WPT4.1 Output Report:

Establishing the performance levels associated with the construction process linked to discussions by the network and overseen by the Steering group.

University of Plymouth

Introduction

This report will cover a range of different activities that helped establish the performance levels associated with the construction process:

- The preliminary work done in building the full scale test walls, that provided much useful data for the finished building
- The render test panels, that informed the choice of finishes for the building
- The process of construction
- The expected performance of the materials used
- A record of the hours involved in the construction of the building
- An outline costing for the construction of CobBauge walls

Full scale test walls

(a more detailed version of this section is available as a separate document in the deliverables)

The test walls were designed primarily to illustrate the strength of the CobBauge composite wall:

- Firstly, to give a visual representation of the load bearing capacity of the system by building a pair of parallel walls.
- The walls would be finished with wall plates and then joists spanning between them.
- The walls would then be loaded with a representation of the typical dead loads of a domestic building
- Finally, the completed wall without openings would be compressed with hydraulic rams to calculate its compressive strength

The walls have also been used for many other tests.

- They are being monitored for moisture content and shrinkage.
- Experimental fixing points have been inserted in the walls
- Different renders are being applied.

Completed Test Wall

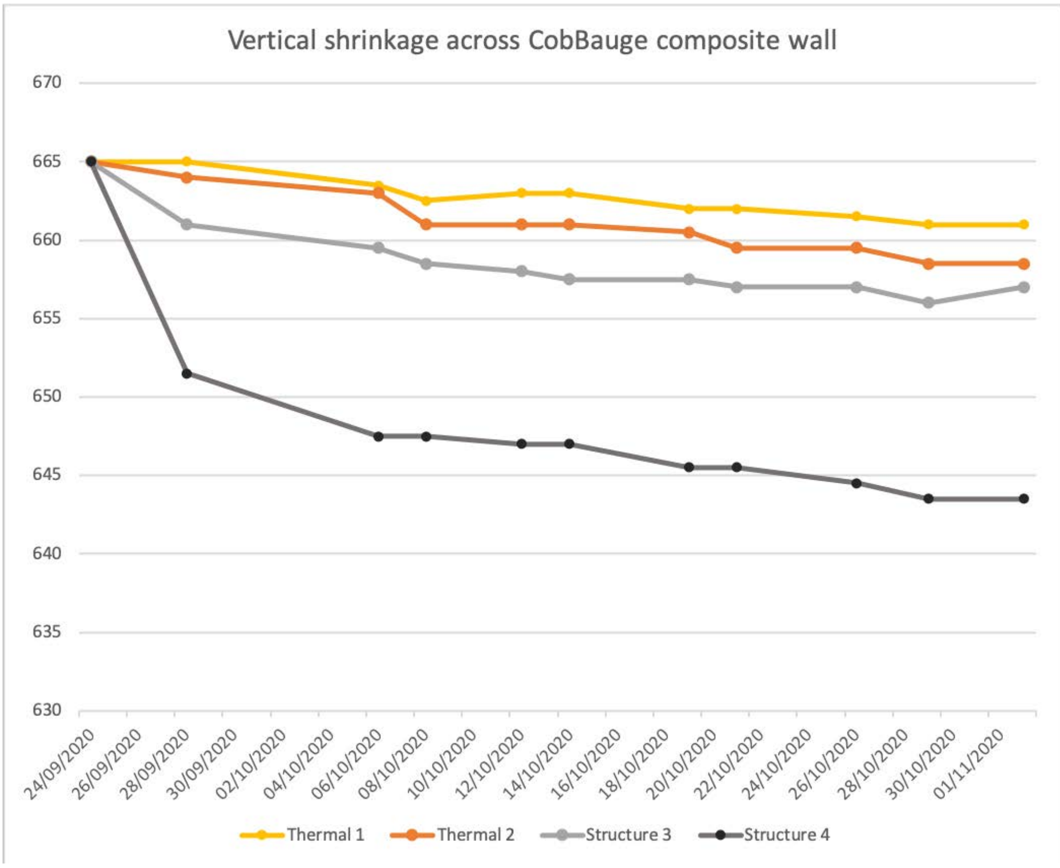
This is the first wall completed.

There is an opening in the wall with a timber lintel over it.
Slightly above that the fixing points for external devices (like drainpipes) can be seen. These are made by embedding a timber frame that goes back to the structural layer to provide enough strength.
This photograph also shows the zig-zag pattern between the structural and thermal mixes. This is the result of placing the material against the slanted face of the separator and should help to increase the bond between the two materials by preventing a clean shear break between them.

Shrinkage in the test walls

The finished walls now have the representative loads applied.
The floor that the walls have been built on is part of a large scale testing rig which incorporates the steel gantry which has a horizontal beam 1.5m above the walls. This is where the hydraulic jacks will be fixed to test the compressive strength of the walls. The floor has a precision cast concrete base with a flat surface.

A cob wall is traditionally built in lifts. These are typically between 450mm and 700mm high. Between lifts the cob is allowed to dry until it is firm enough to support the next lift. When the first lift of the left hand wall was completed, a series of threaded construction screws were embedded into the wall in order to provide data points to record any movement in the wall as it was drying.



This graph shows the changes in the height of the screws over the six weeks of the initial drying of the first lift. In order to best demonstrate the relative behaviours of the two layers of the wall, the figures have been adjusted to give them the common starting point of 665mm. The relationship between the changes in height over time are unchanged.

Applying static loads to the CobBauge test walls.

