WPT4.2 Report:

Dataset that establishes the energy credentials and associated reductions in carbon emissions for the Plymouth prototype CobBauge building

University of Plymouth

May 2023

Introduction

(More detail on the information contained in this report can be found in the appropriate deliverables)

This report will summarise the means by which data on the performance of the Plymouth prototype has been gathered.
Sensors were used to gather data during two phases:

- The construction phase, where they were used to record the moisture content of the walls as they dried, and to record any associated movement in the walls.
- The occupation phase, where a variety of sensors were used to record the effects of human interaction with the building, and the buildings relationship with its own environment.

The sensors used during the construction phase were:

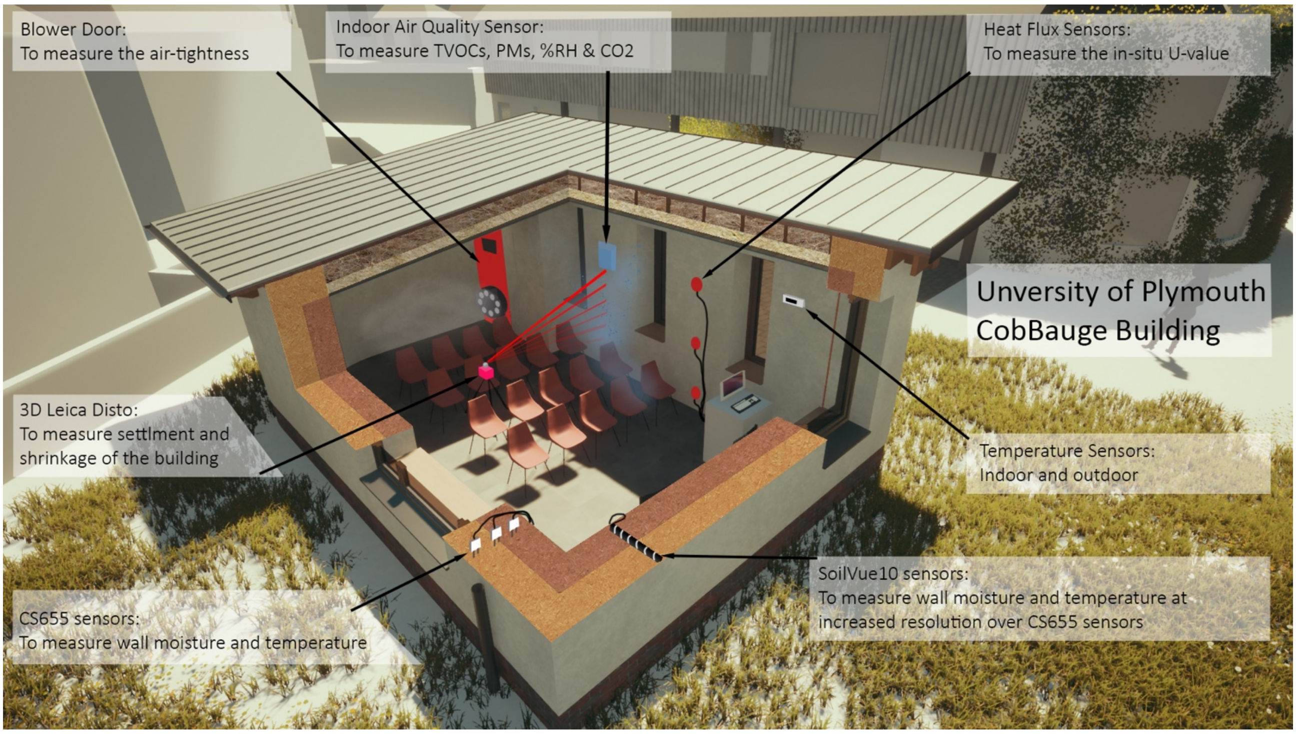
- Campbell Scientific CS655 sensors to measure the moisture and temperature at three depths through the wall
- Campbell Scientific SoilVue 10 sensors which also measure moisture and temperature but at a higher resolution than the CS655 sensors. These give us six sets of data through the wall
- A Leica 3D Disto laser measuring device that was used to accurately track the settlement and shrinkage of the CobBauge walls.

The sensors used for the occupation phase were:

- A blower door apparatus to measure the permeability of the building
- A Synetica Enlink IAQ-C indoor air quality sensor linked a LoRaWan network and pushing live data to a dashboard on the CobBauge website.
- Heat flux sensors to give a real time 'U value' measurement of the buildings insulation value
- A selection of data-logging sensors to measure temperature (inside and out), relative humidity, illuminance (light levels) and electrical power usage.

Areas covered by this report:

- Measurement of the moisture content of the walls and the associated shrinkage rates
- The use of heat flux sensors to record real time U values
- The different sensors used to record the Indoor Air Quality (IAQ)
- External air quality
- Air tightness testing with a blower door device
- Use of thermal cameras to assess the thermal performance
- A method for disseminating the data from an indoor air sensor through a local are network, and the dashboard on the CobBauge website
- Thermal comfort
- Illuminance and quality of lighting
- An evaluation of the role of the specific heat capacity of the CobBauge walls.



3D cutaway drawing of the Plymouth prototype showing the sensors used and their placement in the building

Measuring the moisture in the walls

Methodology:

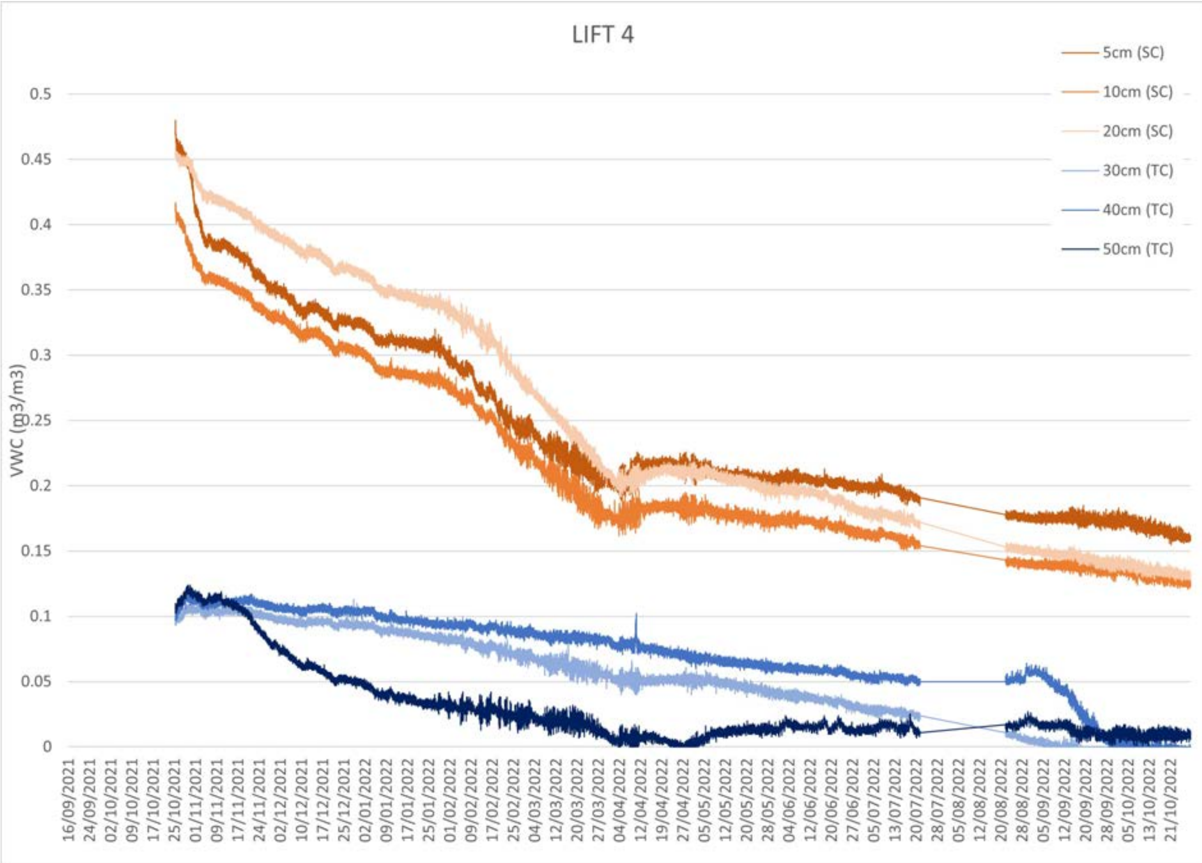
We have 8 moisture probes embedded in the CobBauge walling.

4 x Soilvue 10 and 4 x Campbell CS655 sensors. They are connected to a CR1000X data logger.

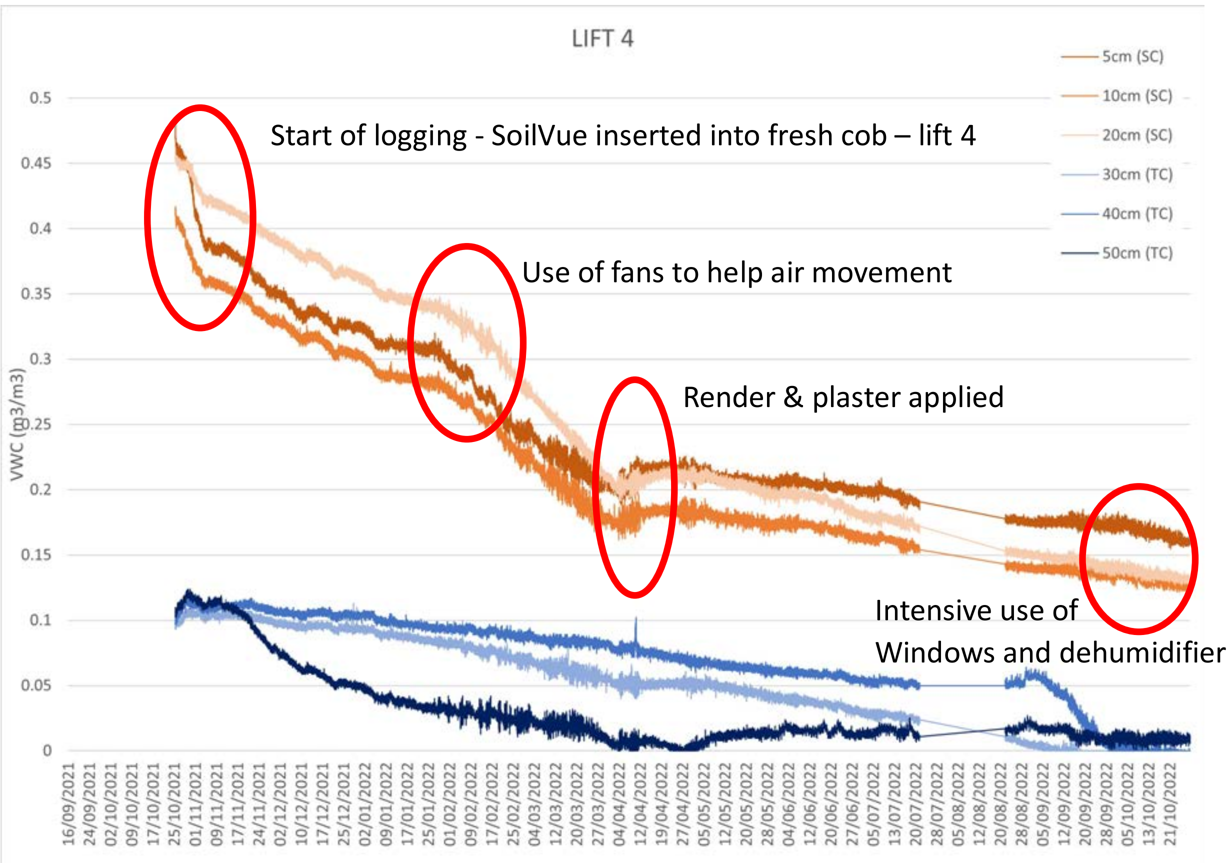
They are monitoring Temperature and Volumetric Moisture Content (VMC)

The results shown here are from the Campbell Soilvue 10 installed in the last lift to be built, lift no. 4

Results:



Graph of the moisture in the walls of the CobBauge building from 16th Sept. 2021 – 21st Oct 2022



The same graph with major events recorded and their effect on the moisture in the walls

The two versions of the graph above show the moisture content of the CobBauge walls measured in six places through the walls. The three shades of brown are the points in the structural mix (dense cob, 2.5% fibre) at 5cm, 10cm and 20cm through the wall. The blue traces are from the three points through the lightweight thermal mix (50% hemp shiv) at 30, 40 and 50cm.

