C. Ecofab Report: Dynamic Response of Real Building Fabric

1. INTRODUCTION

Controlling temperature and humidity are the main functions of a building fabric. Relative humidity (RH) is the ratio of water vapour in the air to the maximum amount that could be held at a given temperature.

1.1 Time Lag and Decrement Factor

There are two parameters which allow evaluation of the thermal performance of a building fabric: time lag (φ) and decrement factor (ƒ). The time taken for a temperature wave to propagate from the outer to the inner surface of the wall is the thermal lag, φ_q, and the decrement factor is the proportion of external temperature wave amplitude experienced inside. In general, if time lag is high and decrement factor small thermal comfort is maximised.

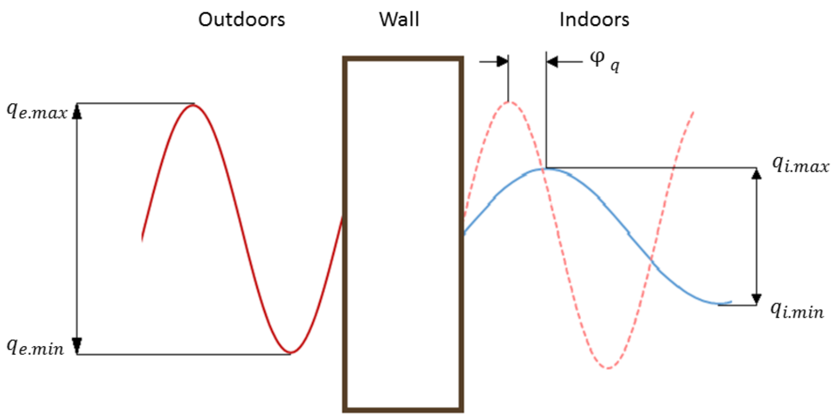

Figure 1. Schematic of heat flux time lag and decrement factor

In this study these metrics are used to evaluate both temperature and RH conditions at the internal and external wall surface and in external and internal air conditions. The following equations are used.

$$f = \frac{\Delta\zeta_i}{\Delta\zeta_e} \quad (1)$$

$$\varphi = \tau_{i.max} - \tau_{e.max} \quad (2)$$

where

ζ = temperature or RH depending on the test

τ = time

i = inside

e = external

1.1.1 Excessive Humidity

Different building materials respond very differently to ambient RH, following a rising or falling exponential function for absorption and desorption respectively. Hygroscopic materials seek moisture equilibrium with time averaged RH of the ambient air.

Excessive humidity can lead to growth of mould and mildew, poor air quality, occupant health problems, loss of thermal resistance, damage or failure of materials and paints, and can affect energy consumption (Plathner, Littler, & Cripps, 1999), (Glass & TenWolde, 2009).

Studies have shown that moulds can germinate and grow at RH above 80% (British Standards, 2002), ASHRAE Standard 62.1 (2014) recommends RH be kept below 65%. Degradation of vegetable fibres such as straw is highly dependent on water content with moisture content above 20 or 25% a danger (Collins M. , Paulson, Finner, Jorgensen, & Keuler, 1987), (BRE, 2011).

This section assesses the risk of microbial growth and fabric degradation.

2. METHODOLOGY

2.1 Building

Two ecofab buildings were studied, both located near Bodmin, Cornwall, Figure 1.

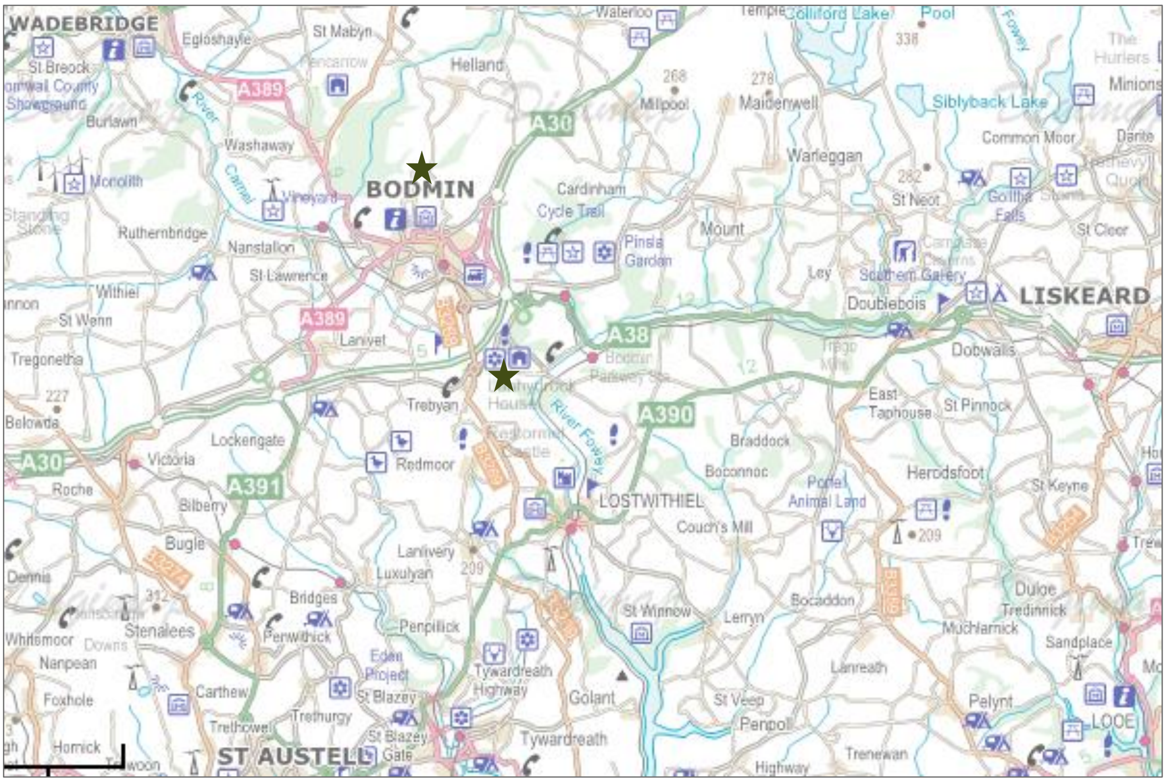

Figure 2. Location of buildings studied is noted by the star (© Crown Copyright and Database Right, 2015)

One, the ecofab office, is constructed of sheep wool panels, the other is a residential property, with walls of straw panel.

Parameters of the buildings are listed below, Table 1.

Table 1. Building parameters

Parameter	Office	Residential
Construction	Wool	Straw
Use	Office	House
Floor area	~74m^2	
Floors	1 plus mezzanine	1
External walls	3	4
Floor finish	Carpet	Concrete with rugs
Wall finish	Plaster and emulsion	Plaster and emulsion
Ceiling finish	Plaster and emulsion	Plaster and emulsion
Furnishings	Densely furnished	Sparsely furnished
Average occupants	5 (3-9)	2, 2 additional regular guests
Building occupancy pattern	Weekdays: 8am – 6pm sealed otherwise Weekends: generally unoccupied, sealed	House occupied full time. Assessed room occupied sporadically.
Room occupancy pattern	The same	Guest room, occupied usually at least weekly
Heating	Unheated for duration of testing	Heated to with underfloor heating
Other factors	Large number of plants. Building purge ventilation not always used appropriately in hot weather	Dense concrete flooring, very sheltered aspect

The floor area and volume of the buildings are shown in Table 2. Location of sensors is shown in Figure 2, Figure 3 and Figure 4.