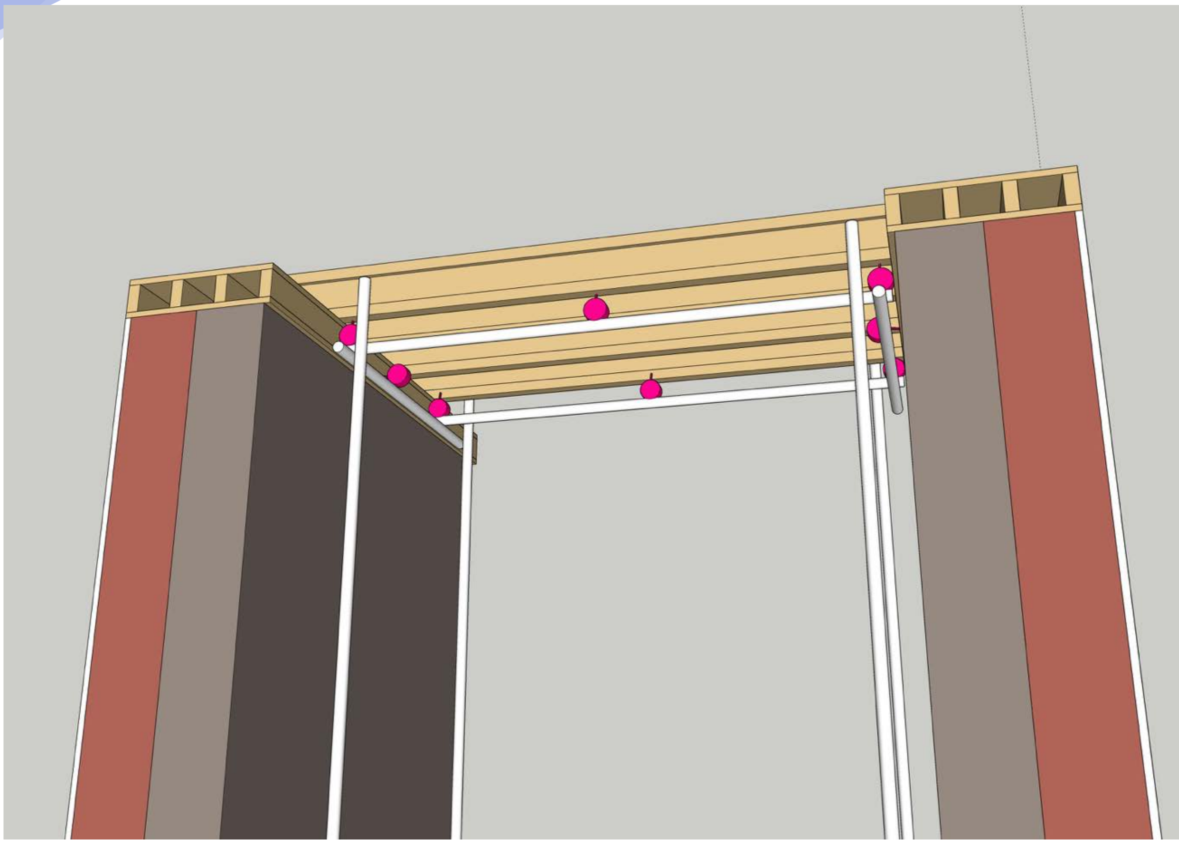
The object of this test is to apply the typical dead loads of a building to a pair of structural walls constructed with the CobBauge composite material.

The walls have been constructed with substantial timber wall plates on top of them and then bridged with a floor made up of timber I-beams.

The test walls with wall plates and a 'floor' spanning between them. Also showing the targets applied to the faces of the walls for the Leica 3D Disto measurements

Loads will be applied to the top of the structure in stages. The first stage is to add a tonne to each end of the floor in the form of 25kg sand bags. This will create a visual impression of the load on the walls. Subsequently, additional weight will be added in the form of weights used to test cranes. The maximum on each wall will be 4.7 tonnes.

The primary source of data for measuring any deflection of the walls caused by the increasing loads will be through the use of dial gauges attached to a scaffolding platform. These gauges are data logging, and will give a continuous picture of any movement in the walls. Six gauges will measure vertical deflection, and two more will measure horizontal deflection.



The gauges (in magenta) on a scaffolding frame measuring deflection on the 'floor' of the structure.

The secondary data source will be through the use of a Leica 3D Disto. This is a laser measuring device that takes a series of measurements from fixed points and relates them to a datum. This will enable us to create a three dimensional picture of the movement of the wall as the loads are applied.

Leica 3D Disto set up on a tripod and controlled from a tablet computer

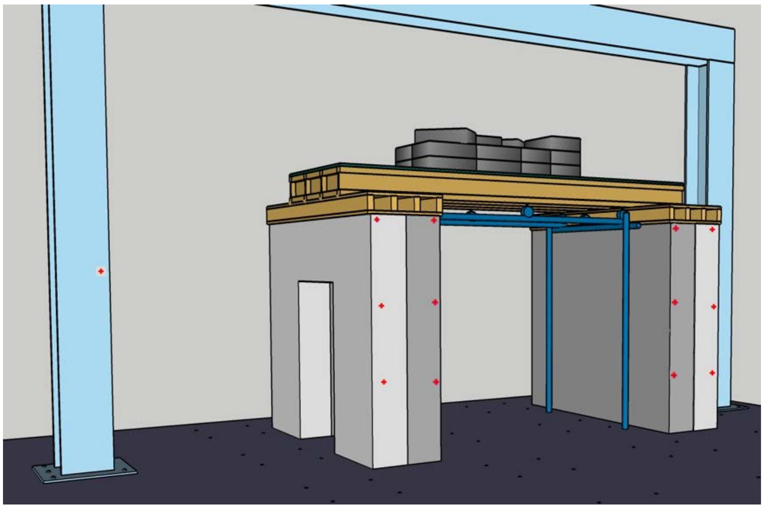
The Leica Geosystems 3D Disto is a surveying tool for capturing and projecting accurate 3 dimensional measurements. The 3D Disto combines distance and 360° angle measurements to determine the precise position of each measured point and its relationship in 3 Dimensions (Leica, 2015)

The 3D Disto is mounted on a tripod placed on a solid floor opposite the test walls. The use of a datum point on a fixed steel frame adjacent to the walls allows the 3D Disto to be moved if necessary