The events that had the most effect on the moisture in the walls are highlighted in the second graph. They are:

- A pronounced loss of liquid in the first couple of weeks at the start of logging. After this the rate of drying continues more slowly until January 2022, when a cold period seems to slow the drying right down.
- Due to concerns about the rate of drying, three large fans were installed in the building. They were arranged in a circle around the building in order to establish a steady air movement. After the fans were installed, we can see an increase in the rate of drying until -
- The internal clay plaster and external lime render are applied. The internal clay plaster appears to be having a pronounced effect, with the moisture levels increasing throughout the 300mmm of the structural mix on the inside of the building.
- Although the building is continuing to dry out, progress is slow, and it is decided to encourage drying by leaving the windows open and using a dehumidifier in the space.

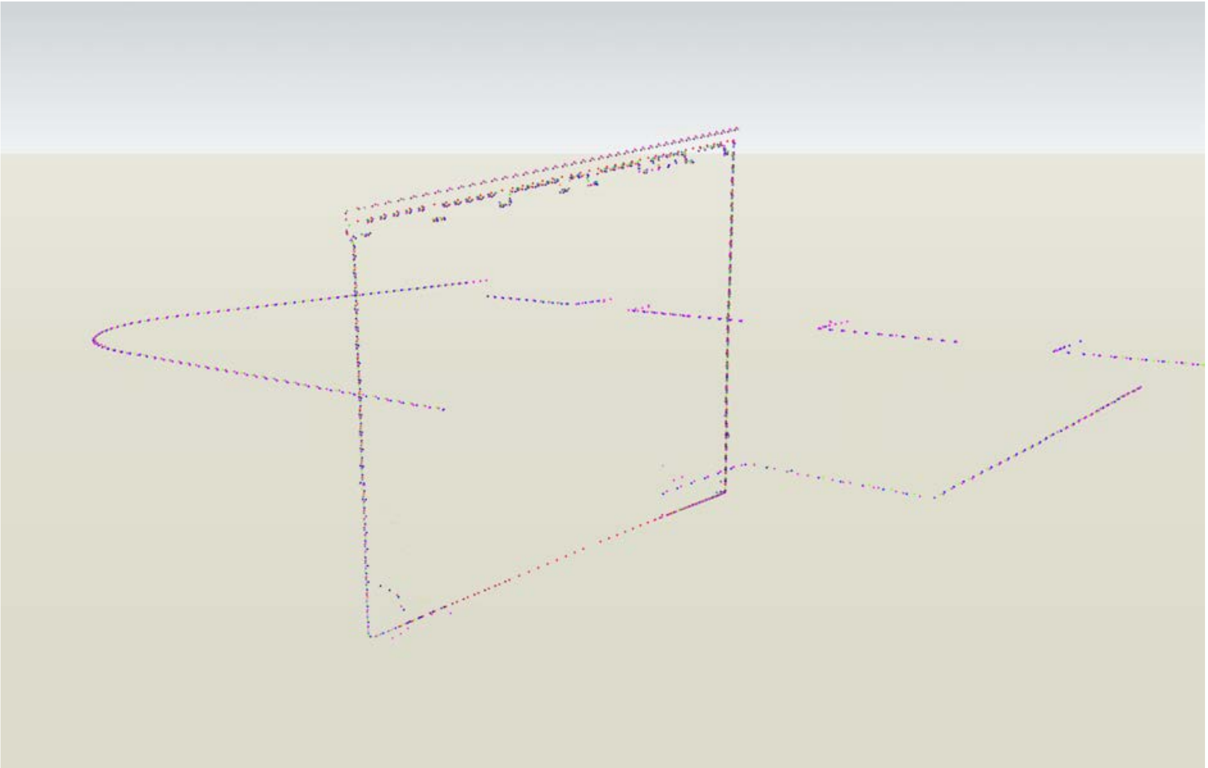
The main observation to be made here is that it has taken perhaps a little longer than expected for the walls to dry out, and that care should be taken over the timing of the internal rendering due to its effect on the drying of the walls.

Measuring the shrinkage in the walls

Measuring the shrinkage in the building with a Leica 3D Disto.

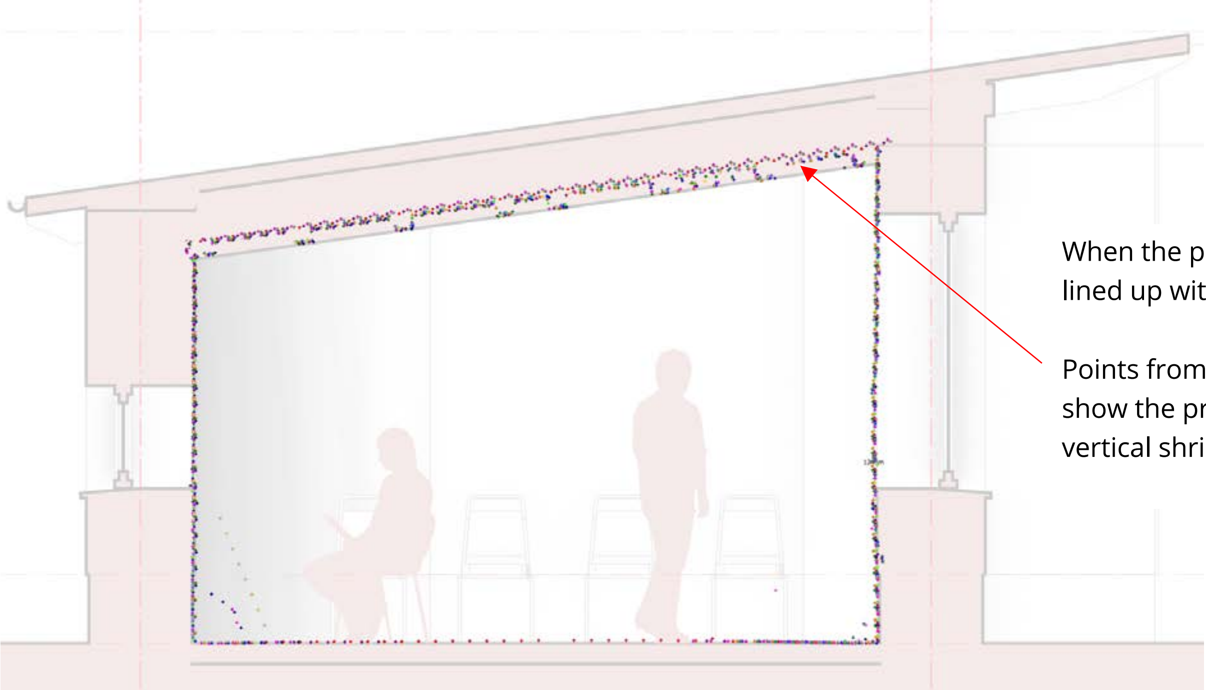
Methodology:

A Leica 3D Disto was set up in the centre of the building and programmed to take laser measurements at 50mm intervals horizontally and vertically around the interior of the building.
This produces a 3D point cloud plan and section that can be imported into a 3D drawing package (SketchUp). This process was repeated over the period that the building was drying in order to record any shrinkage in the walls as they dried



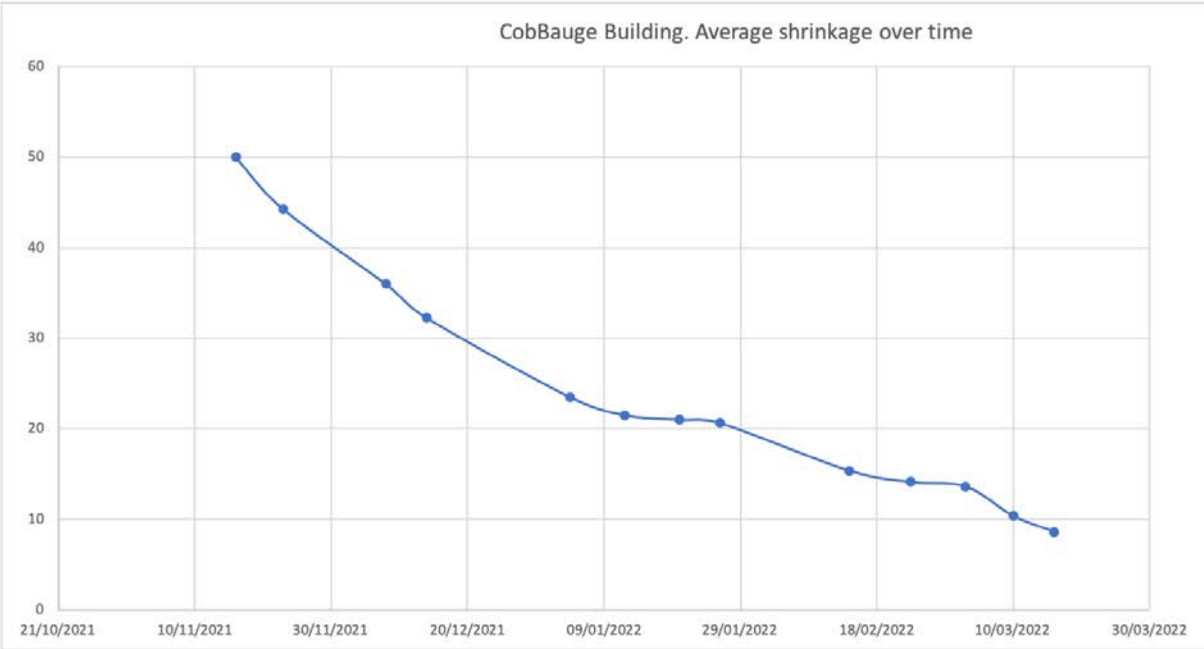
Multiple plans and sections imported into SketchUp

The sectional points taken over time from the 3D Disto were then overlaid onto a sectional drawing of the building provided by the architect.