Table 2. Dimensions of buildings studied

	Office	House
Room area	$46m^2$	
Ground floor area	$75m^2$	
Total area (including first floor)	$122m^2$	
Floor volume	$117.6m^3$	
Total volume	$289m^3$	

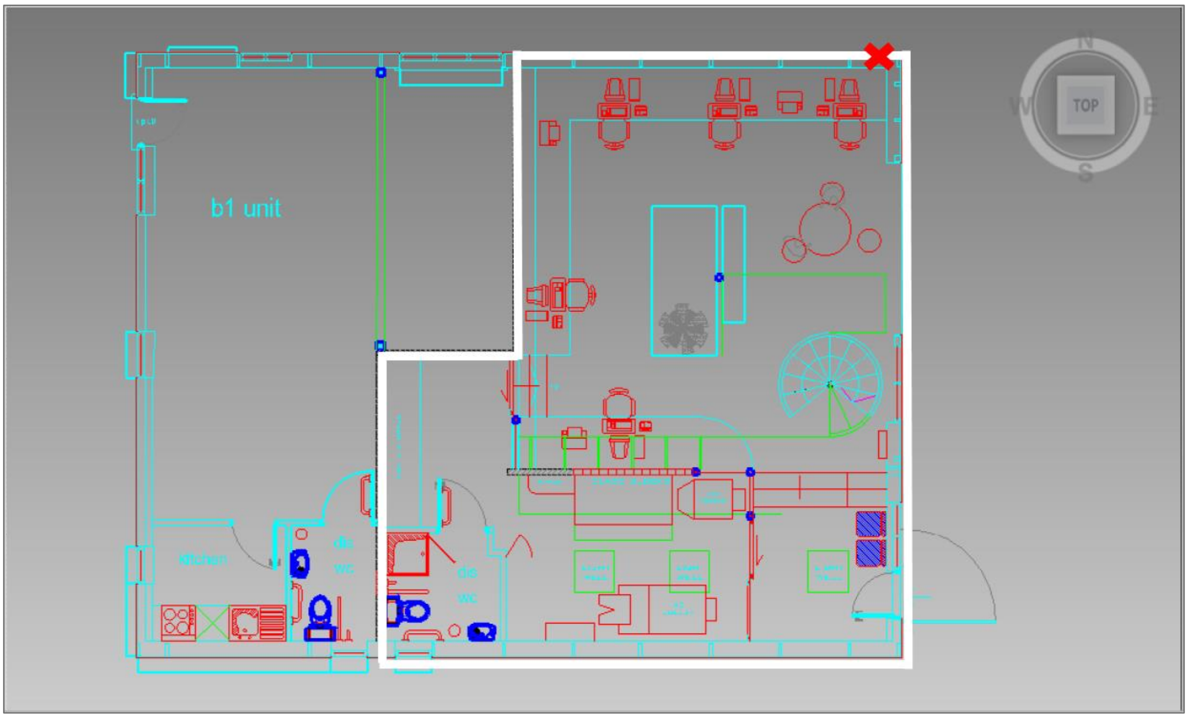

Figure 3. Office plan: red cross denotes sensor location

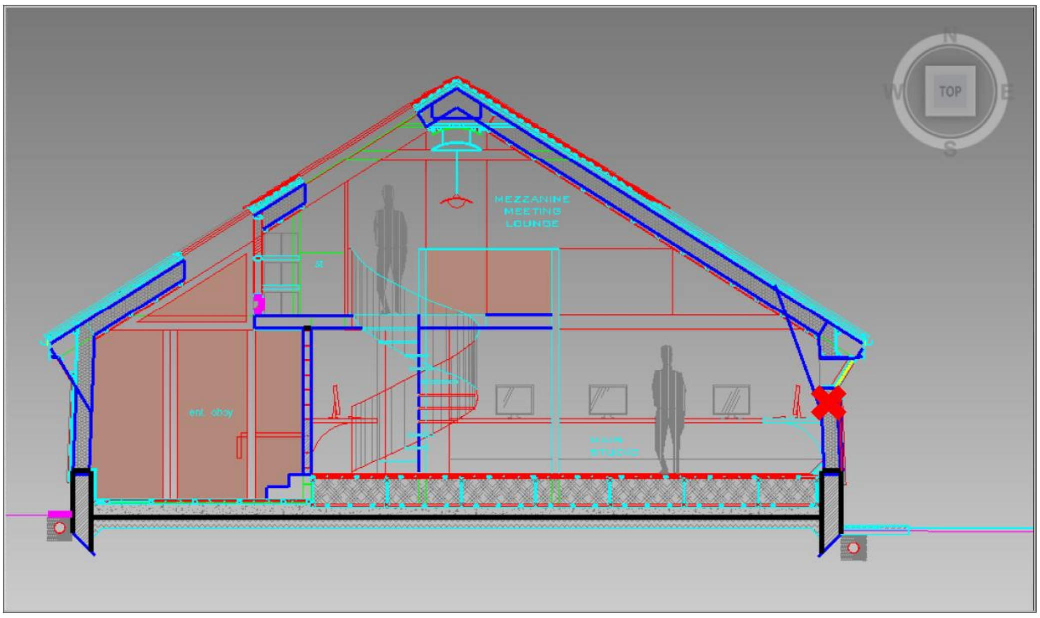

Figure 4. Office elevation: red cross denotes sensor location

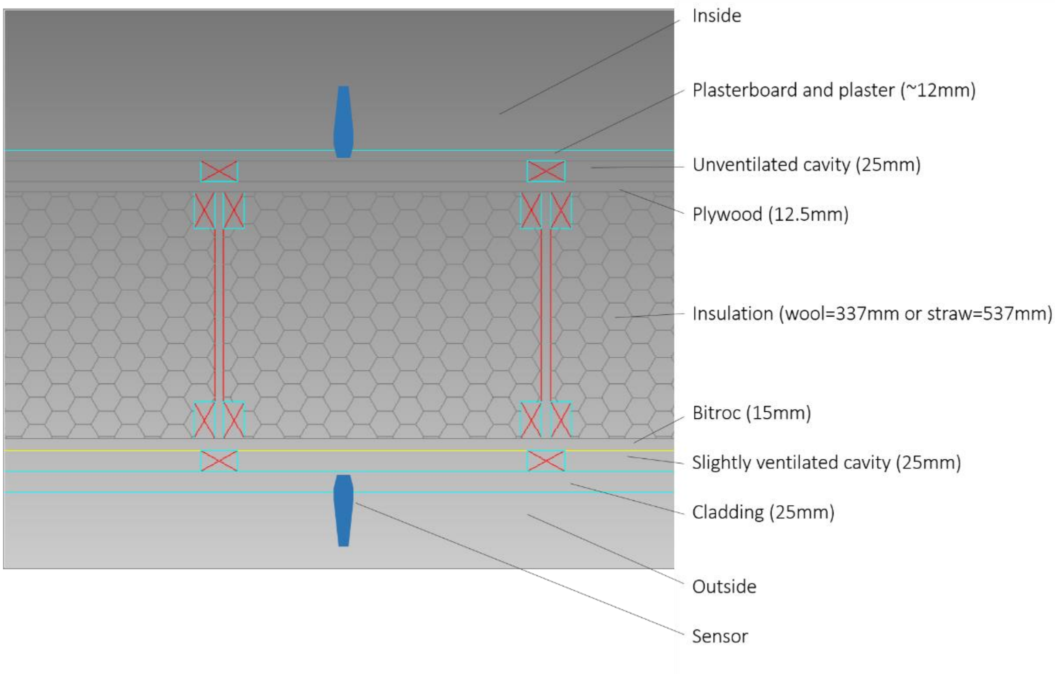

Figure 5. Wall construction and sensor placement

Sensor placement for the house is shown below, Figure 5 and Figure 6.