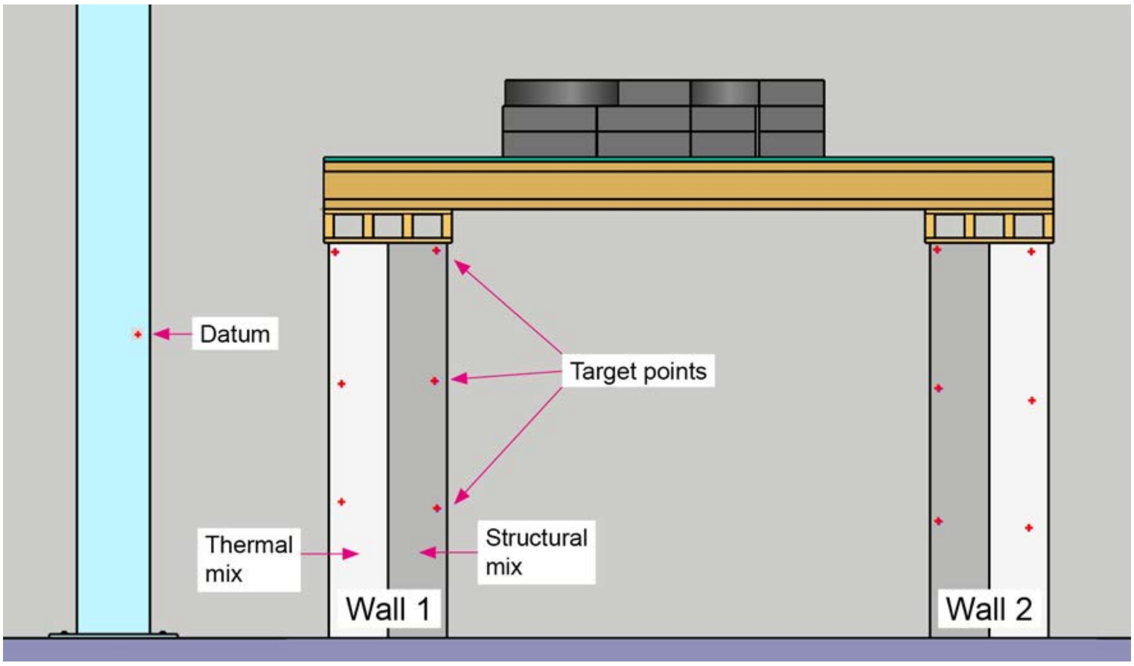
Showing the location of the targets for the Leica 3D Disto fixed to the test walls

Targets supplied by Leica for the 3D Disto are fixed to the walls. On each wall, three targets are aligned vertically on both the structural and thermal halves. They are spaced to give measurements in both horizontal and vertical directions including the ability to track any bowing of the walls under load.

Data from the 3D Disto is exported as a point cloud, and this is imported into a 3D model created in SketchUp of the wall loading experiment. Each point cloud is aligned to the datum point on the steel frame that surrounds the walls in the lab and in the model

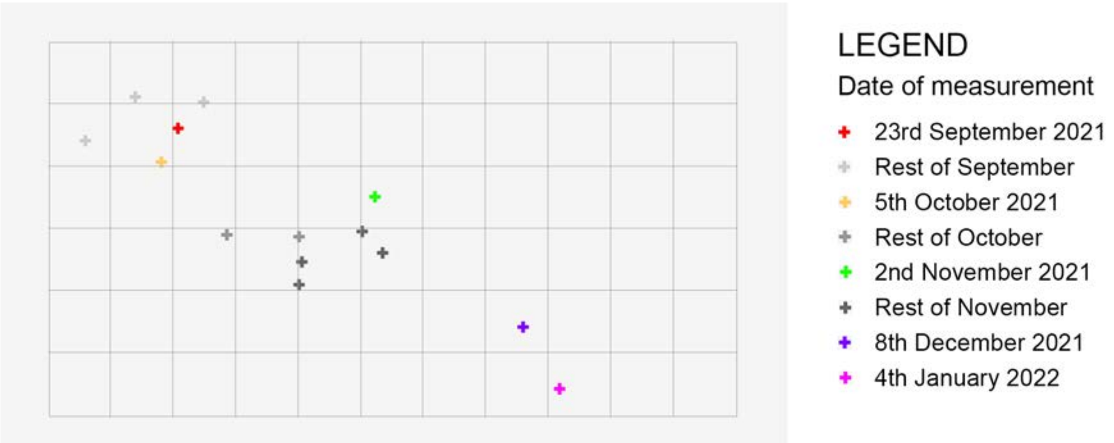


Showing the point clouds recorded from the 3D Disto imported into SketchUp and aligned with the targets on a model of the walls (the scale is too small to show the individual points on each target).



Front view of 3D model with labels

3D point clouds were recorded over a period from 23rd September 2021 to the end of January 2022. Between September and 2nd November the load on the walls was gradually increased. The first stage of loading was applied by placing as many sandbags as could be safely accommodated on the wall structure. This represented a load of 2,574kg across both walls. After 5th October the hydraulic rams were used to increase the load in stages up to an additional 8,743kg



Detail of the points recorded by the 3D Disto on the top right of the structural half of wall 1

The grid overlay is at a scale of 1 square = 1 mm. The movement recorded on this part of the wall is 4mm down vertically and 6mm across horizontally.

The construction of the test walls and the subsequent measurements of the shrinkage and settlement under load have provided invaluable data for the design and construction of the Plymouth CobBauge building. A total load of 11,317kg has produced a maximum vertical deflection of no more than 4mm at the top of the walls

CobBauge test panels

To protect the CobBauge walls, internal and external finishes will need to be applied. In this formulation of the CobBauge wall system, the lighter thermal mix will be on the exterior of the building.