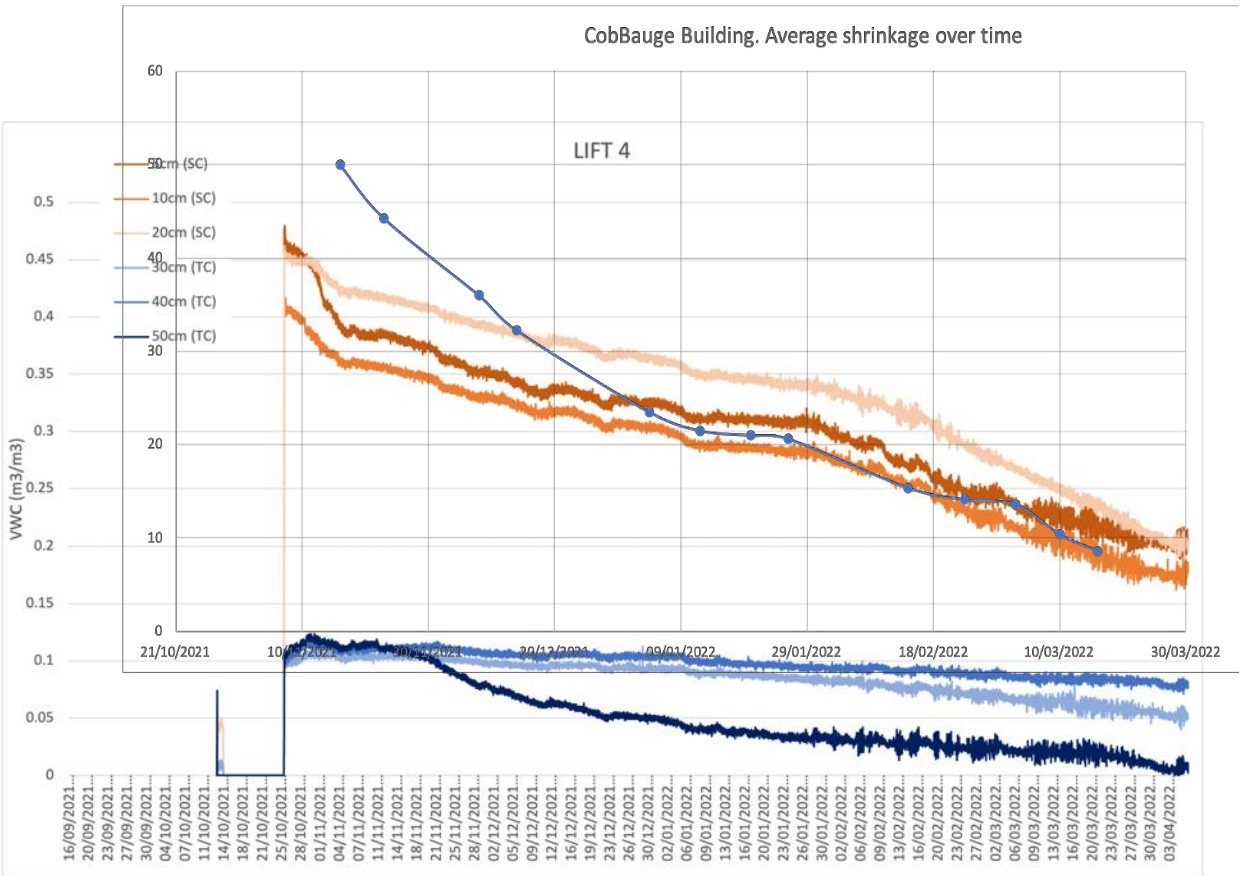


Results:

The distance between the points taken from the ceiling show a rate of vertical shrinkage that can be plotted over time.

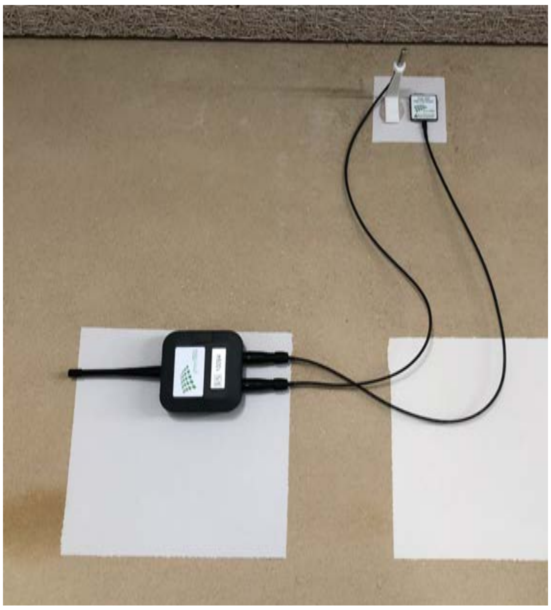


Going back to the chart of the moisture content, overlaying the shrinkage data over the same period, we see a close correlation, especially during the period in January 2022 when the moisture plateaued, with the shrinkage slowing down at the same time.



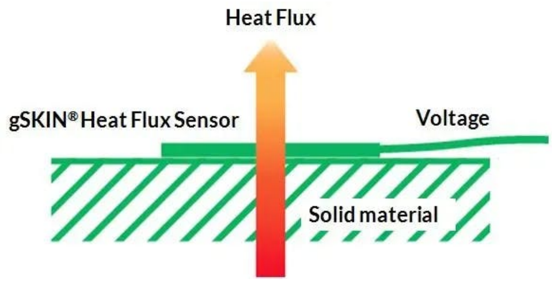
Shrinkage over time from the 3D Disto overlaid on the moisture content of the walls

Heat-flux sensors



Two pairs of Greenteg heat flux sensors have been fixed to two of the walls of the CobBauge building

Heat flux sensors can be used to measure the actual 'U-value' of a building element.

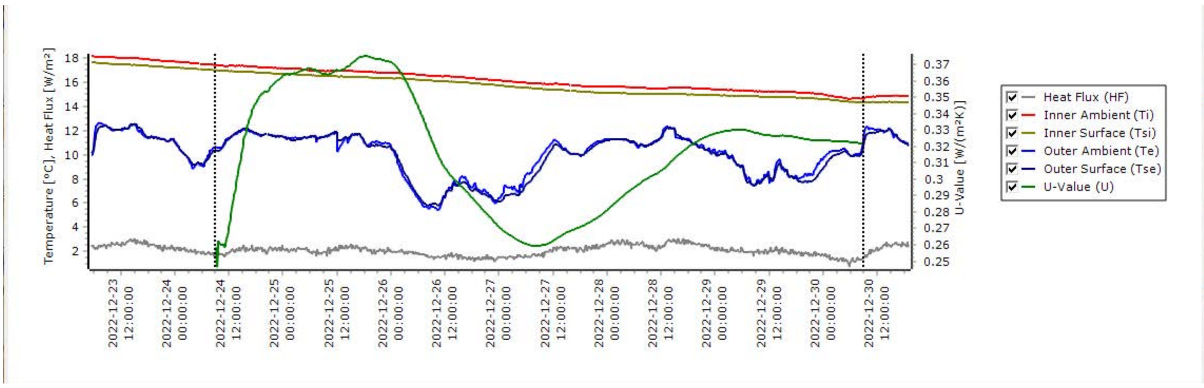


The Heat Flux Sensor generates a voltage signal which is proportional to the heat that passes through the sensor element. Using the appropriate formula, this can be converted into measurement of the heat flowing through the wall, thus giving a real-time indication of the thermal efficiency of the wall and therefore an actual U-value

The U-value of a building element is normally calculated during the design process, and it is this calculation that is used to achieve building regulation approval

Plymouth + finishes				
	Density kg/m3	**Thickness m**	**Cond. W/m.K**	**Resistance m2 K/W**
Internal surface		n/a	n/a	0.12
Internal earthen plaster		0.03	0.44	0.07
Structural Crediton	1635	0.300	0.44	0.68
Ottery 50% Hemp shiv	340	0.300	0.13	2.31
Lime render		0.03	0.60	0.05
External Surface		n/a	n/a	0.06
Total Resistance				3.29
U-Value W/m2K				**0.30**

The calculated U-value of this CobBauge wall is 0.30 Watts per metre squared Kelvin (Wm^{2}K)
Which is exactly the figure required under UK Building regulations



Readings taken from the heat flux sensors shown above give an actual measured average U-value of 0.29W/m2.K
Demonstrated that the CobBauge wall exceeds the building regulations set for this building.

Indoor Air Quality (IAQ)

The factors that go to make up the indoor air quality of a building are:

- Volatile Organic Chemicals (VOCs)
- Formaldehyde
- Particulate matter measured in different sizes (PM1, PM2.5, PM5, PM10)
- Relative humidity
- CO2 levels
- Temperature levels

The indoor air quality of the Cobbauge building is monitored in two ways, by portable devices, and fixed data logging sensors

The principal portable devices used are:

Grey Wolf IAQ gas sensor

Grey Wolf particulate meter

External air quality measurements

In order to make valid judgements about the indoor air quality, it is essential to record the overarching external factors:

- Relative humidity
- CO2 levels
- Temperature levels
- General weather conditions

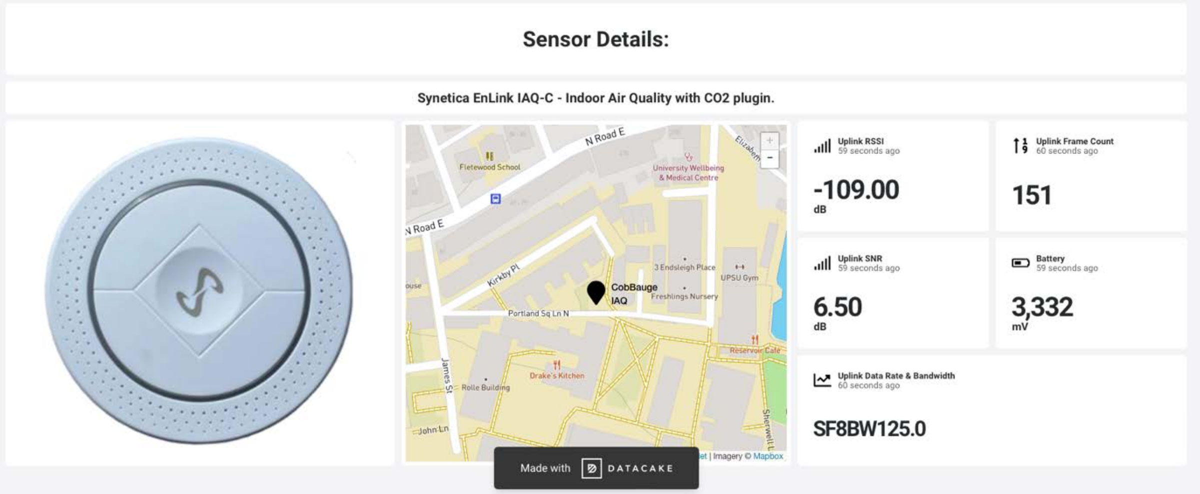
The portable sensors are useful for making on the spot readings, and making comparisons with other buildings, but the most detailed picture of the indoor air quality comes from the use of a Synetica Enlink IAQ-C data logging sensor

This is connected to a wireless network called 'LoRaWan' and can be viewed through any computer, and is also available through a dashboard on the CobBauge website

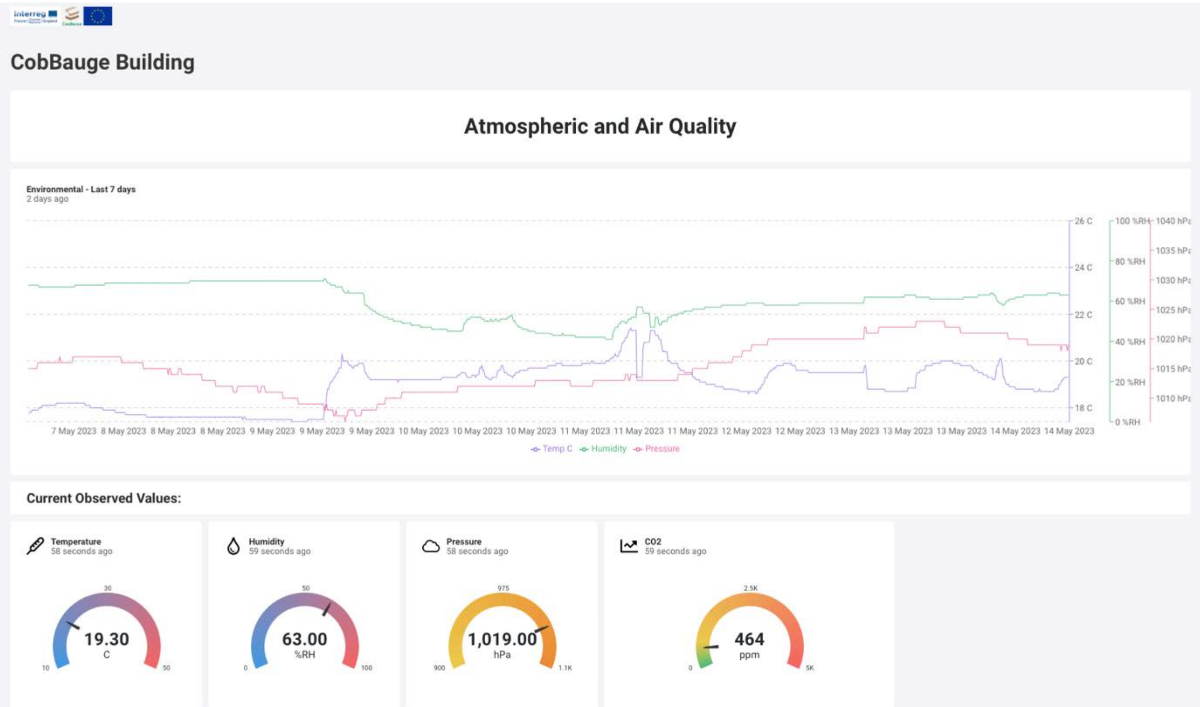
LoRaWAN is a low-power, wide area networking protocol built on top of the LoRa radio modulation technique. It wirelessly connects devices to the internet and manages communication between end-node devices and network gateways.