Figure 6. External sensor placement, house

Figure 7. Internal sensor placement, house

2.2 Measurements

Measurements were taken in five minute intervals from July 7th until December 19th (office) and September 30th until January 22nd (house).

Temperature and relative humidity measurements were taken from the zones shown below, Table 2. The aspect was chosen as representing the most exposed to environmental extremes. A pyranometer mounted on the office building façade with the same exposure as the external probes monitored irradiance from July 7th until September 30th.

Table 3. Sensor placement

Parameter	Office	Residential
Aspect	Westerly corner South facing wall	West facing wall, centre
Location	Downstairs office	Storage space in spare bedroom
Placement	1 - Shielded external air conditions	1 - Shielded external air conditions

	2 - External wall fabric	2 - External wall fabric
	3 - Internal wall fabric	3 - Internal wall fabric
	4 - Internal air conditions (centre of room 2m height)	4 - Internal air conditions (adjacent to wall)
Height above ground	~2m	~1m
Distance from eave	~2m	~2m

The equipment used for the measurements is shown below, Table 3. On 30th September items 1 to 3 were removed from the building and replaced with USB dataloggers (item 5).

Table 4. Equipment used in building performance sensing

Item	**Parameter**	**Instrument**	**Number**
1	Insolation	Delft CM 6B Pyranometer	1
2	Thermocouples		4
3	Relative humidity sensors		2
4	Dataloggers	Gant 1200 series Squirrel	2
5	RH and temperature	Lascar EL-USB-1 datalogger	8

2.3 Results and Discussion

2.3.1 Temperature

Indicative plots of building temperature response are shown below, Figure 7, Figure 8. Internal temperature conditions in the wool building lag the external cycle by a number of hours and peaks and troughs are smoothed. Internal temperatures of the straw building remain exceedingly stable. Caution must be exercised in the analysis of the straw building behaviour due to the use of heating.

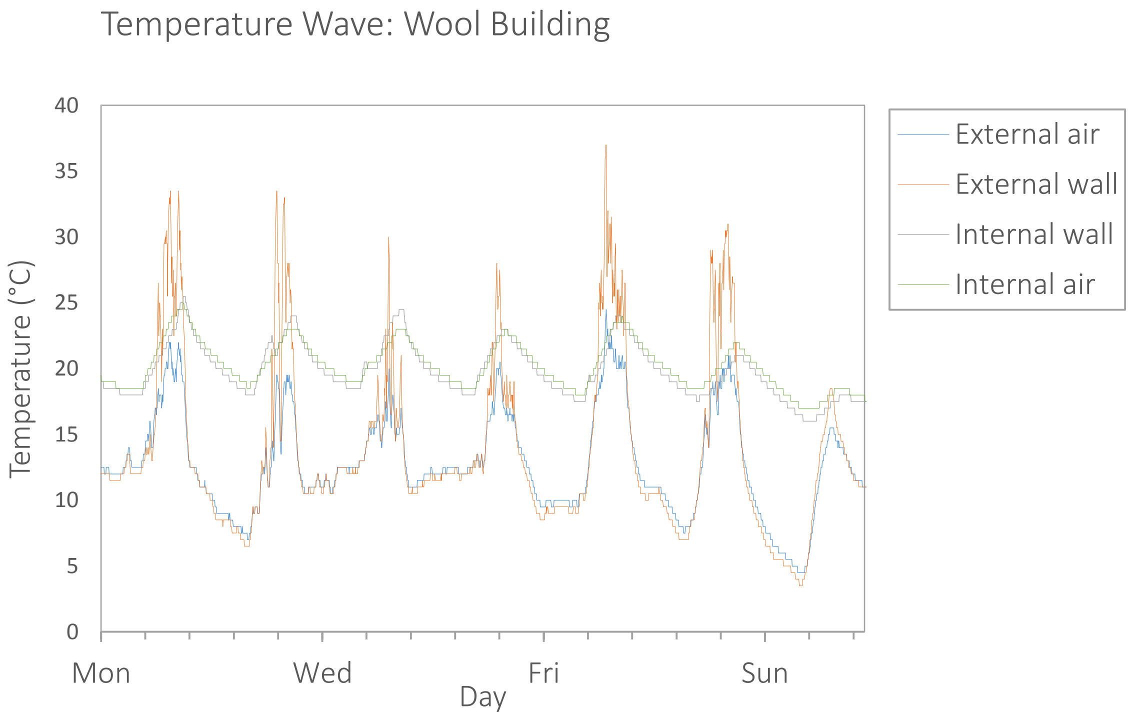

Figure 8. Temperature fluctuation, wool building, W/C 6th October

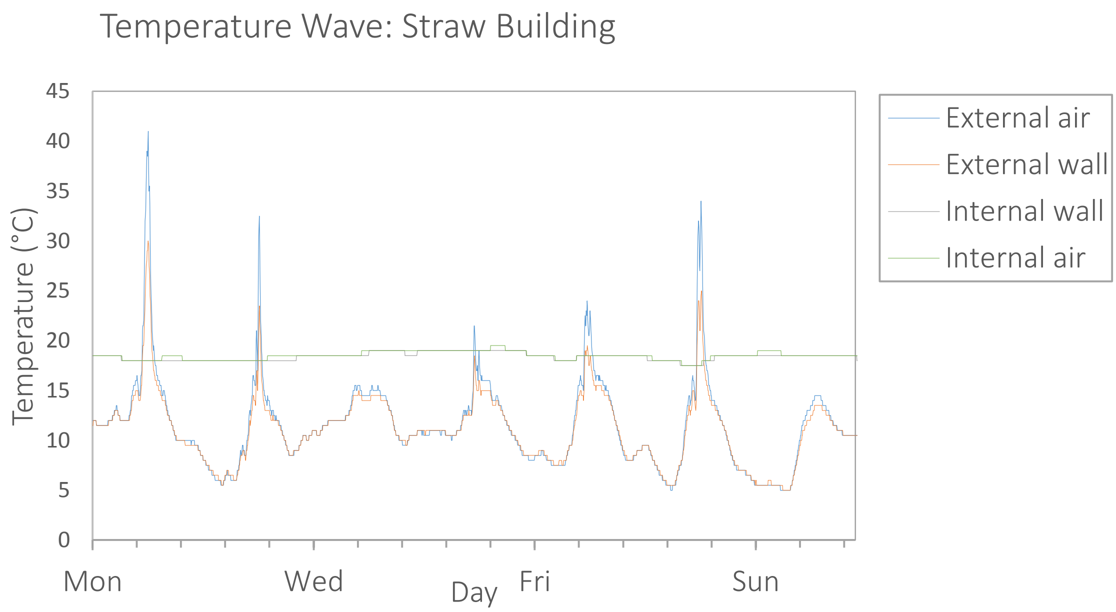

Figure 9. Temperature fluctuation, straw building, W/C 6th October

Over the duration of the testing thermal damping in the straw building is greater than in the wool building, and more consistent, Table 5.