In order to ascertain the most effective external finish, it was decided to construct a series of test panels. Each panel would have a different render, and a choice of two paint finishes where appropriate.

A wood-block sensor would be placed in the thermal mix behind the render on each panel.

The panels would be assembled outside on a frame that faced the predominant weather systems in Plymouth, and the moisture content behind each of the different renders would be recorded to give an indication of the effectiveness of the different renders.

Seven render panels were assembled and then taken to a site on the University campus and supported on a timber frame, placed against a south-west facing wall. The orientation ensured that the panels would be facing the predominant weather systems here in Plymouth.

The panels were protected by a short sloping roof, but were otherwise unprotected from the prevailing wind and rain.

The moisture content of the wood-block sensors was recorded regularly during the course of six months, from 15th December 2020 through to 22nd June 2021. This was considered a long enough period to gauge the differences in the performance of the different renders on test.

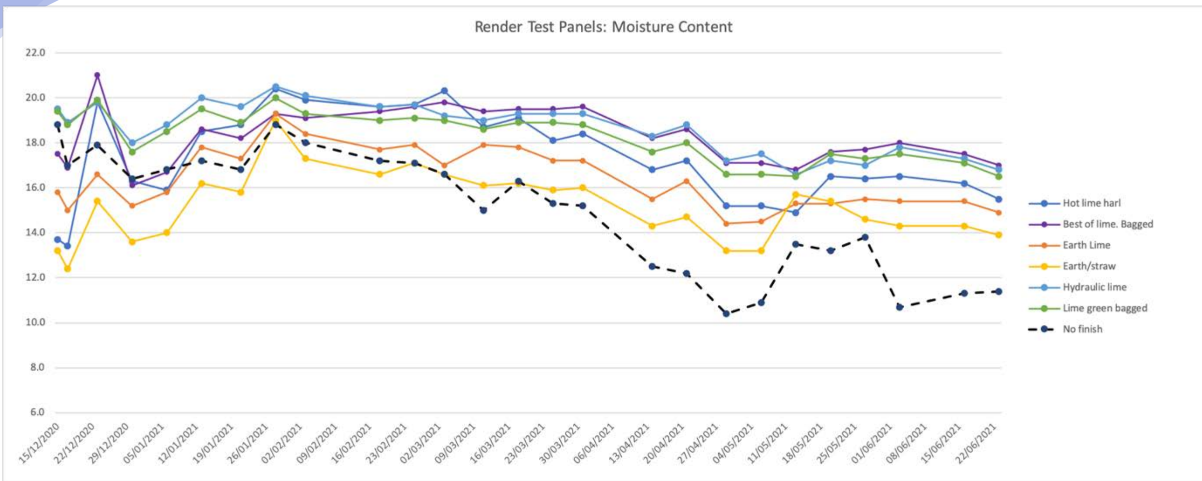
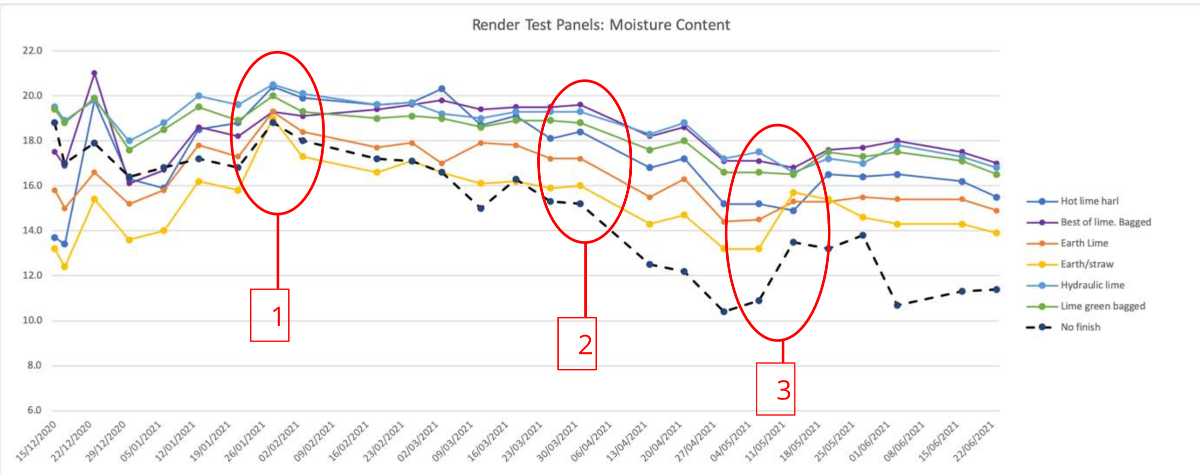


Fig.5 Results showing changes in moisture content over six months

Results

The results, shown above, are interesting in that they display some clear patterns of behaviour. After the first month, during which time the panels are adjusting to the conditions outside the lab, the moisture content of the thermal mixes behind show some interesting results.



1. During January there was unusually heavy rain in Plymouth which brings the levels up to a peak at the beginning of February, with all the panels showing increased moisture content, and the values are closer together than at any other time.
2. By the end of March, the panels are drying out, and showing a clear order of moisture content that will continue through the rest of the tests. The four lime mixes show the highest moisture content, followed by the two earth based renders. The panel that consistently shows the lowest moisture content is the panel with no render applied. This might seem counter-intuitive, but it is connected to the vapour permeability of the renders. As long as the periods of drying are longer than the periods of wetting (rain), then the more permeable finishes will be dryer - and therefore the panel with no finish will be the driest of all.
3. In May, there is a sudden heavy rainstorm that raises the moisture content of the more permeable finishes (including no finish), but hardly effects the less permeable lime renders.

The results of the moisture measurements over time might indicate that having no finish at all is the best way to keep the building dry. However, that isn't necessarily the main purpose of the finish. The render on the exterior of a building has two other important jobs: To protect the building from accidental damage and to look durable.