Results.

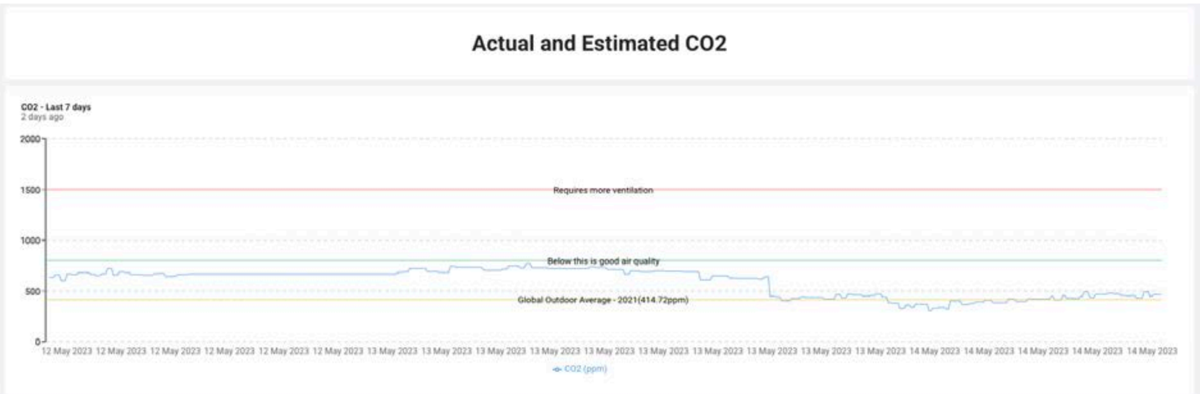
The results of the IAQ monitoring are displayed on a dashboard. The live IAQ results look like this:



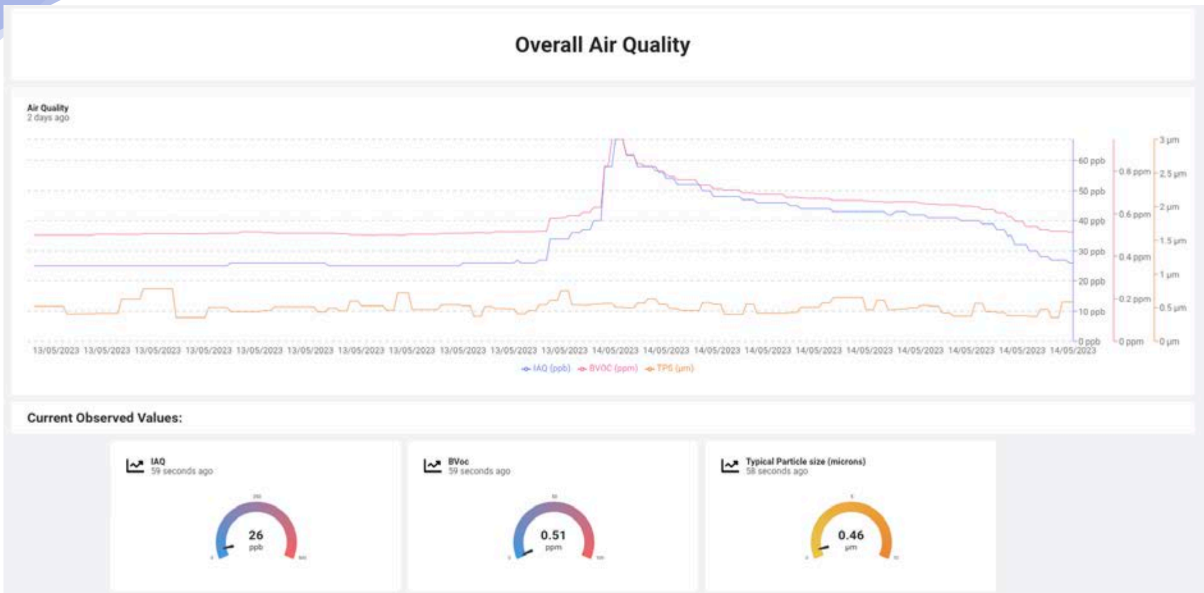
Details of the sensor and its location



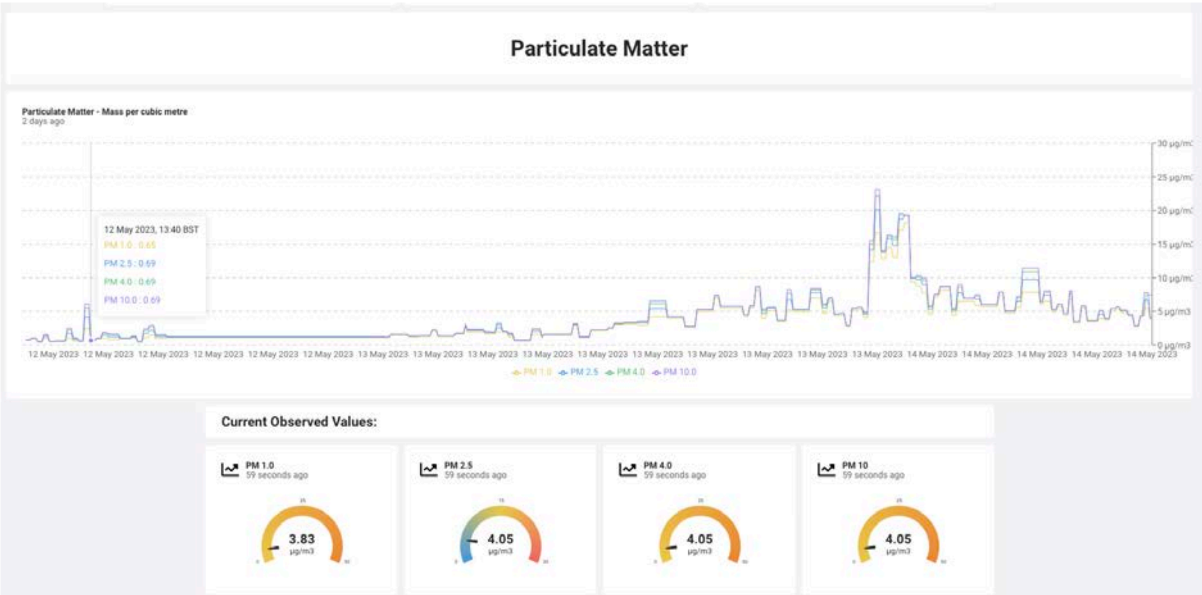
The first page covers the internal air temperature, pressure, and relative humidity.



The next section records the CO2 levels in the building



This section covers the Volatile Organic Chemicals



And finally, the different sizes of particulate matter are recorded.

Analysis.

The results of the IAQ monitoring shown above are for a period in the middle of May, 2023. Because we can monitor the use of the building we can draw some conclusions about the environment inside it.

The principal factor that governs the IAQ of the CobBauge building are the people occupying it. In the results shown above, there is a period when the building is unoccupied, followed by a period of occupation. In every section (apart from CO^2) It is the people in the building who are bringing in VOCs and particulates, and affecting the temperature and relative humidity.

Air-tightness testing.

All buildings in the UK are required to achieve a level of air-tightness or permeability. This is sensible as heat energy can be lost through unidentified ventilation. 'Build tight and ventilate right' is the principal.

The standard method for testing permeability is the blower door test. After all the known ventilation sources are closed (window trickle vents tec.), the door is sealed with a special unit that contains a large fan. This fan is then used to pressurise the building so that the level of permeability can be measured.

Blower door system installed at Plymouth.

The Blower door is controlled through a laptop computer which gives a detailed set of results (below)

Average static pressure, before	ΔP_{01}	-0.56	ΔP_{01-}	-1.19	ΔP_{01+}	0.69

Building pressure [Pa]	-66.59	-62.54	-58.24	-53.84	-50.88	-50.22	-44.3	-36.08	-36.21	-30.9	-23.05	-19.84
Test Fan 1 [412464] B2 Pa	90.6	85.3	76.7	68.8	68.1	61.7	55.9					
Test Fan 1 [412464] B1 Pa								109.5	111.2	89.2	61.5	49.4
Static pressure, after [Pa]	1.14	-0.39	1.01	0.84	0.67	-0.76	0.46	0.90	-1.58	-1.89	0.63	1.07

Average static pressure, after	ΔP_{02}	0.18	ΔP_{02-}	-1.15	ΔP	1.1, 1.1, 1.1, 1.2,
Temperature, after	indoors	22.2 C	outdoors	22.1 C		

Show Graphs

Induced pressure [Pa]	-66.39	-62.34	-58.05	-53.65	-50.69	-50.03	-44.1	-35.88	-36.01	-30.7	-22.86	-19.64
Total flow, Q_c [m³/h]	438.353	424.013	400.054	377.325	375.745	356.468	339.617	256.549	258.692	229.620	*190.827	
Corrected Flow, Q_m [m³/h]	445.956	431.368	406.993	383.870	382.263	362.651	345.508	260.999	263.179	233.603	*194.137	
Corrected flow Q_{env} [m³/h]	445.791	431.209	406.843	383.728	382.122	362.517	345.380	260.903	263.082	233.517	*194.065	
Error [%]	-2.5%	-0.6%	-0.4%	0.3%	4.8%	0.5%	6.4%	-4.6%	-4.1%	-2.7%	3.5%	

Correlation, r^2	0.9838	Confidence Limit 95%	
Intercept, C_{env} [m³/h/Paⁿ]	13.748	10.11	18.70
Intercept, C_L [m³/h/Paⁿ]	13.710	10.08	18.65
Slope, n	0.835	0.75431	0.91594

Calculate

Clear data set

Clear point...