Table 5. Thermal damping characteristics at the two properties

	Wool building		Straw building	
	Air-air (%)	Fabric-fabric (%)	Air-air (%)	Fabric-fabric (%)
August	-	14	-	-
September	31	20	-	-
October	30	17	13	16
November	38	33	13	22
December	39	46	13	26
January	-	-	12	25

In comparison to other construction types the wool building performs very well and the straw building (including underfloor heating) damps thermal extremes exceedingly well, Table 6 and Figure 9.

Table 6. Thermal damping characteristics of other external wall constructions calculated according to EN ISO 13786:200

External wall	Decrement factor (fabric-fabric) (%)	U value (W/m^2K)
Timber frame, brick outer leaf [1]	55	0.28
Timber frame, brick outer leaf	31	0.15
Full fill brick and lightweight aggregate block[2]	24	0.28
Full fill brick and lightweight aggregate block	19	0.12
Full fill brick and dense aggregate block[3]	23	0.28

[1] Mineral wool insulation

[2] PIR insulation with plastic drainage panel

[3] Polystyrene bead insulation

Full fill brick and dense aggregate block	22	0.15

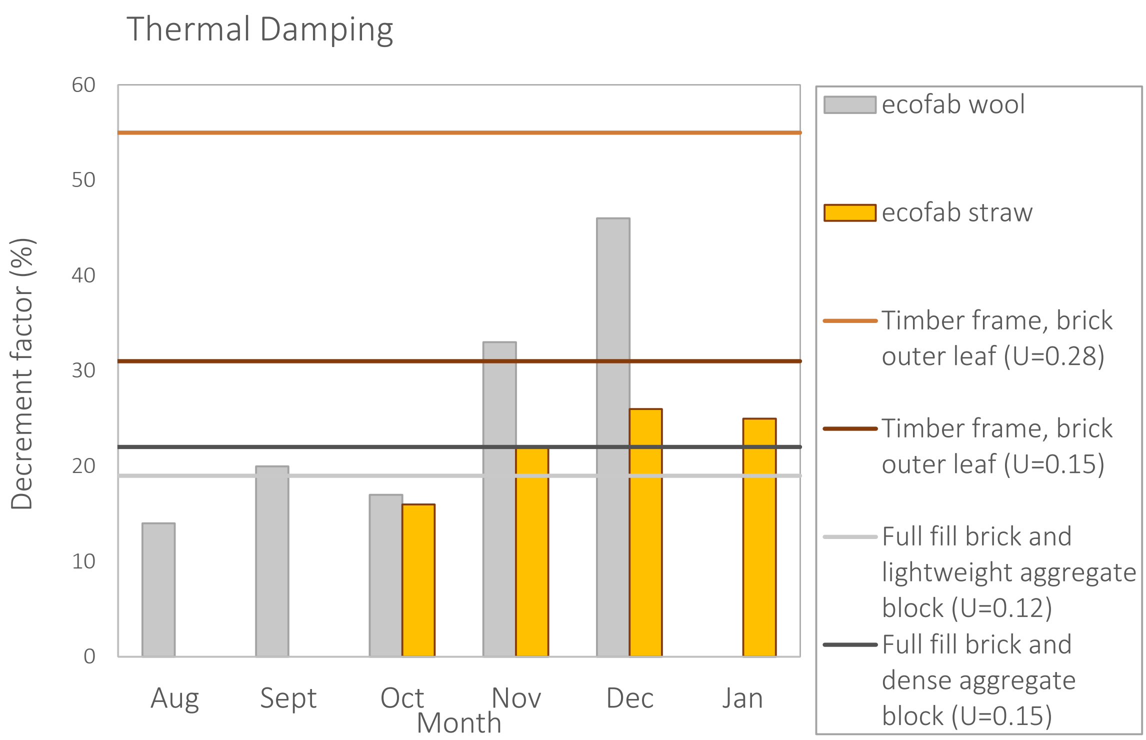

Figure 10. Thermal damping by construction type

Both buildings outperform the less insulated timber frame build. The wool build outperforms the more insulated timber frame and the dense aggregate block build until October and betters the lightweight aggregate block in two months. The straw outperforms the timber frames in all cases, competes with the dense block but is generally less damping than the lightweight block. Both fabrics generally perform better in earlier months.

Fabric-to-fabric thermal delay characteristics of the two buildings can be compared to a range of construction types, Table 7, Table 8, Table 9 and Figure 10, with the delay of temperature maxima the best comparator.

Table 7. Thermal delay characteristics for periods covered, wool building

Time period	Air-air: maxima	Air-air: minima	Fabric-fabric: maxima	Fabric-fabric: minima
August	-	-	3h 15m	3h 16m
September	1h 50	2h 29	2h 13m	2h 56m
October	1h 53m	2h 20m	2h 22m	2h 56m
November	2h 28m	5h 28m	2h 27m	5h 35m
December	3h 38m	3h 32m	2h 59m	4h 05m

Table 8. Thermal delay characteristics for periods covered, straw building

Time period	Air-air: maxima	Air-air: minima	Fabric-fabric: maxima	Fabric-fabric: minima
October	8h 23m	4h 04m	8h 54m	4h 10m
November	10h 50m	6h 57m	11h 54m	5h 57m
December	3h 38m	5h 39m	7h 09m	4h 22m
January	7h 49m	4h 13m	5h 23m	7h 00m

Table 9. Thermal delay characteristics of external wall constructions calculated according to EN ISO 13786

External wall	Decrement delay	U value
Timber frame, brick outer leaf	07h 36	0.28
Timber frame, brick outer leaf	10h 42	0.15
Full fill brick and lightweight aggregate block	11h 00	0.28
Full fill brick and lightweight aggregate block	13h 30	0.12
Full fill brick and dense aggregate block	09h 42	0.28
Full fill brick and dense aggregate block	10h 36	0.15