Fig.6 Panels showing signs of wear at the end of the experiment.

In fig.6 we can see that some of the panels are showing signs of wear. The panels in the middle are the earth based renders, and are both losing some of their painted finish. Of the lime based renders, only one is self coloured, and doesn't need an additional painted finish, and that is the second panel from the left, finished with the 'Best of Lime'. This render was the best performing of the proprietary lime finishes and shows the least discolouration and wear. It was also supplied by a well-established manufacturer and came with a warranty. This made it the final choice for the CobBauge building.

The Process of Constructing a CobBauge Building

(More detail on this section can be found in the 4.1 deliverable)

Formwork

Design and construction of formwork

The contractor is to construct the formwork that will be used to shape the CobBauge walls.

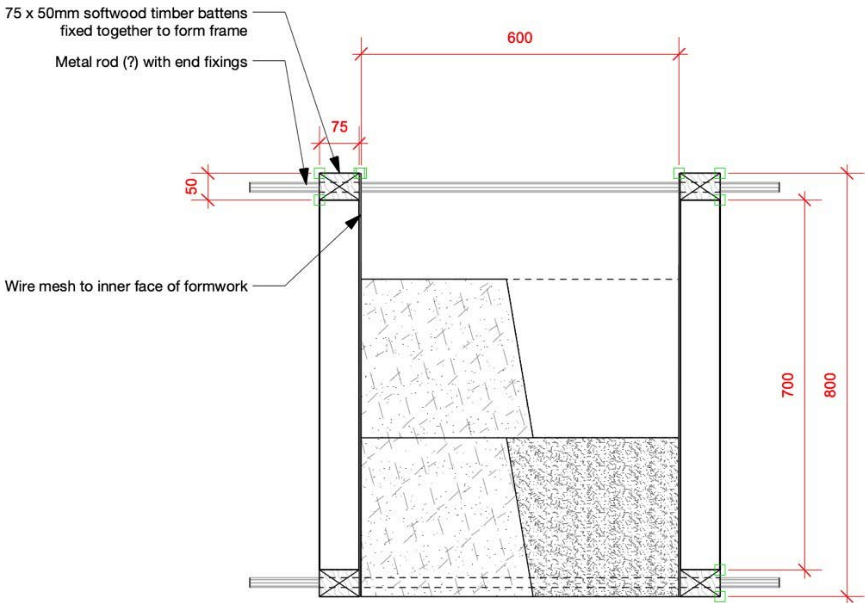
Formwork comprises of two sections of framework that are spaced over the thickness of the intended wall and held in place with long bolted rods / threaded rebar at two or three locations along the length of the formwork, both top and bottom.

The method of constructing the formwork is not prescriptive, though past examples of formwork used in the construction of CobBauge walls have been formed from timber and metal framing.

(Photo: Matthew Fox)

To ease / enable the removal of the formwork after completing a lift of CobBauge, it is important to use wire mesh sides to the formwork frame. This mesh is located on the inner / cob side of the frame. The use of wire mesh also aids the drying process and provides a visual indicator of the compaction of the material within the formwork. Mesh gaps / holes should be around 25mm2.

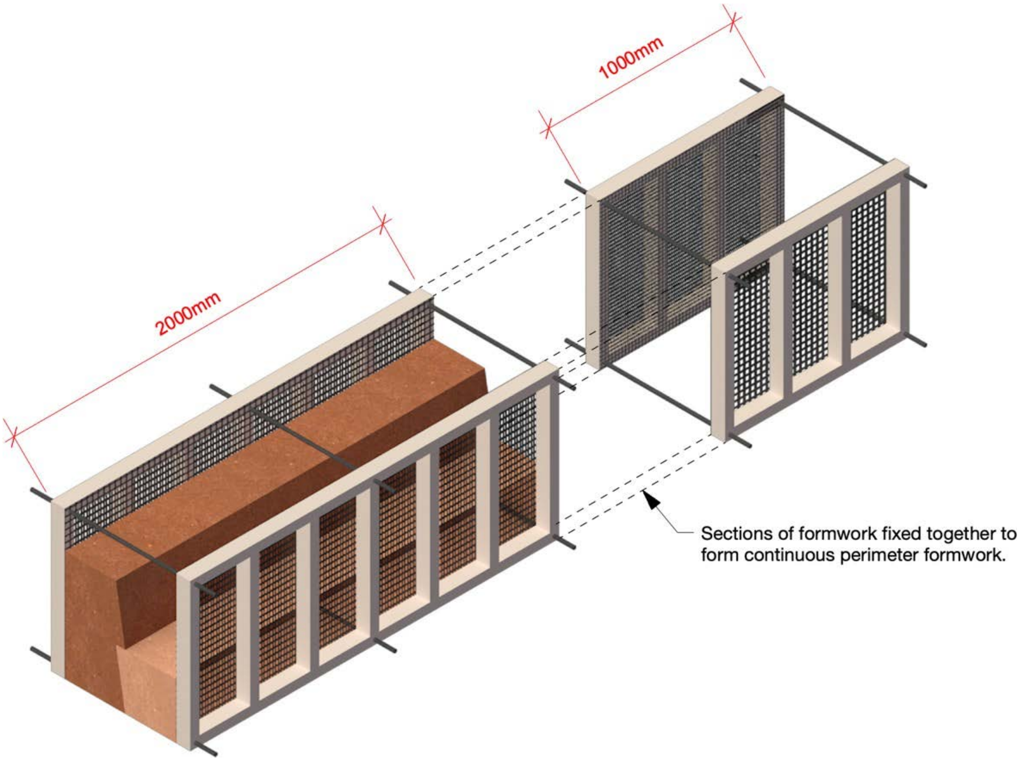
To further aid relocation of the formwork, it is suggested that any excess cob material (that has compressed through the wire mesh) be scraped away while it is still wet. Should this dry around the mesh, it could become difficult to detach the formwork from the cob surface.