Change m³/h

	Results	Uncertainty
Air flow at 50 Pa, Q_{50} [m³/h]	359.66	+/-2.7%
Air permeability at 50, AP_{50} [m³/h/m²]	3.4854	+/-5.7%
Equivalent leakage area at 50 Pa [cm²]	40.72	+/-2.7%
Air changes at 50 Pa, n_{50} [/h]	5.073	+/-5.7%

Finish time 16:20:04 Get Time

New set Delete set

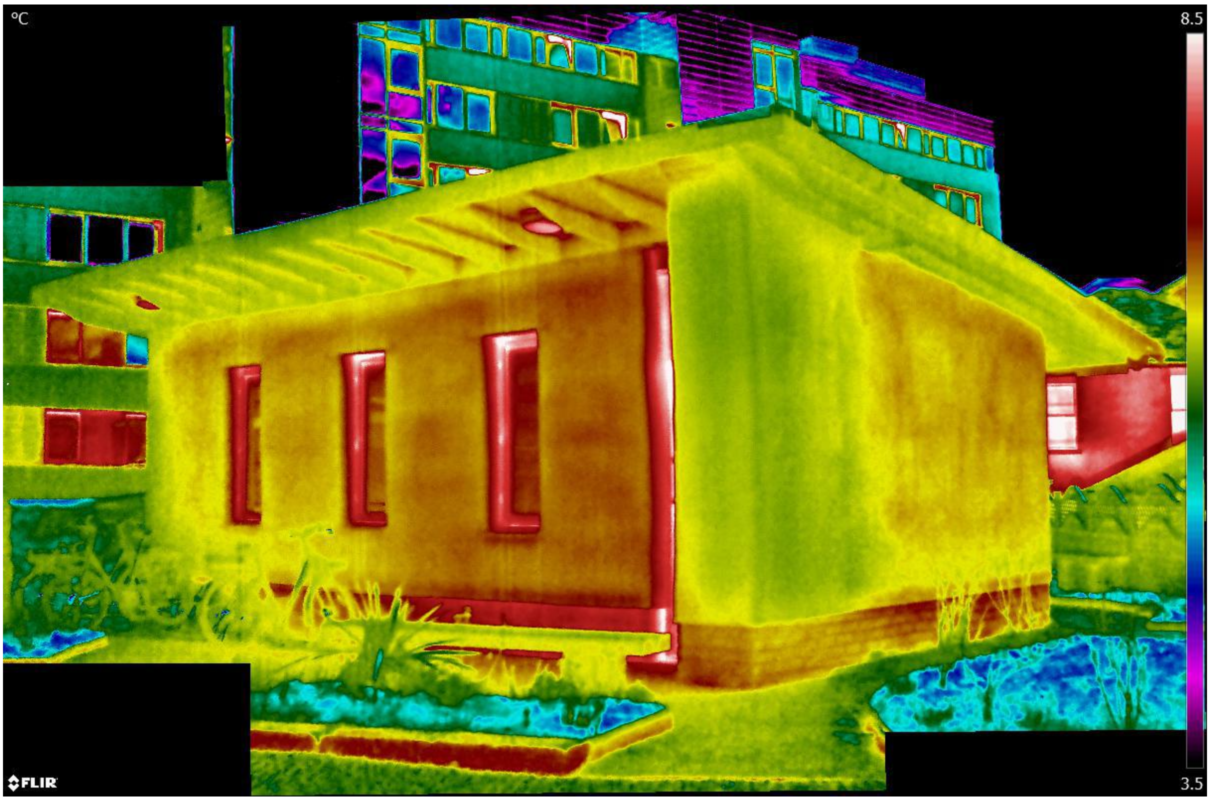
	Results	Uncertainty
Air flow at 50 Pa, Q_{50} [m³/h]	359.66	+/-2.7%
Air permeability at 50, AP_{50} [m³/h/m²]	3.4854	+/-5.7%
Equivalent leakage area at 50 Pa [cm²]	40.72	+/-2.7%
Air changes at 50 Pa, n_{50} [/h]	5.073	+/-5.7%

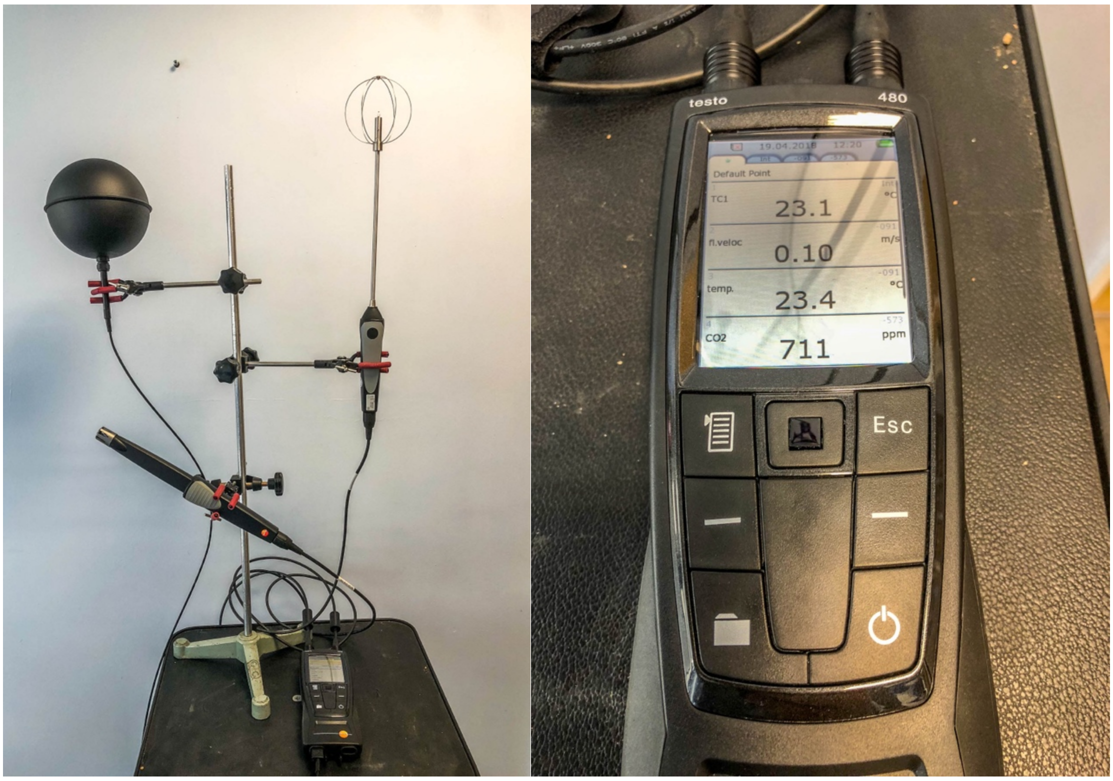
The results were:

- Permeability at 50Pa:
  3.48 – 4.05 m3/h/m2 after two measurements
- Current English building regs require that new dwellings achieve an air leakage of around 5 m3/h/m2 or less.
- This building comfortably exceeds the building regulations.

Thermography

The use of thermographic imaging cameras has been pioneered at Plymouth.
The image below shows a consistently good performance for the CobBauge building, with most of the heat loss occurring around the windows and door which is consistent with well insulated buildings. The section of wall that is nearest the camera is showing as colder. This si because it is outside the thermal envelope of the building.





Testo 480 comfort meter with associated sensors.

A Testo 480 Thermal comfort Meter has been used to calculate the Predicted Mean Vote (PMV) for the theoretical occupants of the building. The result was within the +/- 5% margin that is acceptable to over 90% of inhabitants (below).

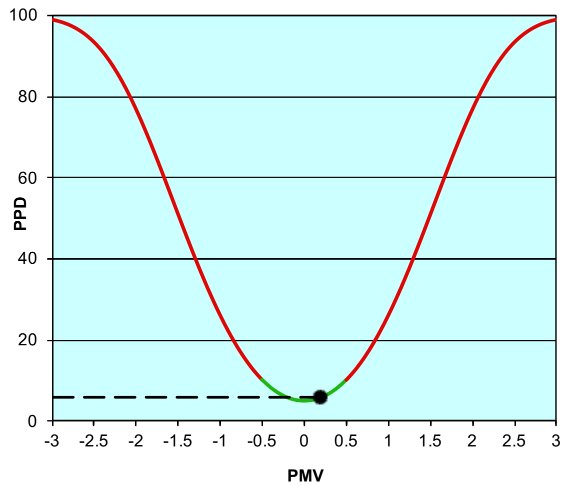
Parameter	Input	
Clothing (clo)	1.40	[0 to 2clo]
Air temp. (°C)	22.5	[10 to 30°C]
Mean radiant temp. (°C)	22.5	[10 to 40°C]
Activity (met)	1.0	[0.8 to 4met]
Air speed (m/s)	0.10	[0 to 1m/s]
Relative humidity (%)	29.7	[30 to 70%]

Calculate PMV

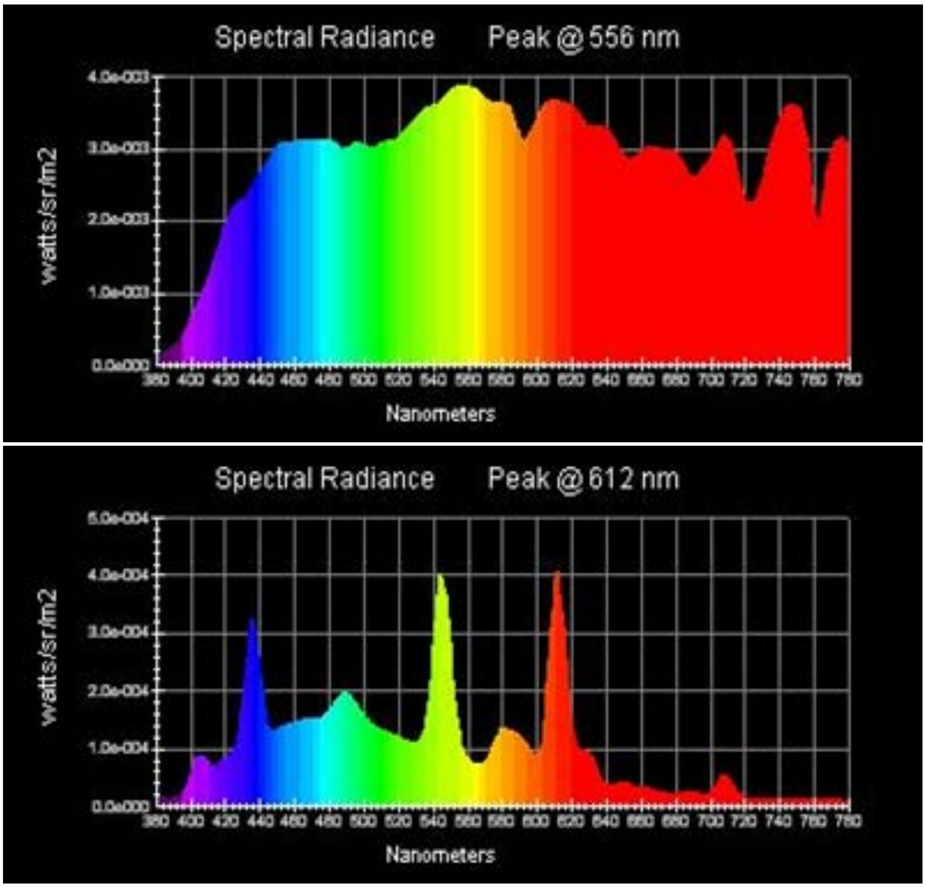
Parameter	Results
Operative temp. (°C)	22.5
PMV	0.2
PPD	5.8

Number of iterations: 6

Modified by Håkan Nilsson
Department of Technology and Built Environment
Laboratory of Ventilation and Air Quality
University of Gävle