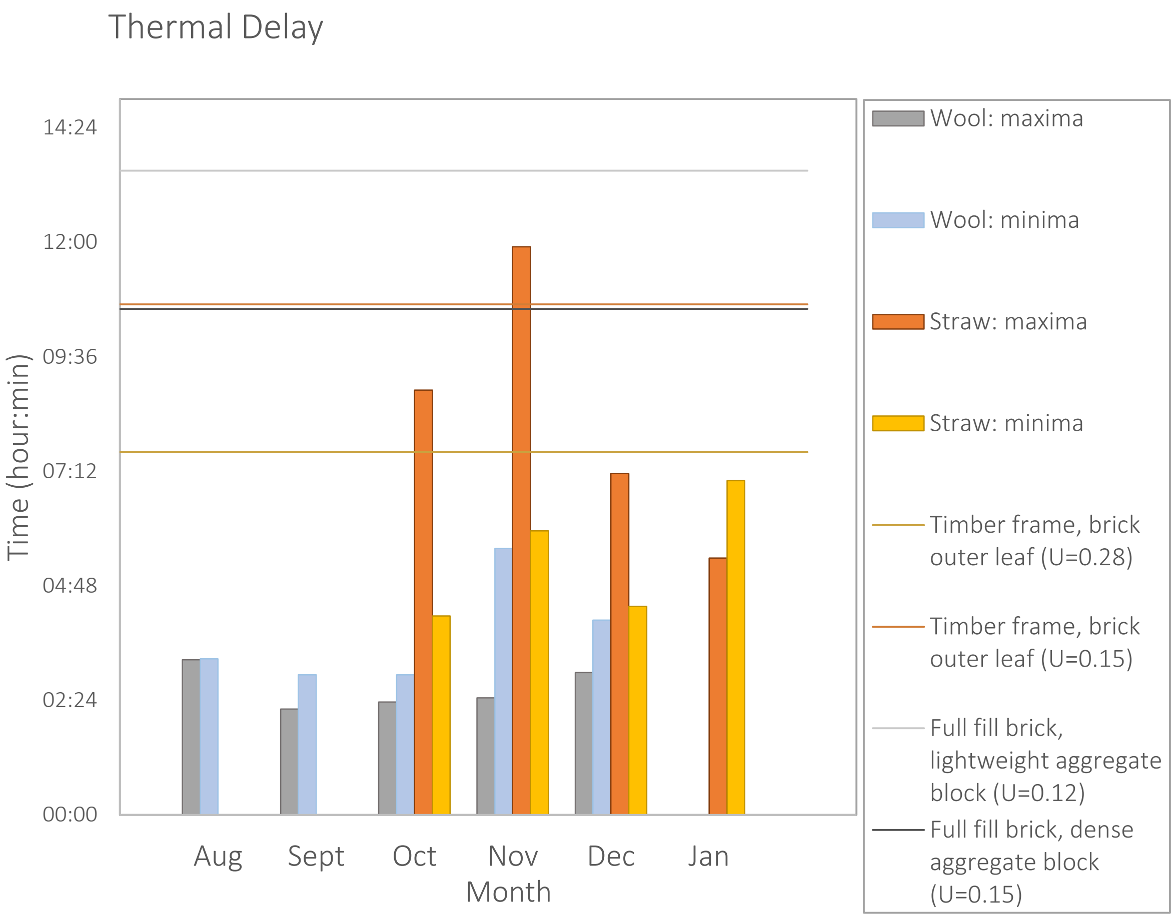

Figure 11. Thermal delay by construction type

In general, the buildings studied fail to provide the length of thermal delay provided by walls which incorporate block or brick. The exception in this test is the performance of the straw building in delay of high temperatures in October and November. The straw building outperforms the wool building.

The straw building delays high temperatures better than low, with the wool showing an opposite, but less pronounced, trend. The results from the straw house should be regarded with caution due to the presence of central heating in adjacent rooms and the difficulty in correlating internal temperature fluctuations to external conditions.

2.3.2 Relative Humidity

Internal relative humidity of the wool building show significant damping, Figure 11. Figure 12 shows similar tends at the straw insulated building, with even greater damping.

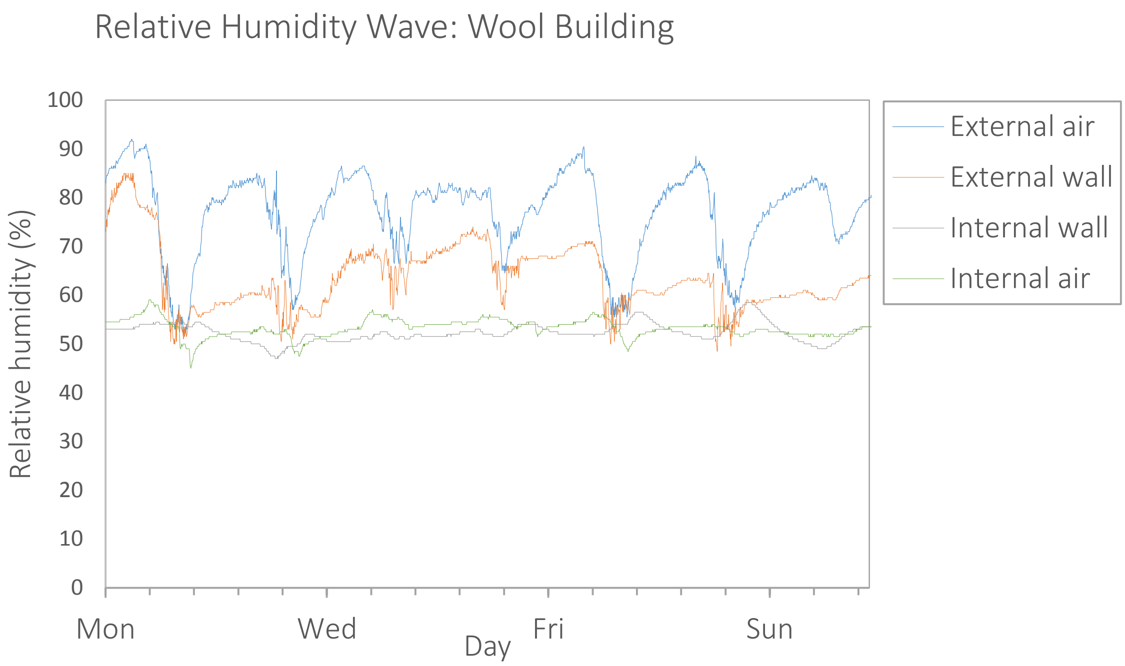

Figure 12. Week RH fluctuation, wool building, W/C 6th October

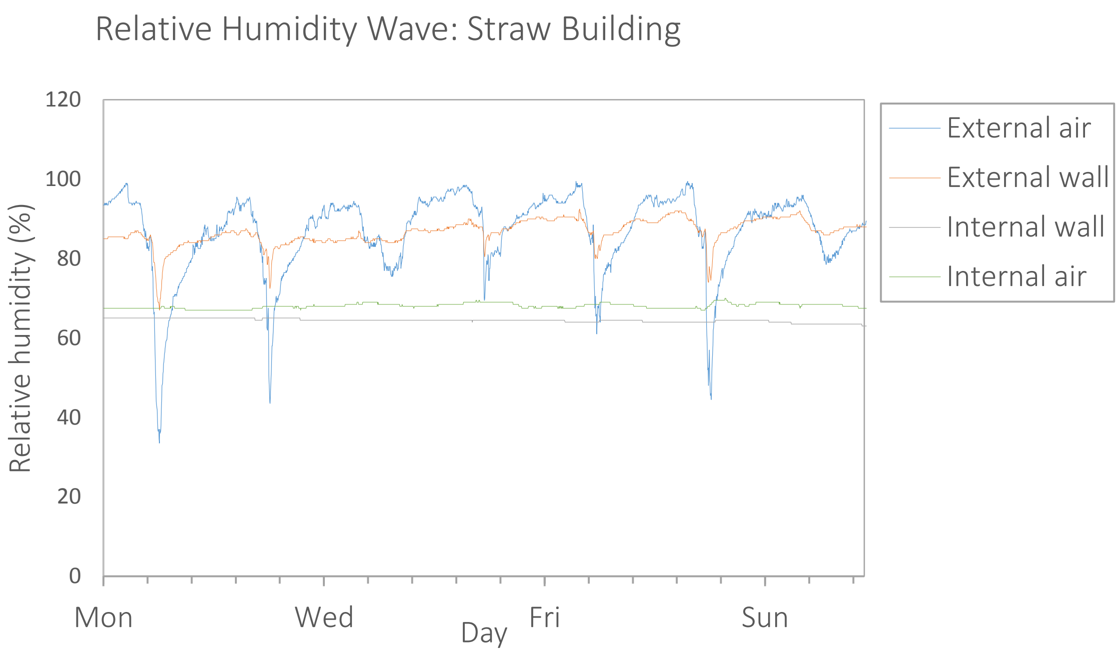

Figure 13. Week RH fluctuation, straw building, W/C 6th October

Damping of external relative humidity fluctuations is generally more pronounced in the straw building, and slightly more consistent, Table 10 and Figure 13. Damping of air conditions is more effective than fabric-to-fabric damping in both cases. It is not possible to compare these results to other building types using EN ISO 13786.