(Source: Fox Ecological Architects)

There is no prescribed length of formwork that can be used; however, contractors should be mindful of the weight and manoeuvrability of the formwork. Past examples of CobBauge formwork have comprised of 3m long sections. Even at 3m length, this formwork was found to be heavy and awkward to move.

Lengths of 2m or 1m might be more practical and contractors could consider methods of bolting / connecting multiple short sections together.



Source: Fox Ecological Architects)

In addition to the formwork holding the cob material in place, there is an additional tool, which is used to separate the thermal cob layer from the structural cob layer The shape of this tool enables one 250mm high sub-lift to be formed during construction. This is a timber placement tool, which comprises of two angled timber surface. The angle of the timber is such that it provides a slight angled batt to the face of the structural cob layer, and also makes it easier to remove the placement tool.

(Photo: Lloyd Russell)

The contractor will be required the construct this placement tool.


(Photo: Matthew Fox)

The procedure for laying cob involves putting the placement tool into the formwork. A 200 - 250mm sub-lift layer of structural cob is placed in the void between the placement tool and the formwork mesh. This cob material is compacted into the void by foot and or with a hand stamping tool. The hand stamping tool shown in the photos below comprises of a plywood plate fixed to the end of a mattock handle.

The cob is compacted until there are no voids within the structural cob layer. Once this section of structural cob has been laid, the placement tool is removed and re-positioned adjacent, but slightly overlapping the first section of cob, ready for a continuation of the structural cob layer.

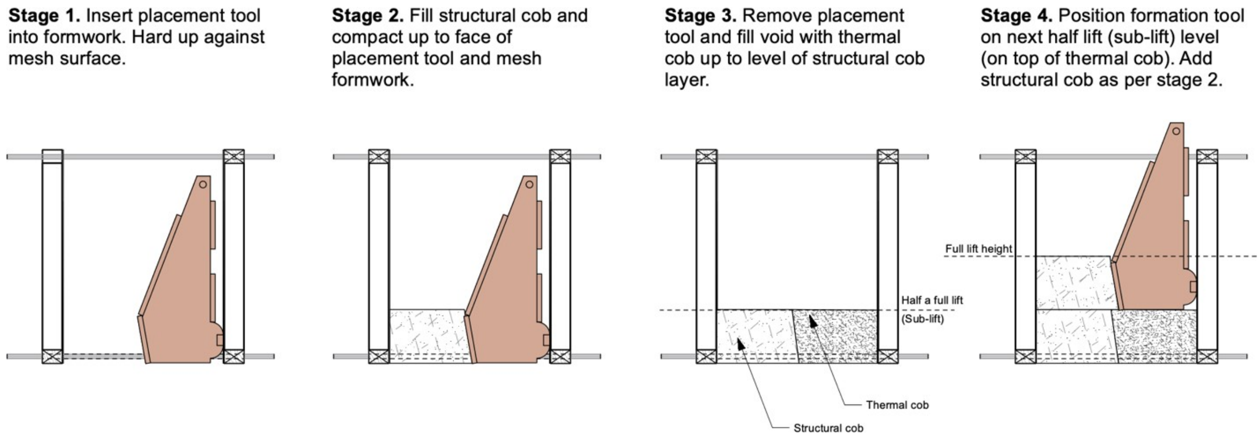
Additional structural cob is then laid along the length of the formwork / wall etc. until the entire perimeter of the building has a 250mm sub-lift layer of structural cob.

Once 250mm of the structural layer has been completed, a 250mm high layer of thermal cob can be placed up against the face of the structural cob. The thermal cob is also compacted into the void between the structural cob and the formwork using the hand stamping tool, though this layer requires less force than used with structural / traditional cob. The aim with compaction is to remove voids between the material rather than compress the material, which will impact on the density and thermal conductivity performance.


Photo showing filling of thermal cob layer against structural cob layer. (Photo: François Streiff)

When a complete 200 – 250mm sub-lift layer of thermal and structural cob have been laid into the formwork, the placement tool is laid on top of the first layer of thermal cob, ready to accept the next

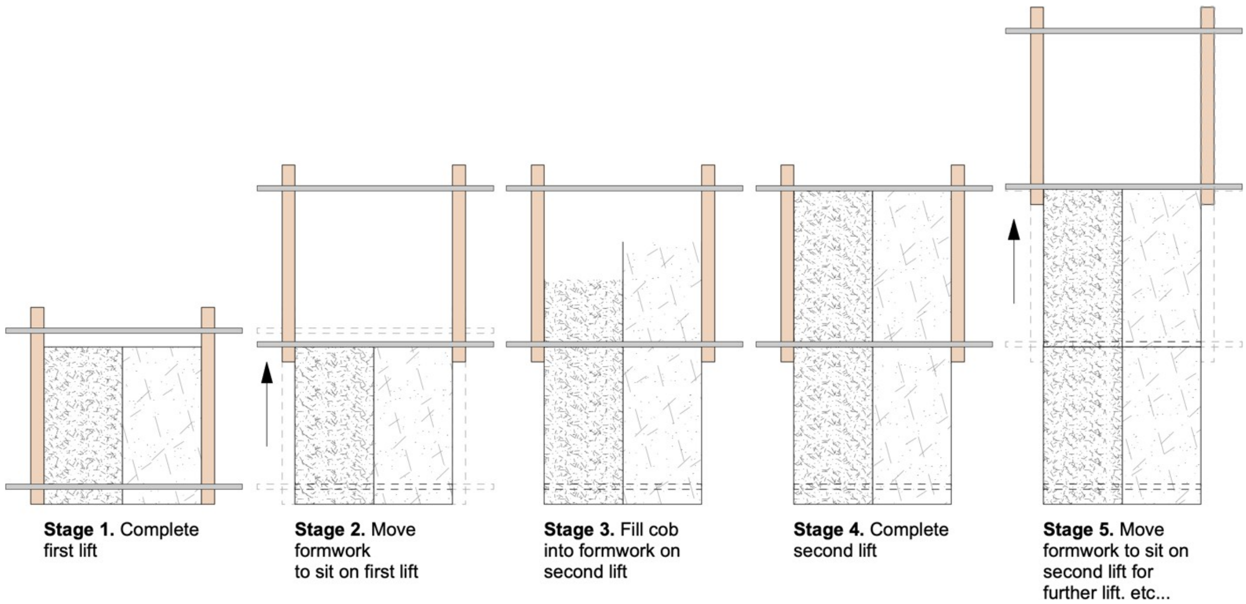
200 – 250mm sub-lift layer of structural cob. The above process is repeated until there are two or three 200 – 250mm layers of both cob materials. This should bring the CobBauge wall close to the top of the formwork and signifies the completion of a single / full lift of cob.