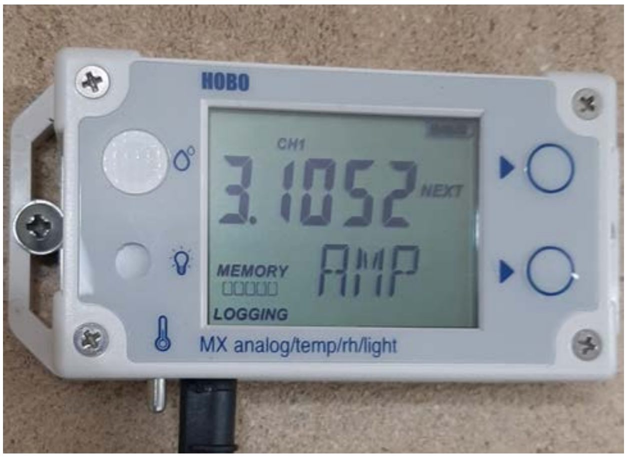


Lighting temperature

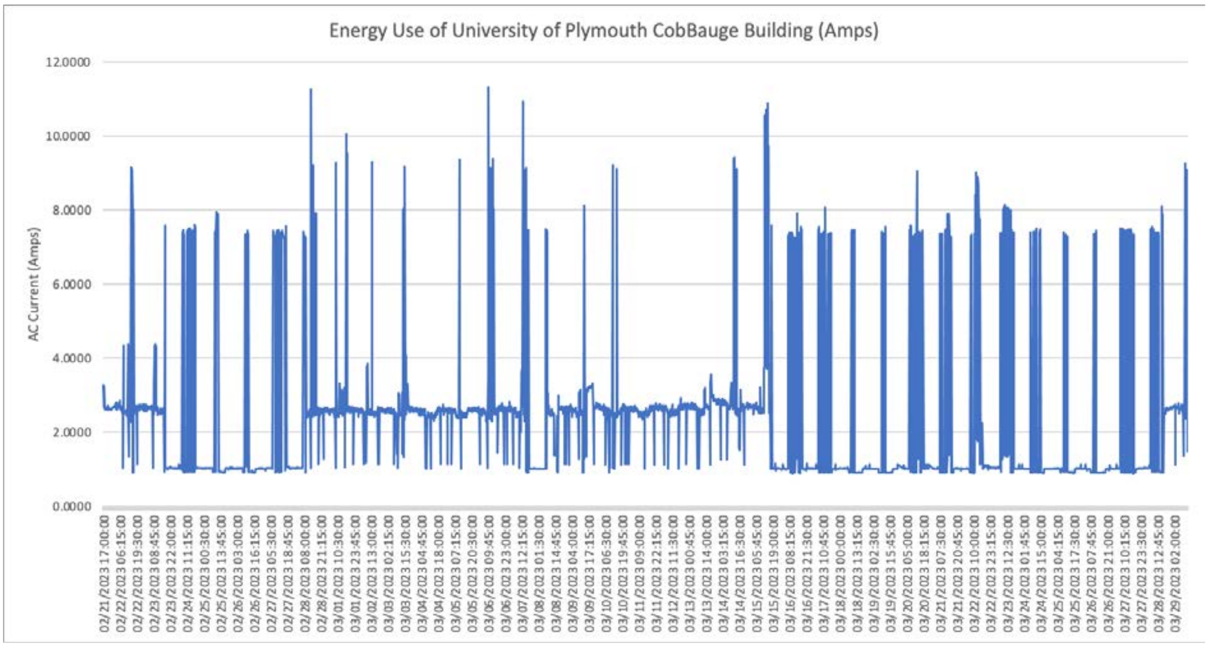


Spectral radiance results for Daylight (top) and the artificial lighting (below) for the CobBauge building. The result under artificial lighting shows a wider spread of radiance with three distinct peaks. This is better than normal low energy lighting which normally has only one peak, and a lower spread.

Energy Use



Hobo data logging electrical energy meter



Results of the electrical energy used between 21st Feb and 29th March 2023

From the results above we can calculate the actual electrical energy used for space heating in the CobBauge building and compare it with different standards used in the UK.

Energy use for space heating:

Building regulations	74.5 kWh/m2/yr
AECB standard	48 kWh/m2/yr
PassivHaus	15 kWh/m2/yr
CobBauge	44 kWh/m2/yr

It can be seen that the CobBuage building exceeds both the building regulations requirement and the AECB standard. The building was not designed to be PassivHaus compliant.

Specific Heat Capacity

'The house stays cool in summer and warm in winter'.
Thermal Mass is often discussed in the role that the materials used in construction can play in the passive control of internal environments.
The property of a material to provide 'thermal mass' is called 'specific heat capacity' or 'volumetric heat capacity', and can be measured.

The Netzsch HFM446 Heat Flow Meter and a section of CobBauge showing the dense cob mix that is on the inside of the wall, and therefore has a direct effect on the internal environment

Using our heat flow meter, we have measured the heat capacity of a range of CobBauge mixes
Here is the result from a typical structural mix (2.5% fibre, density 1635kg/m3)
This gives a Cp-value – specific heat capacity with an average value of 879 J/kg.K across three temperatures.

2.5% fibre	Middle Temp.	N-Factor (HFT)	Q-Total (correction)	Q-Total (test)	Cp-Value (calculated)
	°C		mV·s	mV·s	J/(kg·K)
1	20.0	0.00609	3816	86915	864.706
2	25.0	0.00609	3620	87399	871.785
3	30.0	0.00609	3678	90343	901.810

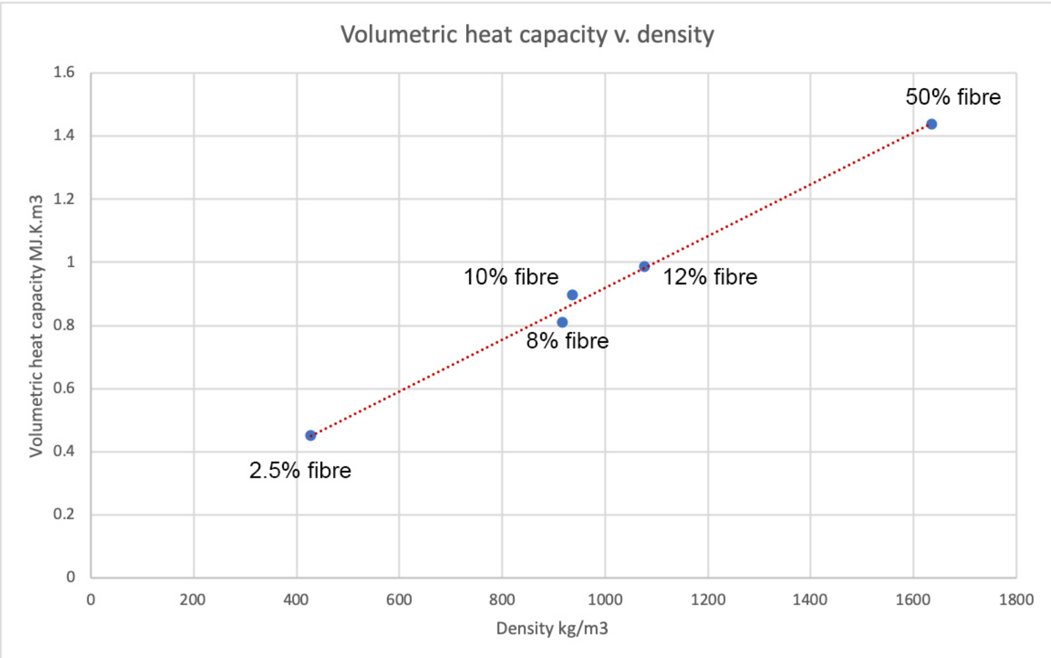
To simplify the results we can take a mean of each of the specific heat values and plot them against the density of the samples.

Sample	Density(kg/m3)	Specific Heat Capacity (J/kg.K)
Fibre 2.5%	1635	879

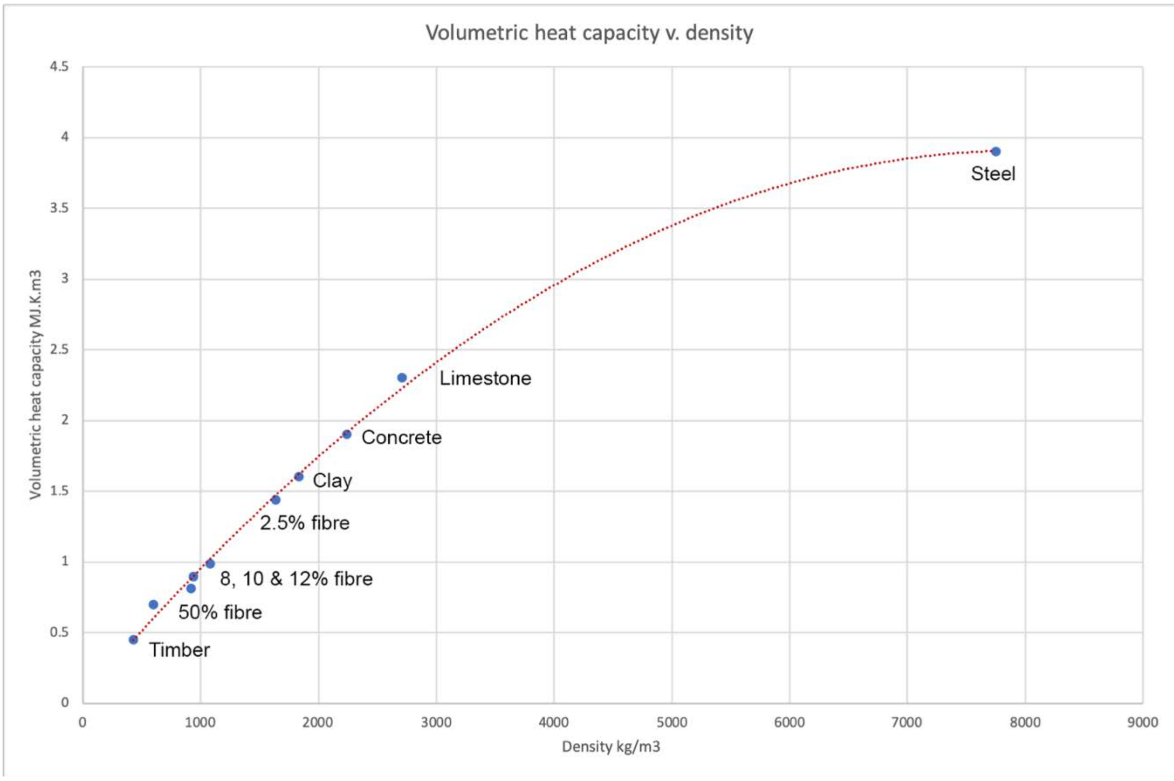
Previous measurements carried out at Plymouth using a more traditional method had established a Figure for cob of 891J/kg.K (Goodhew et al.,1995), which fits with these more recent figures.

Of more use to the construction professional is the figure for volumetric heat capacity, as this gives a figure for a given volume of material (cubic metre).