Table 10. RH damping characteristics at the two properties

	Wool building		Straw building	
	Air-air (%)	Fabric-fabric (%)	Air-air (%)	Fabric-fabric (%)
August	-	25	-	-
September	22	59	-	-
October	21	65	11	20
November	20	24	11	45
December	19	45	9	39
January	-	-	19	36

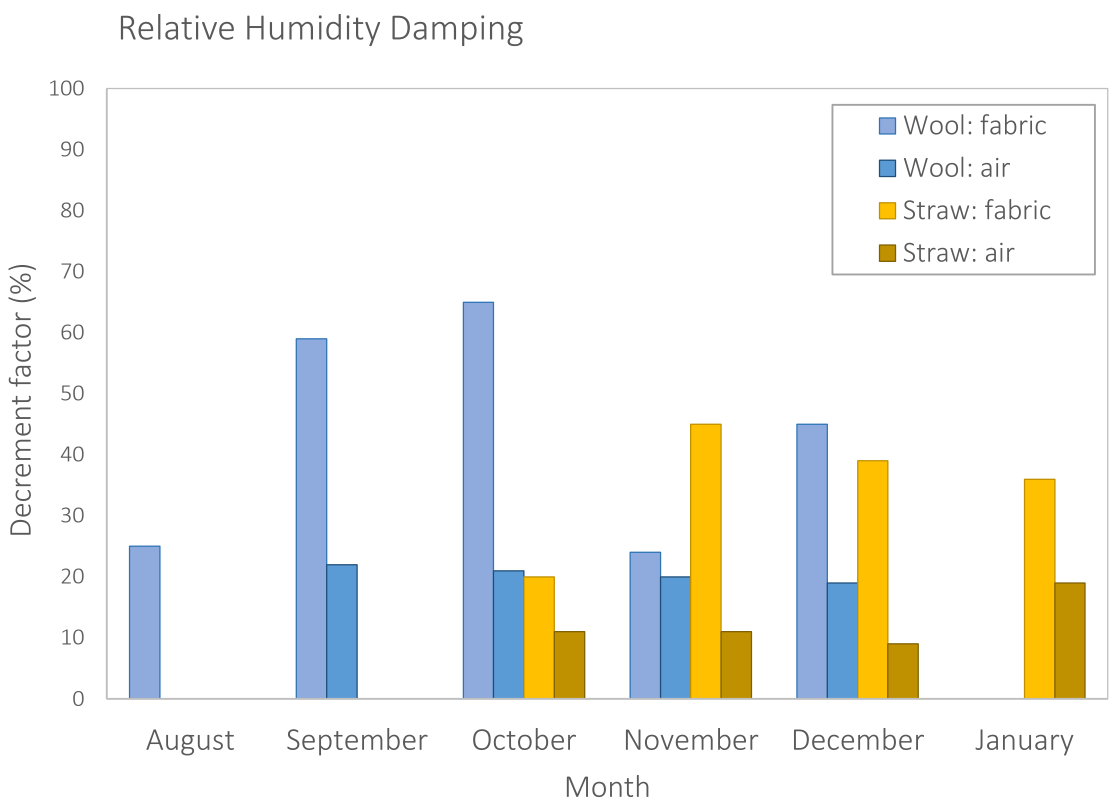

Figure 14. Relative humidity damping

Delay of external relative humidity peaks and troughs is shown in Table 11, Figure 14, Figure 15 and Figure 16.

Table 11. RH delay, wool building

Time period	Air-air: maxima	Air-air: minima	Fabric-fabric: maxima	Fabric-fabric: minima
August	-	-	14h 04m	16h 45m
September	04h 07m	05h 43m	08h 50m	15h 49m
October	03h 51m	03h 20m	08h 47m	16h 23m
November	05h 13m	04h 39m	09h 57m	14h 22m
December	10h 37m	08h 22m	05h 14m	12h 12m

Table 12. RH delay, straw building

Time period	Air-air: maxima	Air-air: minima	Fabric-fabric: maxima	Fabric-fabric: minima
October	9h 02m	11h 24m	7h 51m	10h 24m
November	8h 07m	10h 26m	5h 29m	10h 21m
December	8h 47m	6h 24m	5h 54m	10h 03m
January	2h 30m	12h 50m	5h 56m	07h 54

A similarity between the ability to delay relative humidity highs and lows is seen in both buildings over all months, excepting the straw building air-to-air measurements in January, Figure 14. Overall, the straw building appears to perform better than the wool building at delaying RH of the air, Figure 15, while the wool building performs better in fabric-to-fabric delay, Figure 15. Minimum wall relative humidity is delayed better than maxima in both buildings, Figure 15.