Illustrated use of placement tool with sub-lifts. (Source: Fox Ecological Architects)

Re-positioning the formwork

When constructing lifts of cob above the first lift (or when forming a CobBauge wall on top of a raised plinth), contractors are to sit the connecting bolts on top of the previous lift before attaching the formwork frames (See method for raising the cob in Figure 12).



This will help to support the formwork for the new lift. It is important to carefully, but forcefully remove the buried rods from the CobBauge walling while it is still wet. Using lengths of bar that are threaded along the entire length will aid removal by un-screwing them from the wall if necessary.

Illustrated method for raising formwork. (Source: Fox Ecological Architects)

How the performance levels will be maintained during the construction of a CobBauge building.

(More detail on this section can be found in the 4.1 deliverable)

This is an outline of the methodology to be used by project teams to assess the quality assurance and performance levels of the CobBauge material during construction. This document has been prepared by academic researchers on the Interreg funded CobBauge project in collaboration with members from the CobBauge steering group and is based upon laboratory research and development of the CobBauge construction system.

Project design team members, contractors and material suppliers should refer to this document when reviewing the quality and performance levels of a CobBauge building / wall construction.

Aspects of performance level quality assurance include:

1. Mix ratios
2. Structural quality
3. Thermal quality
4. Fabrication quality
5. Methodology for forming CobBauge wall
6. Further information

Mix Ratios

This section presents an indication of the mix ratios that should be followed to achieve certain performance standards for both the structural and thermal cob layers.

These ratios are based on specific soils and might not be representative of other soil types. It is recommended that the soil characteristics are determined before proceeding with a CobBauge mix, as an inappropriate soil can lead to results that might not meet design guidance set out in this document.

The mixture for the structural layer is very similar to that of traditional cob. The mix ratio should therefore aim to be approximately 2.5% fibre by dry weight of soil. In practice, this roughly equates to 1 bucket of fibre to 1 bucket of soil.
The fibre can comprise of either:

- Wheat Straw
- Flax Straw
- Hemp Straw
- Reed

The thermal mix has a much lower density to that of structural cob. This lower density gives the thermal cob its insulative properties, so it is essential that the following mix ratio and procedures are followed to comply with thermal regulations.

A mix ratio of 50% fibre by dry weight of soil is required for the thermal mix. In practice, this roughly equates to 3 buckets of fibre to 1 bucket of soil slip. Though should be verified with researchers at Plymouth University before proceeding with this ratio.

The fibre should be no greater than 50mm in length and can comprise of either:

- Hemp Shiv
- Flax Shiv

Adding the fibre

Once the correct water content is achieved for the slip, the chosen fibre can be added to the mixture. Fibre should be added a little at a time before being slowly mixed into the soil. Mixing of the soil can be either by machine or hand.

Structural quality

It is important to review the quality of the "structural" cob layer at set intervals during the construction of the wall build. The specific quality indicator for this cob material is structural load bearing capacity.

To assess the structural load bearing capacity of the structural layer of CobBauge, contractors are to form 3 cylinders of the lower (within 600mm of plinth) and middle (within 1.2m of plinth) lifts structural cob material, which are to be sent for laboratory compressive strength testing once obtained stable moisture content.

Sample preparation methodology

During the first lift of a CobBauge wall, contractors are to form at least three number cylinder samples of the same material used for the structural layer of this wall.

Cylinders should be formed using cylinder moulds of the following dimensions:

- Diameter: 150mm
- Height: 300mm

The image below shows a typical example of an acceptable cylinder mould, and alongside it an example of a structural cob test sample.

Laboratory testing

All thermal samples are to be sent away for thermal conductivity testing in a laboratory specialising in this method of assessment. There, samples will be measured using a Heat Flow Meter (Operated in accordance with the manufacturers methodology) to determine the mixtures thermal conductivity.
The following photograph shows a Netzsch HFM446 heat flow meter (HFM), which is acceptable for measuring sample thermal conductivity.

Results from the samples (taken from this batch of material) are to be averaged and should not fall below a thermal conductivity value of **0.12W/m.K**, unless another value is specified by the architect.

If the one or more of the samples vary considerably or are not similar to the average, it is suggested that a further three samples are prepared and measured.
For further information on CobBauge or should contractors / construction professionals have any specific questions in relation to a CobBauge building, they are advised to contact the contract administrator and or CobBauge research team (cobbauge@plymouth.ac.uk).