Sample	Density(kg/m3)	Volumetric Heat Capacity (MJ.K.m3)
Fibre 2.5%	1635	1.438
Fibre 8%	1077	0.988
Fibre 10%	936	0.898
Fibre 12%	916	0.810
Fibre 50%	428	0.451



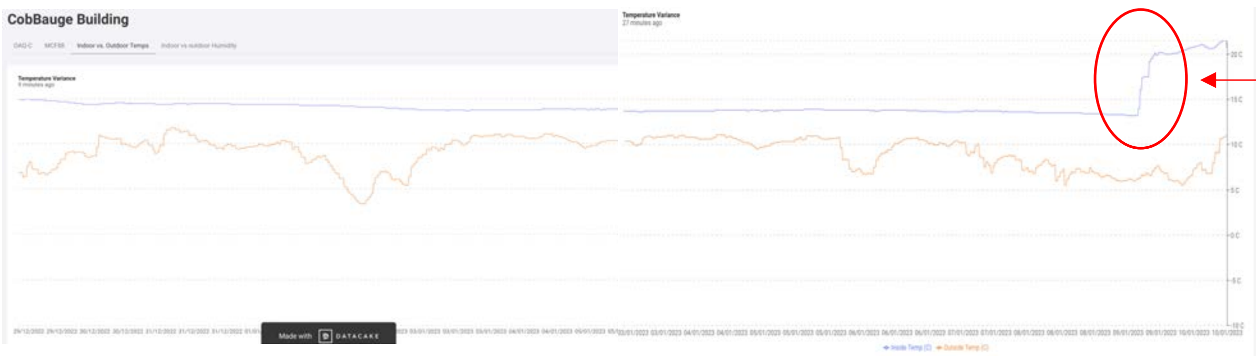
The results for a range of five different CobBauge mixes show a consistent result for the volumetric heat capacity of the cob samples.



Graph showing the five CobBauge mixes against a range of other construction materials.

The graph above shows that the results for the five CobBauge mixes are consistent against figures from a wider range of materials found in construction.

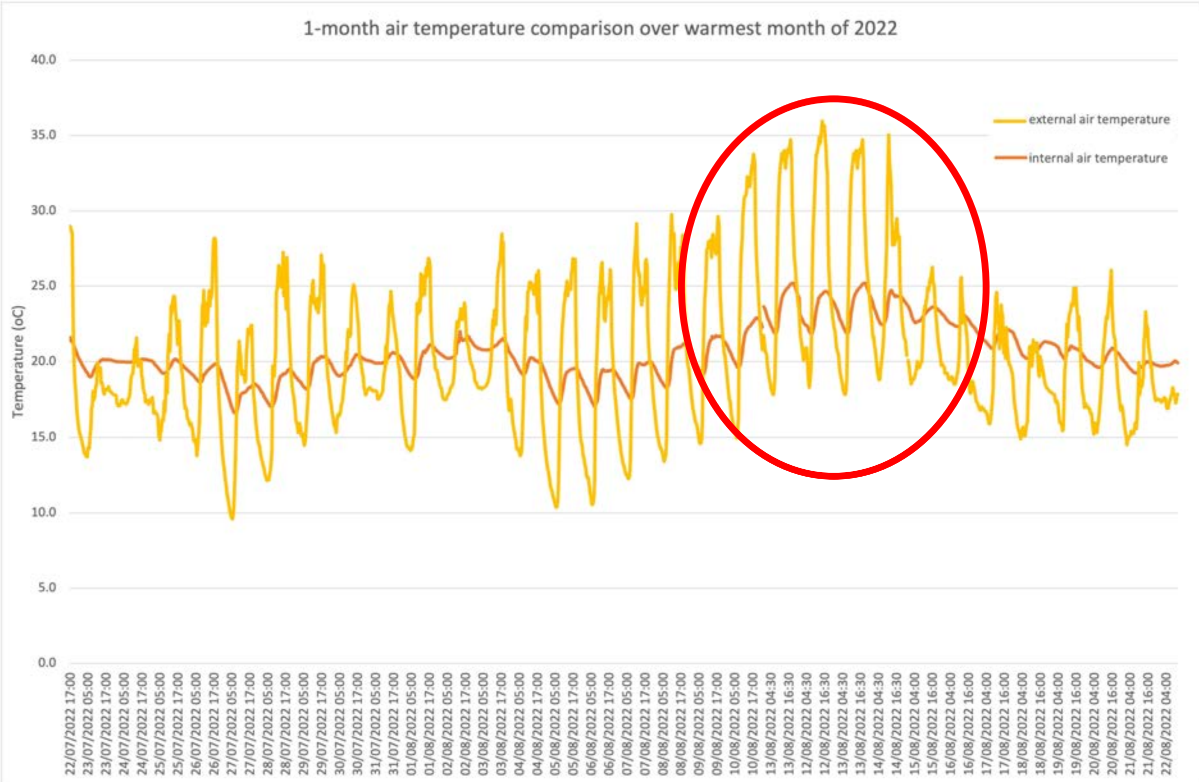
Storing heat energy in winter



The qualities of increased Thermal Mass in the Building can be demonstrated by this graph that shows the internal temperature very gradually decreasing over the Christmas break (with the heating turned off). The total loss was less than 2° C over a period of two weeks.

The effects of the thermal mass might suppose that there would be a lag in the heating of the building after the break, but here we see the air temperature rising quickly back to the operating temp.

Summer cooling



Internal and external temperatures during summer heatwave, with focus on August 10th – 14th 2022

During the four days that external temperatures reached 36.5ºC, the internal temperature stays steady without exceeding 25ºC. If we look at the preceding days, the internal temperature is staying somewhere around equidistance between the peaks and troughs of the external diurnal shifts, as might be expected. When the external temperatures increase, the internal temperature exhibits two interesting behaviours; the average internal temperature is now only 30% of the external levels, and the internal temperature doesn't appear to be increasing.

Behaviour of the two composites that make up the wall

The literature tells us that mass (volumetric heat capacity) works to dampen diurnal temperature changes

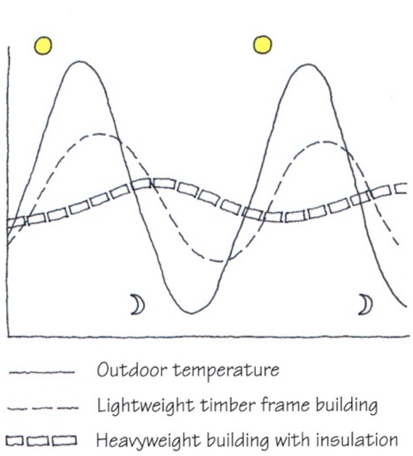
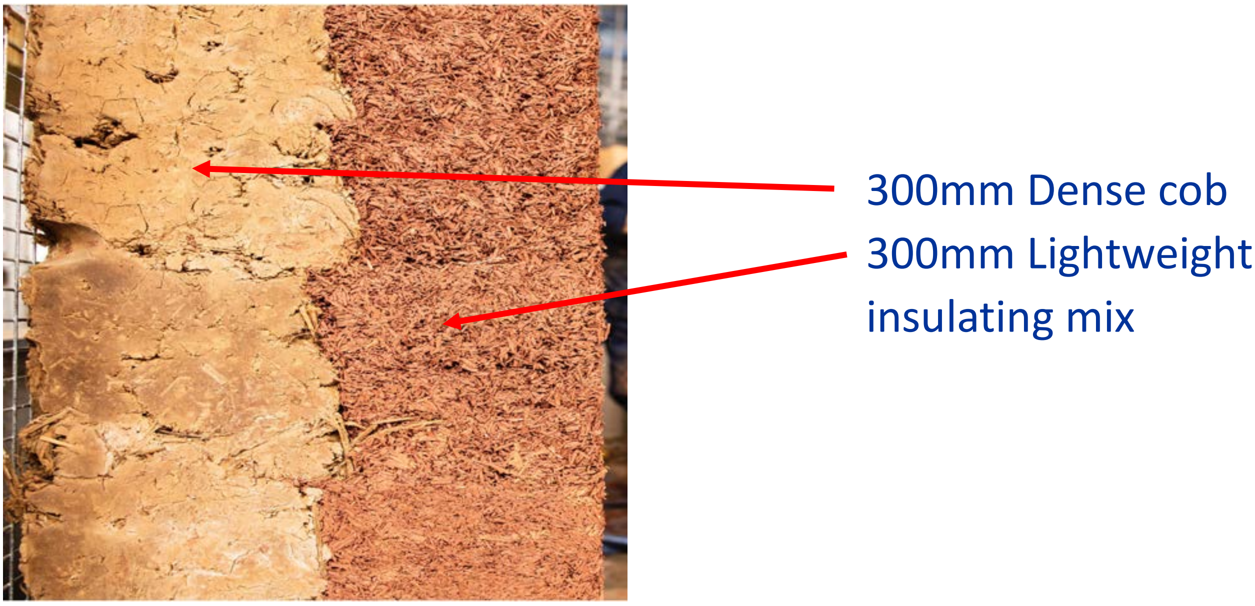
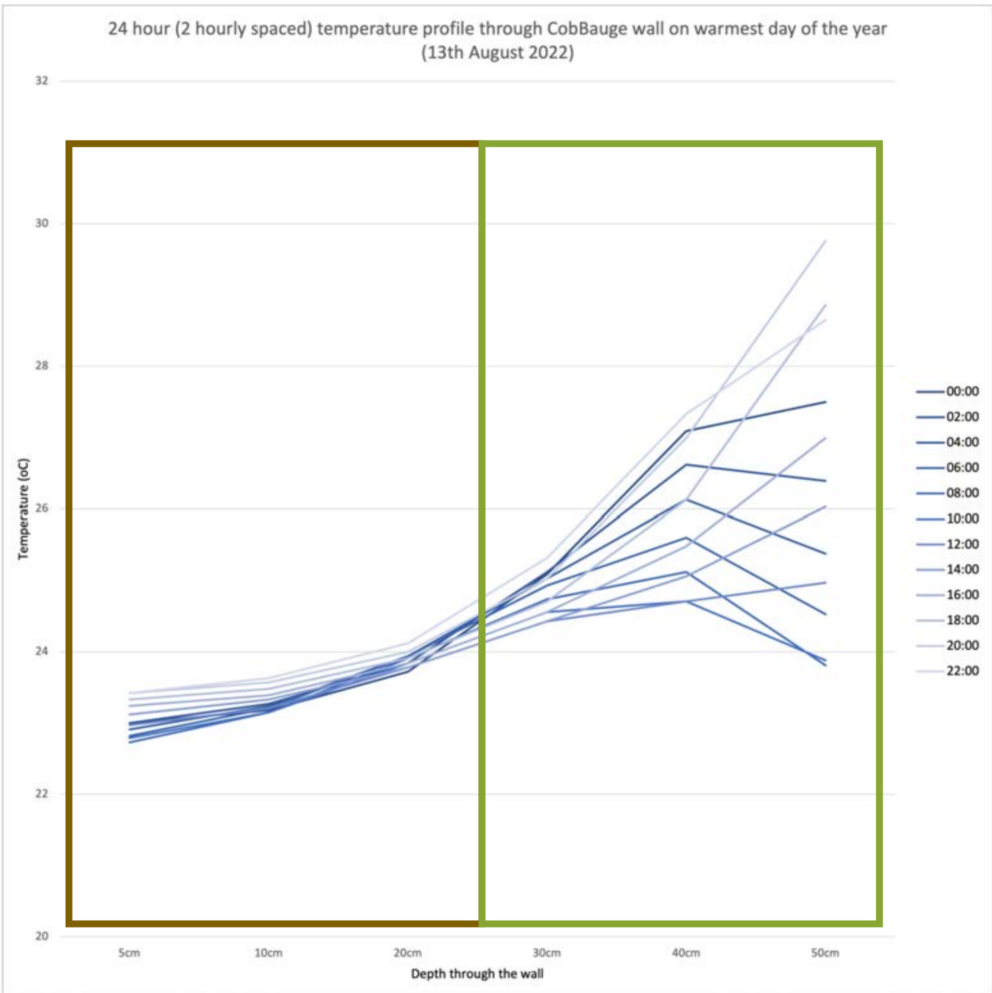


