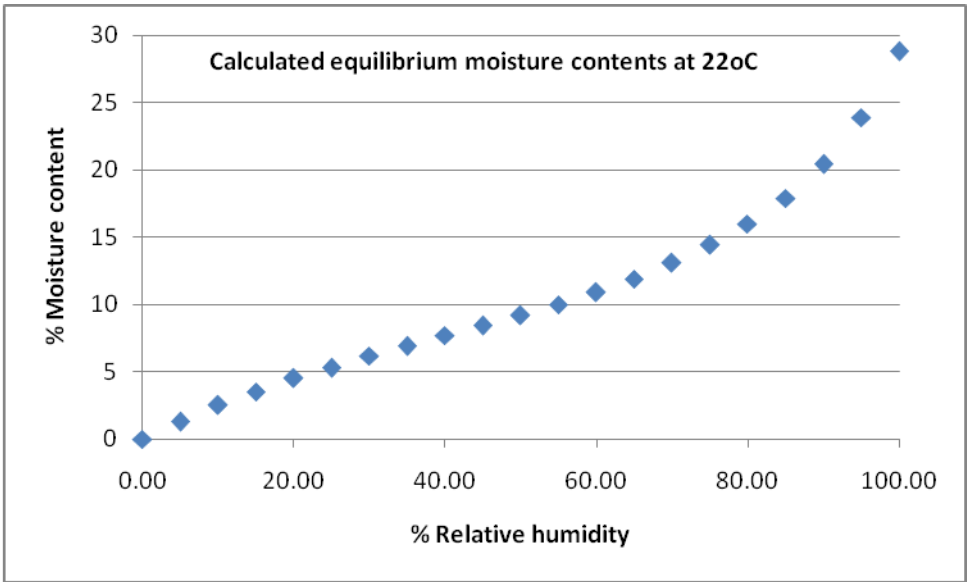



*Graph 82: Bishopstone Church: Temperature-corrected surface and deep moisture content readings from principal rafter at N eaves level*

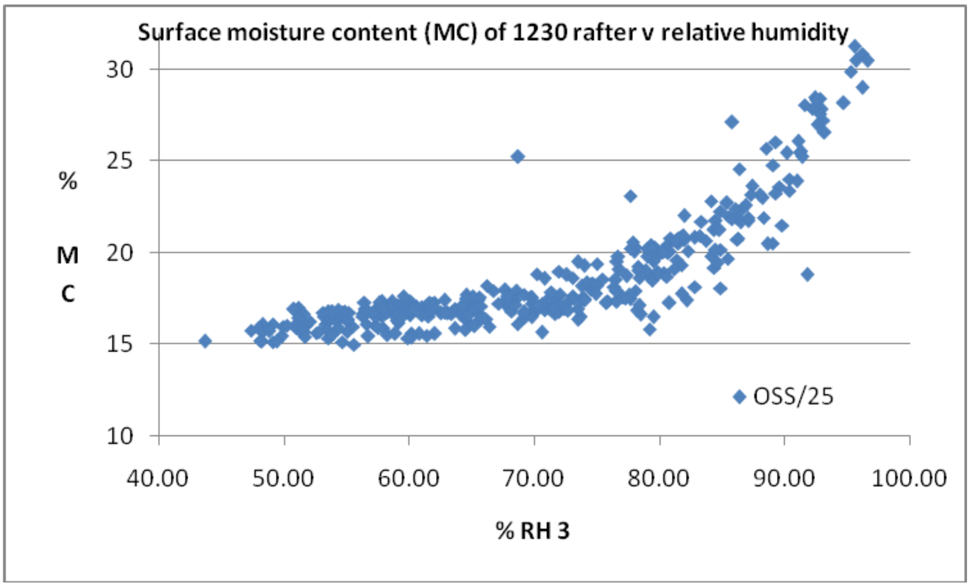
Wood surface temperature is sometimes a little different to air temperature and can be used to provide a more calibrated resistance moisture measurement. However, the fluctuation in moisture contents found by this investigation means that the increased accuracy has very little practical application.

Surface moisture contents in damper buildings tend to stay higher than deep throughout the year. Graph 83 shows a standard equilibrium moisture content curve, which helps to explain the difference in surface adsorption between summer when humidities are low and winter when humidities become high as the temperature drops.

Between about 20% RH and around 65% RH moisture contents increase steadily and gradually as humidity increases. Surface moisture content fluctuations respond to humidity change during the summer months when the humidity is low, but the magnitude of the variation is small. Above about 65% RH the sigmoid curve in Graph 83 becomes much steeper and a small increase in humidity produces a much greater increase in moisture content. If the humidity increases from 60% – 70% then the equilibrium moisture content increases by 2.2%; from 70% – 80% this increases to 2.9%; from 80% – 90% to 4.4% and from 90% relative humidity to 100% the moisture content increases by a massive 8.4%. This effect gives us the basic winter variation shown in Graph 82, which may then be increased further by changes in the wood surface properties. The response is illustrated in Graph 84, using data from Lincoln Cathedral. The scatter of data points becomes broader above about 65%.