Calculating the labour content of the construction process

Manhours used for the CobBauge walls on the Plymouth Prototype

During the course of building the Plymouth prototype a record was kept of the individual hours worked on the CobBauge process, from the creation of the mixes to the implementation in the formwork of the walls

	Friday, 20 August 2021				Monday, 23 August 2021			Tuesday, 24 August 2021	
	Paul	Ivor	Sol	Freddie	Paul	Sol	Chris	Paul	Sol
Digger		8.5							
Cob arrival					3	3			
Formwork							3		
Adjusting Formwork									
Window boxes/lintels									
Laying structural									
Laying thermal									
Cob mix off site	8.5		4.5						
Labouring									
Mixing Thermal									
Preparing slip				5.5				6.5	6.5
Trimming									
Protection: OSB, Tarps									
Event	Off site cob mix								

	Wednesday, 25 August 2021			Thursday, 26 August 2021			Friday, 27 August 2021				Wednesday, 8 September 2021			Thursday, 9 September 2021		
	Paul	Sol	Chris	Paul	Sol	Chris	Paul	Sol	Chris	Sub Total	Paul	Sol	Will	Paul	Sol	Chris
Digger																
Cob arrival																
Formwork																
Adjusting Formwork																
Window boxes/lintels																
Laying structural	5			8			8				8			6.5		
Laying thermal		5			8			8				8			6.5	
Cob mix off site																
Labouring			5			8			8				8			6.5
Mixing Thermal																
Preparing slip																
Trimming																
Protection: OSB, Tarps																
Event	Lay first layer 250mm									Second layer						

These figures are taken from the hours that were recorded by the contractors and researchers on site.

They are the hours that have been paid for under the contract

(Therefore, there is no allowance for separating out the time spent on breaks or for lunch or dropping what you're doing to go and help on another part of the process. If you record the exact time taken to lay a metre of CobBauge or to mix a cubic meter of mix, it will be a lot less than the actual time taken to build the walls).

The surface area of the CobBauge walls for the Plymouth prototype including openings is calculated as $46.05m^2$

The manhours were broken down as follows:

Digger driving off site	16.5
Cob mixing offsite	29
Cob mix unloaded on site	6
Formwork installation	188.5
Adjusting Formwork	4
Window boxes/lintels	29
Laying structural cob	105.5
Laying thermal cob	101
Labouring on cob	111.4
Mixing Thermal cob	36
Preparing slip	44.5
Trimming cob	10
Protection: OSB, Tarps	8
Total manhours	799
Per m^2 of CobBauge wall	17.35

The walls were built up from 250mm layers, with two layers forming a lift
Each lift was built using 600mm formwork.
The length of each layer (excluding openings) is 24.045m
The length of a layer including openings is 19.445m

If we take just time taken to lay a layer of CobBauge just including the mixing, labouring and laying of the material, the manhours per m^2 are 8. This is an average of the times taken over a number of layers after the workers had adjusted to the technique. The first layer took 10.48hours per m2, and the best was 6.78

The manhours used to build the formwork (two sets at 600mm high) was 117 hours, so this is 2.43 per linear m

Provisional costing for the CobBauge walls

A further spreadsheet was used to calculate the financial costing of the process for the Plymouth prototype

Area of wall (m2)	46.05	m2						Labour Rates UK	
Gros Internal Floor Area	28.8	m2	Assumes rectangular building					Skilled £/hr	£25
								Unskilled £/hr	£15
			Labour						
Activity	Manhours	£/hr	Cost						
Digger	16.50	£25	£413						
Cob arrival	10.00	£15	£150						
Formwork	176.50	£15	£2,648						
Adjusting Formwork	26.50	£25	£663						
Window boxes/lintels	52.50	£25	£1,313	367.00	1679.50				
Laying structural	144.00	£25	£3,600						
Laying thermal	167.50	£25	£4,188						
Cob mix off site	29.00	£25	£725						
Labouring	147.00	£15	£2,205						
Mixing Thermal	42.50	£15	£638						
Preparing slip	52.00	£15	£780						
Trimming	18.50	£25	£463						
Protection: OSB, Tarps	20.00	£15	£300						
Total hours	902.50		£18,083	Still being updated					
Hours/m2	19.60		£393						
Formwork									
Construct formwork	117.00	£25	£2,925						
Formwork materials			£4,726	TBC					
Total			£7,651						
Materials									
Cob			£500	TBC					
Hemp			£1,165	TBC					
Ply (lintels, window boxes etc)			£317	TBC					
Fixings - bolts			£50	TBC					
Total			£2,032						
Plant									
				TBC					
Total			£0						
Other						First lift	Last lift	Percent diff.	
Skip			£500		Hours	63	33	52.38	
Total			£500						
			Cost	£/m2 of wall	£/m2 GIFA		Optimised		
Total labour			£18,083	£392.67	£627.86		£205.68		
Total formwork (divide by 10)			£7,651	£166.15	£265.66		£16.61		
Total materials			£2,032	£44.13	£70.56		£44.13		
Total plant			£0	£0.00	£0.00		£0.00		
Total other			£500	£10.86	£17.36		£10.86		
Total			£28,266	£614	£981		£277.28		
Hemp alone				£25.30					

Actual cost	£/m2 of wall
Total labour	£392.67
Total formwork	£166.15
Total materials	£44.13
Total other	£10.86
Total	£614

Normalised cost	£/m2 of wall
Total labour (times 52.38%	£205.68
Total formwork (divide by 10)	£16.61
Total materials	£44.13
Total other	£10.86
Total	£277.28

The average cost for an insulated brick and block cavity wall is around £230 per m2

At the bottom of the spreadsheet there are two Totals: one for the actual costs, and the second as an exercise in normalising these costs.
This was done as an attempt to get a more realistic idea of the costs going forward. The Plymouth building was the first prototype built in this country, and therefore will have taken longer to build than future CobBauge projects.
The two differences between the two sums are:

1. The labour costs have been reduced by about half. This is based on advice from our Quantity Surveyor.
2. The cost of the formwork has been divided by ten on the assumption that the formwork will be re-used at least ten times

The revised build cost figure of £277.28 per m^2 compares favourably with a typical cost of a masonry cavity wall of £230 m^2.

Conclusion

This report is a summary of the performance levels associated with the construction process for CobBauge linked to discussions by the network and overseen by the Steering group.
More detail of the various processes discussed in this document can be found elsewhere in the documentation for the CobBauge project. The main source is the technical section of the website: http://www.cobbauge.eu/en/technical-documentation/