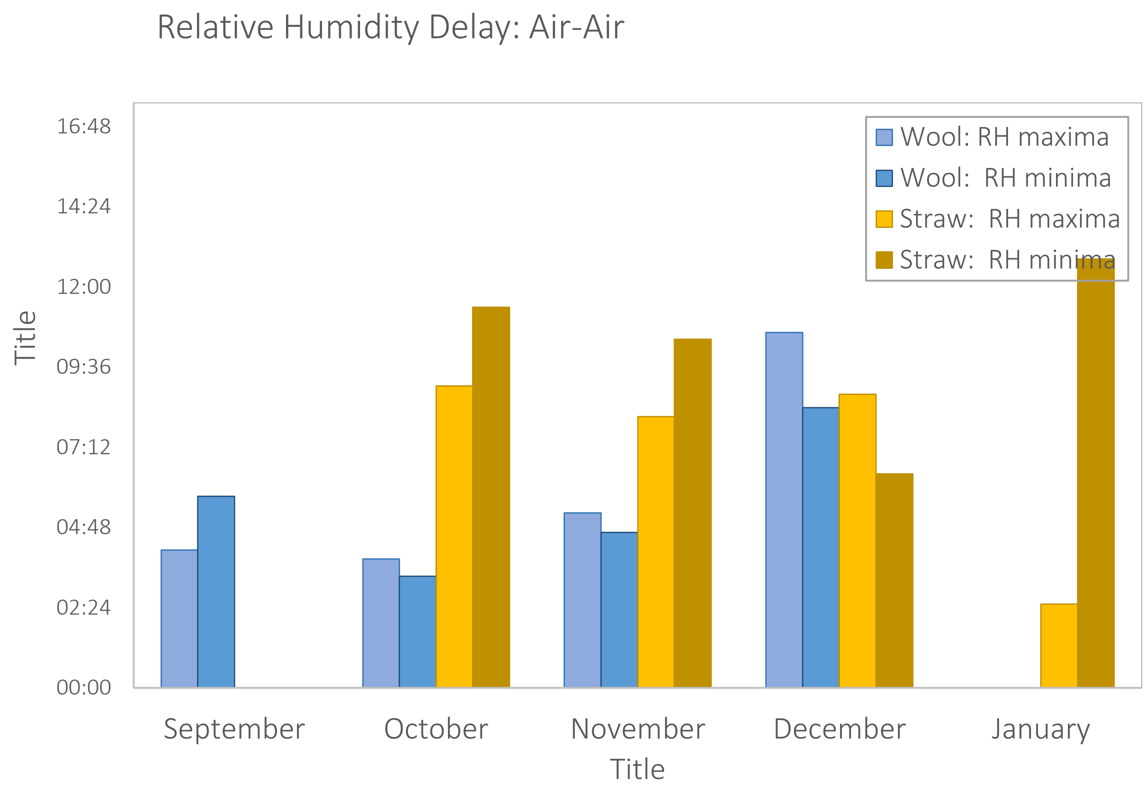

Figure 15. RH delay from air-air measurements

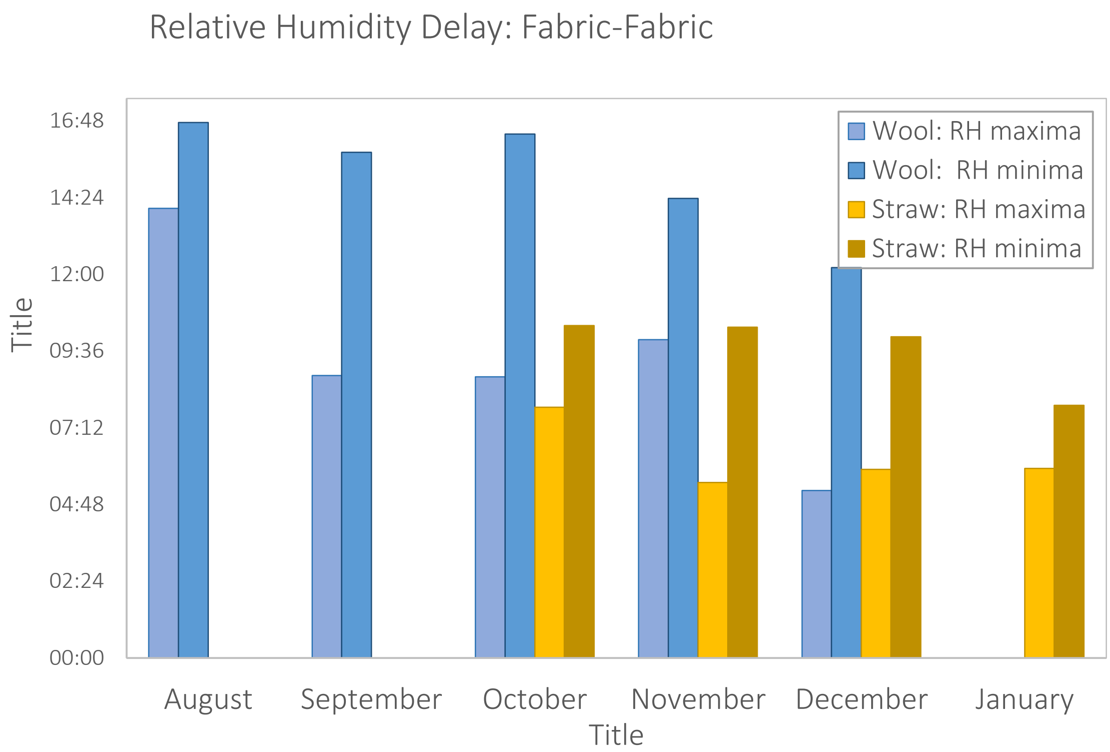

Figure 16. RH delay from fabric-fabric measurements

Averaging high-delay and low-delay values shows that the fabric of the wool building gives the longest delay although the air of the wool building most rapidly follows external relative humidity with the straw fabric and air delays closely correlated to one another between these two extremes.

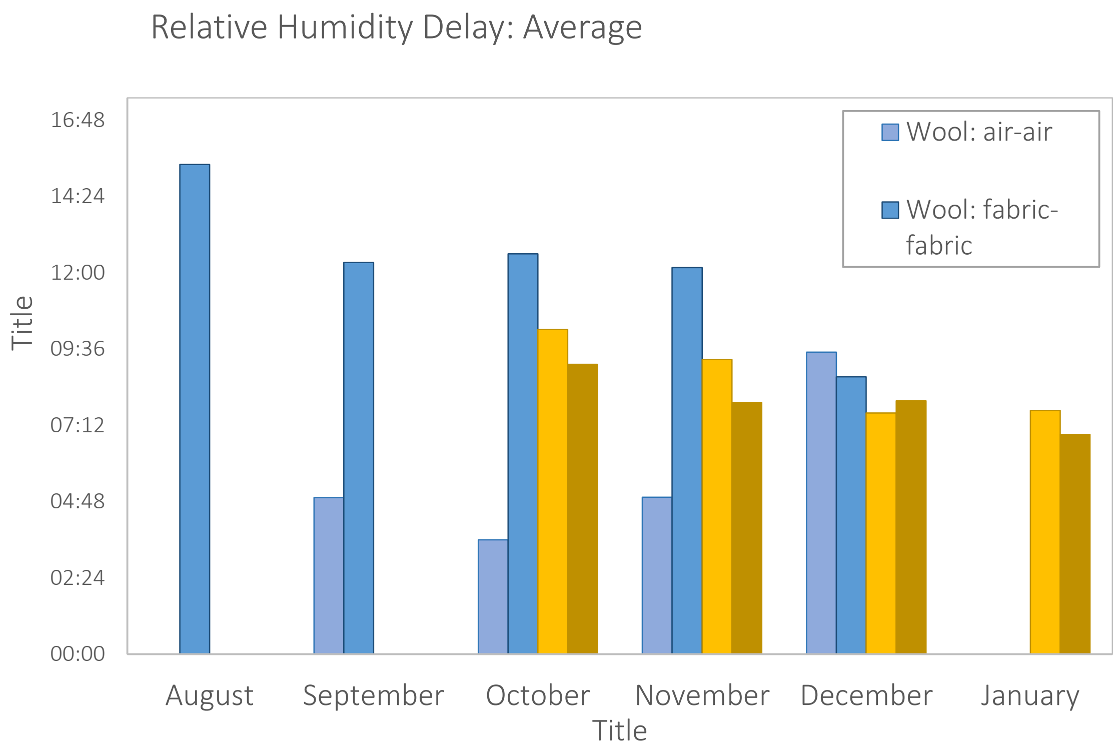

Figure 17. Average RH delay in ecofab buildings

Average relative humidity values are shown for the sensor points in Table 13 and Table 14 and the trends are shown graphically, Figure 17. The straw building sees highest RH conditions with average RH for the month in the mid-sixties for the internal wall and around 70 for the air.