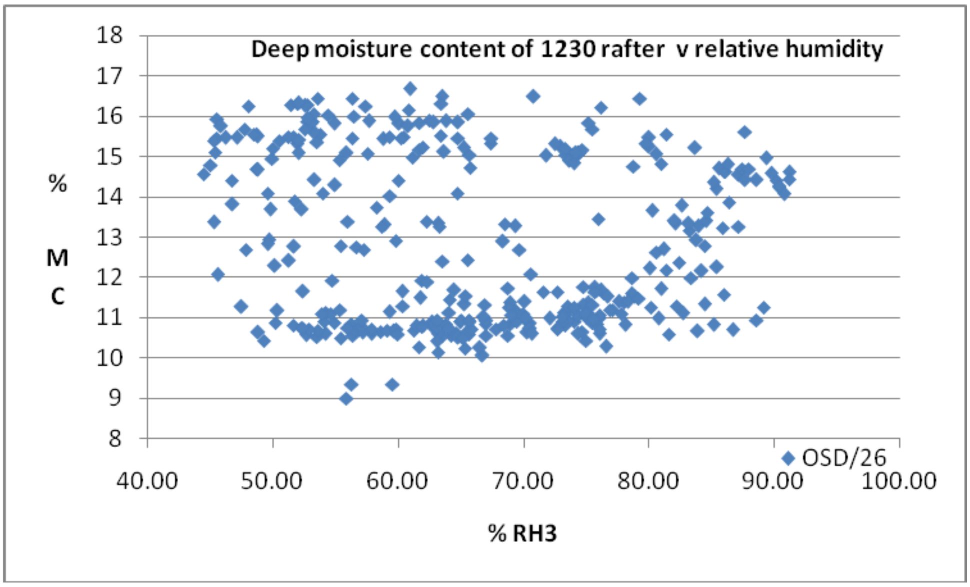



*Graph 83: Calculated equilibrium moisture content at 22°C versus relative humidity*




*Graph 84: Surface moisture content readings from rafter at Lincoln Cathedral plotted against relative humidity*

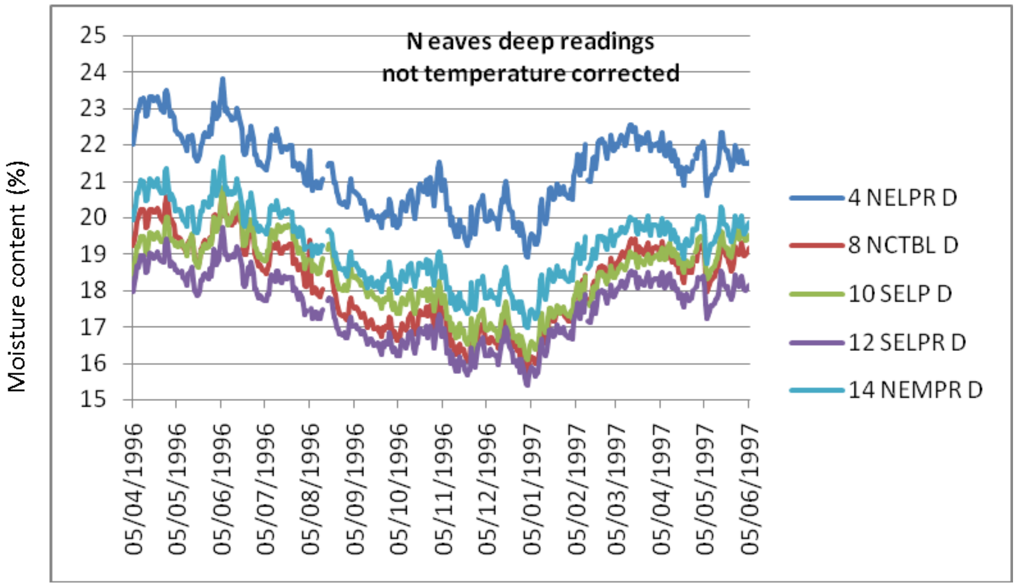
The deep moisture content is not influenced by the surface environment (Graph 85) and the deeper wood remains wetter during the summer months.




*Graph 85: Deep moisture content readings from rafter at Lincoln Cathedral plotted against relative humidity*

Experiments 1 and 2 in section 6 showed that moisture variation within the same timber can be considerable. Tables 3 and 5 show that variability occurs in the heartwood as well as in the sapwood, although Table 3 suggests that sapwood tends to be the more variable. Experiment 2 looked at moisture uptake at a range of humidities and Table 4 suggests again that variability is greater at high humidities.

Surface readings are very variable but deep readings, as found in Tables 5 and 6, may also show significant variation in a roof. Graph 86 shows a range of deep readings from the N eaves at Bishopstone demonstrating this variation.




*Graph 86: Deep moisture content readings from timbers at N eaves level, Bishopstone Church*

None of the results from this study demonstrate that increased moisture fluctuation necessarily becomes more extreme as buildings age. However, a building of considerable age may have experienced many different changes in environment, including perhaps surface timber decay. It must, therefore, become increasingly likely that surface hygroscopicity has become modified over the centuries.

Whatever the cause, an incautious surveyor with a moisture meter might conclude that there was a serious damp problem in a dry roof, depending on the time of year, the particular timbers investigated, and even the section of timber probed. A 'dry' reading probably indicates a dry roof. But, in practice, so might a 'damp' reading.

Deep readings using a hammer probe fitted with insulated electrodes would be more useful but these are difficult to use on hard oak. Taking surface readings and then knocking the probe in to provide a gradient would provide more information, but its significance would still be difficult to fathom.

Therefore, a moisture meter survey should include readings from numerous timbers, deep readings as well as surface readings, and also compare moisture contents from a range of timber types if there have been repairs. However, the variations between timbers, within timbers, and the humidity fluctuations throughout the year make it difficult to envisage any practical use for a timber moisture content survey in a medieval roof except, perhaps, to identify wet timbers in contact with masonry where there might be concealed decay.

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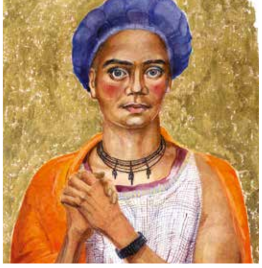



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ISSN 2398-3841 (Print)
ISSN 2059-4453 (Online)