Illustration by Huw Heywood

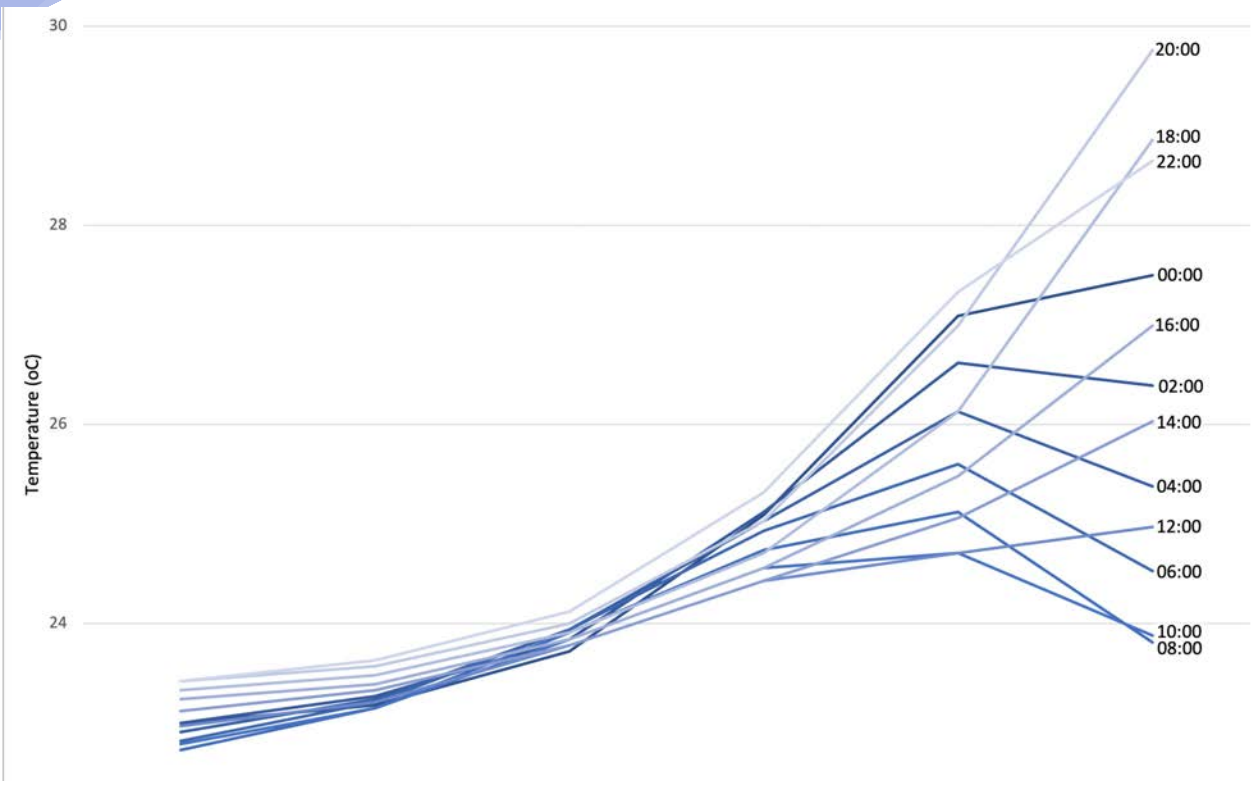
In comparison to the temperature in a lightweight structure, the energy storage in a heavyweight structure results in the temperature showing more damping and more time lag

This can be demonstrated by looking more closely at how the temperature changes through the two layers of the CobBauge wall





This graph shows how the temperature changes through the depth of the wall at two hourly intervals on the warmest day with an overlay showing the dense mix (left, brown) and thermal mix (right, green)

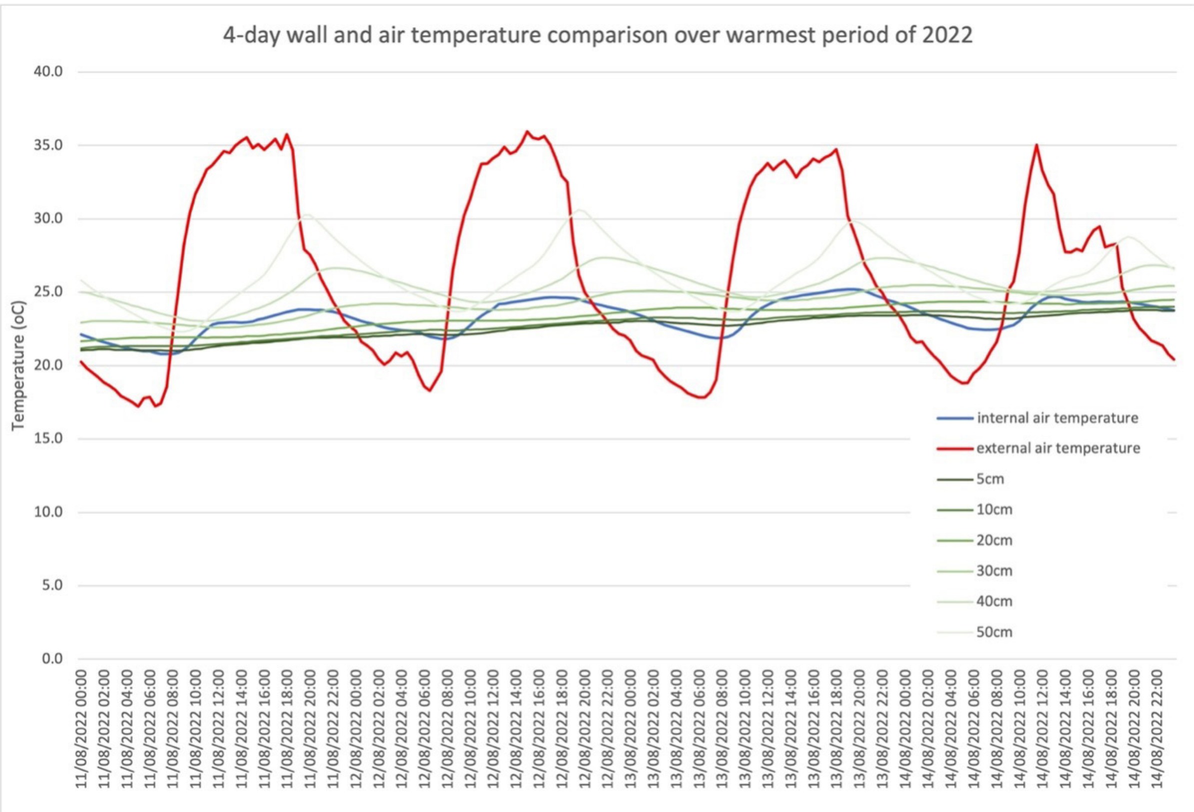


Looking more closely, with the times attached to each trace.

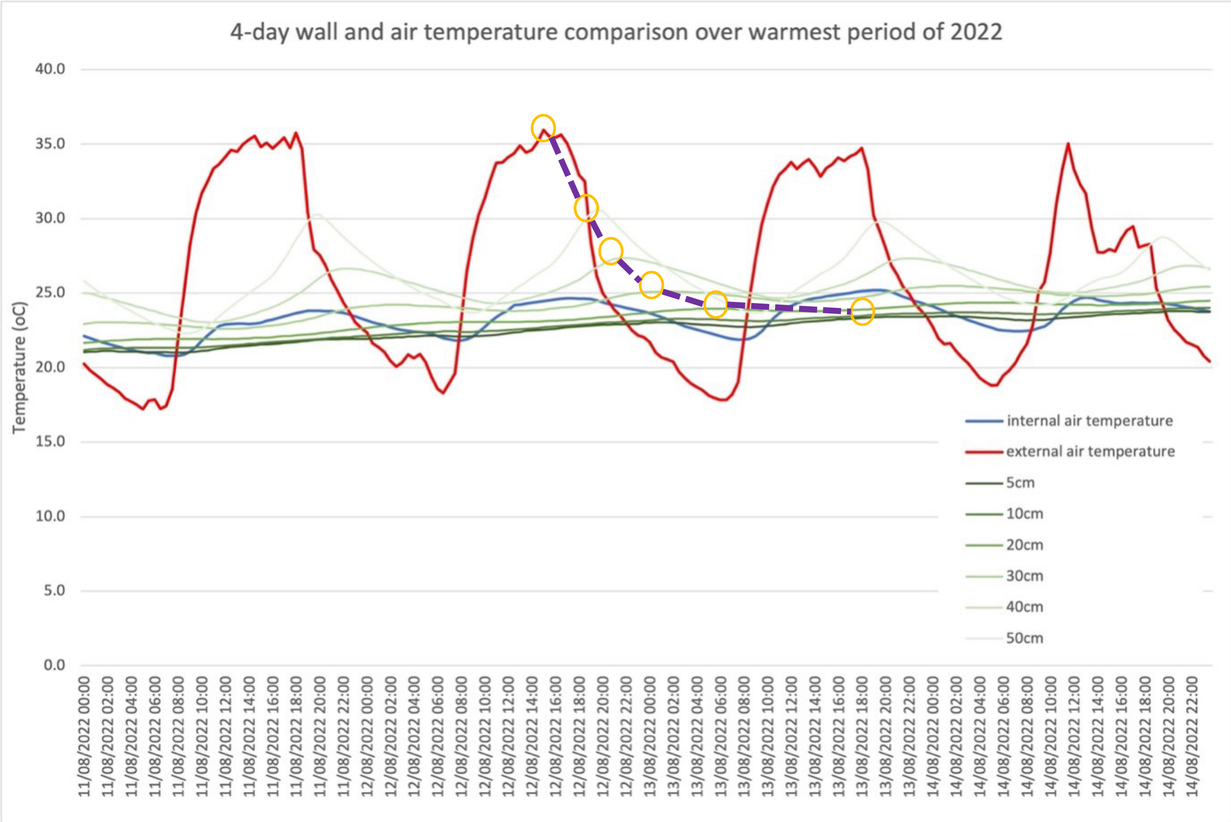
From 00:00, the temperature is dropping evenly until 08:00, when temperature has dropped to 23.8ºC degrees. From 10:00, the temperature rises until it reaches 29.7ºC at 20:00 This is the highest temperature inside the thermal mix, so there is already a significant lag compared to the external air temperature.

In the centre of the lightweight thermal mix, we reach the point where the temperature swings have about a 12 hour lag

At the start of the dense structural mix, the temperatures have come together - and towards the inside of the building, they stay to within one degree over a 24-hour period



Graph showing the changes in temperature through the wall over the period of the heatwave. Distances from the inside, so the paler traces are towards the outside of the thermal mix



The same graph with yellow circles highlighting the peaks in temperature as they travel in time.

Overlaying the peaks in temperature over time from the peak of the external temperature at 16:00, we can see a clear pattern as the delay in temperature travels through the wall. The thermal lag in this wall is about 24hrs. As we get further into the structural mix the peaks are harder to trace to the extent that that the trace that is 5cm from the inside shows only a very gradual increase in temperature of about 2°C over the four days of the heatwave.

Conclusion.

The Plymouth prototype CobBauge building has been monitored and assessed in the following areas:

- Measurement of the moisture content of the walls and the associated shrinkage rates
- The use of heat flux sensors to record real time U values
- The different sensors used to record the Indoor Air Quality (IAQ)
- External air quality
- Air tightness testing with a blower door device
- Use of thermal cameras to assess the thermal performance
- A method for disseminating the data from an indoor air sensor through a local area network, and the dashboard on the CobBauge website
- Thermal comfort
- Illuminance and quality of lighting
- An evaluation of the role of the specific heat capacity of the CobBauge walls.

All the areas tested have produced encouraging results, with none of the monitoring producing data which indicates anything other than a performance which surpasses the designed specification and exceeds the expectations of the project as a whole.