Table 13. Average internal RH, wool building

	Internal wall (%)	Internal air (%)
August	54	-
September	53	53
October	55	56
November	57	58
December	51	52

Table 14. Average internal RH, straw building

	Internal wall (%)	Internal air (%)
October	65	68
November	66	71
December	65	69
January	60	66

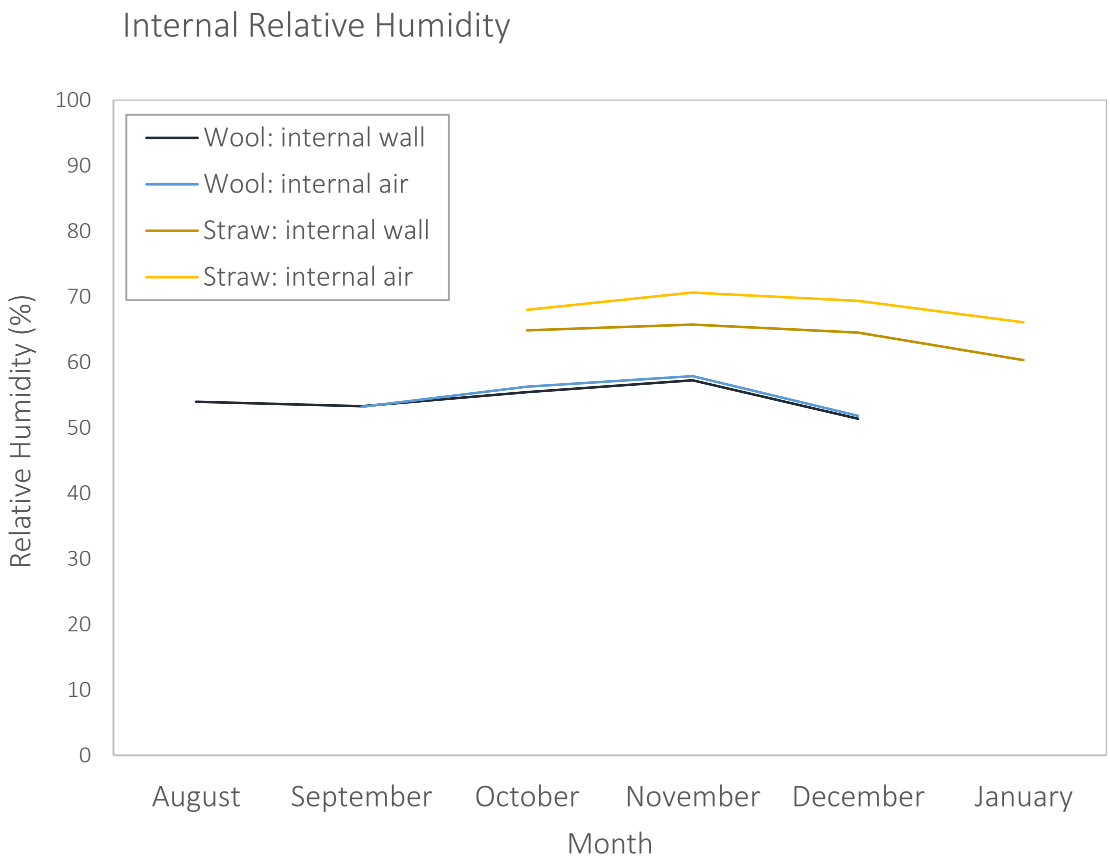

Figure 18. Average internal RH

The straw building sees considerably higher relative humidity in all cases, with the air in both buildings at higher RH than the wall itself. Time spent at the highest values of RH are shown in Table 15 and Table 16.

Table 15. Time spent at high RH, wool building

	Internal wall		Internal air	
	over 65%	over 70%	over 65%	over 70%
August	5h 40m	0h 0m	0h 0m	0h 0m
September	1h 6m	0h 0m	0h 0m	0h 0m
October	1h 6m	0h 0m	0h 0m	0h 0m
November	2h 15m	0h 0m	9h 48m	0h 0m
December	34h 24m	0h 0m	30h 20m	0h 5m

Table 16. Time spent at high RH, straw building

	Internal wall		Internal air	
	over 65%	over 70%	over 65%	over 70%
October	244h 35m	0h 0m	586h 40m	27h 40m
November	391h 20m	0h 0m	616h 50m	44h 25m
December	235h 25m	0h 0m	524h 10m	133h 45m
January	0h 0m	0h 0m	377h 15m	0h 0m

Considerable time is spent with both internal wall and air at RH greater than 65% in the straw built house, some time is spent with internal air in excess of 70% RH. The wool building sees internal wall conditions at above 65% RH for a short duration in most months but almost never sees any conditions over 70% RH. The trend is for increasing RH from summer to November, with a decrease in both properties after this period.

2.4 Conclusions

2.4.1 Damping

In general the results show that both straw and wool walls make a significant contribution to the damping of temperature and moisture, effectively smoothing peaks and troughs in external conditions.

Temperature damping of both buildings competes with that of more conventional material constructions. Neither building fabric tested provides the level of thermal delay of block or brick constructions under these conditions. The straw building outperforms the wool building in temperature damping and delay.

Relative humidity damping is generally more pronounced in the straw building and slightly more consistent. Average relative humidity delay in the fabric of the wool building ranges from around nine hours to around 15 and a half hours. The straw provides shorter delays with a range of seven to just over nine hours.

2.4.2 Delay

It appears that the wool building allows only a short delay from change in outdoor air conditions and those indoors, with three of the four months studied averaging a delay of between three and a half and five hours. The fabric readings however, of between nearly nine and fifteen and a half hours, suggest that the peaks and troughs outside are being delayed more effectively than it seems by the fabric of the wall and that internal air fluctuations may be due to other sources.

The straw building suffers the most time at high values of RH, perhaps due to its situation: adjoining a bedroom, adjacent to a bathroom and without an external opening. It should also be kept in mind that in the straw house heating is used and there results some difficulty in consistently correlating internal fluctuations to external conditions.

2.4.3 Potential for Unhealthy Conditions

Studies have shown that moulds can germinate and grow at a relative humidity of above 80%, ASHRAE recommends relative humidity be kept below 65% to reduce the occurrence conditions which can lead to microbial growth (British Standards, 2002), (ASHRAE, 2014). Ashour (2003) states that above approximately 70% equilibrium RH microbial activity is more likely to occur and straw may become unstable. It is recommended by the BRE (2011) that in-service moisture content of straw bale build not normally exceed 20-25% and Collins et al. (1987) cite moisture content above 20% as likely to cause biological degradation of straw.

With regards to microbial growth conditions in the straw building may provide, with the fabric RH averaging around the value which ASHRAE recommend should not be exceeded. The value stated by British Standards is not reached in monthly averages however.

Hygroscopic materials will reach equilibrium with the humidity of the ambient air and straw bale is expected to reach a certain equilibrium moisture content (EMC) for a corresponding RH, Table 17. Considering the temperature and RH ranges seen by the building it is likely that the EMC of the bales is not expected to exceed 13.5% or approach dangerous levels.

Table 17. EMC at range of RH values and 20°C for straw bale (Ashour, 2003)

RH (%)	EMC at 15°C (%db[4])	EMC at 25°C (%db)
53	11.1	11
65	13.5	12.8
75	13.6	13.2
85	15.9	15.7
90	18.1	17.8
96	19.4	19.3

[4] Dry basis

2.4.4 Limitations and Further Study

Primary limitations in this analysis are interference from building use: moisture and heat accumulations from human activity disrupt the clarity of building response to external stimuli. The type of use is also different between the buildings, office and residential, which means that comparisons between the fabrics are biased. Limited length of data acquisition period and number of data acquisition points is also a limiting factor with seasonal trends only just beginning to display.

It would be most valuable to obtain data from the straw house without internal heating. It would be of interest to isolate and analyse building behaviour over certain time periods (for example occupied/unoccupied) for both buildings. An occupancy log and quantification of heat and humidity gains from human activity would be beneficial in order to separate man-made and weather-driven fluctuations.

The high RH values observed in the straw house are of some concern and investigation should be made into their accuracy and whether they are indicative of the building as a whole. Investigation of methods of moisture control should be made, which may be as simple as allowing more regular ventilation to this room. Data of at least a year should be gathered to enable the seasonal patterns which are just emerging to be observed; data from the wettest seasons on the straw building would be of greatest interest.

It would be of value to estimate the expected performance of the ecofab building fabric using the standard EN ISO 13786:2007 and to compare this with real building results.

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