COBBAUGE

A GUIDE FOR DESIGNERS

Photo: Plymouth University, CobBauge project

www.cobbauge.eu

CONTENTS

1 INTRODUCTION

1.1 What is CobBauge?

CobBauge is a new composite solid wall construction, which develops traditional cob construction to meet the thermal performance of modern building regulations. This wall construction is created entirely out of natural materials, of clay subsoil and plant fibres, and contains two layers of different properties: the structural, which is dense inner-face made from cob, and the thermal, which is the lightweight outer-face made from light earth (as explained in Section 2).

1.2 Who is this guide for?

This document aims to inform designers about the generic methods of constructing a building using the CobBauge material. Until the end of the CobBauge research project, in June 2023, this guide is intended as a working document, which develops as the research progresses. This information partners with the *CobBauge - Quality Assurance* document, which also forms part of the tender documentation.

While the principal purpose of this guide is to provide guidance to professional designers, with no prior experience of earth construction, it will also be relevant as technical guidance to professional builders, and as an educational tool to students.

This guide was produced as part of an E.U. Interreg pro.

1.3 What does the guide cover?

This guide describes an overview of the information that a designer will need to understand, when designing for CobBauge construction, and the processes that typical building designs using CobBauge will need to undergo. These processes range from the sourcing of raw materials to the mixing, testing, and drying (Sections 2-4), to the plinth, formwork, drying, openings, potential problems, and scaffolding construction (Sections 5-10). This guide provides generic CobBauge information, therefore it does not provide for all circumstances and ways in which CobBauge might be used.

This is a guide for design, there is a separate CobBauge guide for building.

1.4 Copyright

This Guide has been produced as one of the outputs of the CobBauge research project, which involved six British and French partners with complementary expertise:

- Plymouth University (UK): Lead partner of the project
- Graduate School of Construction Engineers of Caen, (ESITC) Caen (FR)
- Regional Nature Park of the Marshes of Cotentin and Bessin, (PnrMCB) (FR)
- Earth Building UK and Ireland, (EBUKI) (UK)
- University of Caen Normandy, (LUSAC) Laboratory (FR)
- Hudson Architects, Norfolk (UK)

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Further information can be found at the project website **www.cobbauge.eu**

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1.5 Liabilities

The contents of this document are intended to be used as a resource in training to improve the skills and knowledge of builders using CobBauge. The authors accept no responsibility for the design or construction of any individual projects which may be produced.

2 COBBAUGE RAW MATERIALS

2.1 Sourcing materials

The sourcing of materials for the use of CobBauge is an important part of its process as this significantly contributes to the new construction system's low embodied carbon goal. Therefore, to fulfil this, it is encouraged to source the materials from the site itself, or as local to the site as possible. As the clay subsoil makes up the largest proportion of the materials required to make a CobBauge wall, sourcing this from the site is a beneficial way to minimize the project's embodied carbon. While the site's subsoils might not be of the ideal characteristics in its raw form, to be suitable for either the cob or light earth mixes, it may be possible to augment these subsoils with additional clay or ballast so it can be useable (see Section 2.2.1)

2.2 Requirements of subsoil – for structural layer

The earth needed to create the structural layer of CobBauge is the same as that needed for traditional cob. This comprises of a subsoil with a clay content of 12 - 20%, to act as an adhesive for the other parts of the mix, as well as it being well graded (contains a range of particle sizes including fines, sand, and gravel) to improve mechanical resistance and reduce shrinkage (Figure 1). Thorough testing of the subsoils must be conducted to ensure that the clay reactivity and shrinkage rate are suitable for the structural layer of CobBauge wall construction. These tests are outlined in Section 4.

Figure 1. Example of a subsoil suitable for a CobBauge structural layer. Photos: Katey Oven.

2.2.1 Additives to CobBauge structural layer mixes

The subsoil available may not be suitable for cob construction in its natural state, when excavated. However, depending on the soil type, it may be possible and practical to add additional materials to this subsoil to make it suitable to be used for a cob mix. In the case of a subsoil's clay content being too high, it is possible to add ballast to reduce the clay content percentage within the mix. An aggregate mix with a grading from 20mm – dust is recommended to be able to do this. On the contrary, pure clay can be added to the subsoil to raise the total clay content of the mix.

2.3 Requirements of subsoil – for thermal layers

The earth needed to create the thermal layer of CobBauge is the same as that needed for traditional light earth. This comprises of a clay rich subsoil, with a clay content of 60% or more, which Figure 2 exemplifies. This is used to create pourable clay slip, which will adhere the mix's natural fibres together. Results show that the richer and higher strength of the clay, the lower the u-values of the CobBauge thermal layer. This is due to the light earth mix requiring less of it to stick the fibres together, resulting in an overall lighter mix. An effective clay rich subsoil can yield a u-value of 0.23W/m²K for the CobBauge wall system. The content of clay within light earth mixes has not been found to make shrinkage an issue for the thermal layer.

Figure 2. Example of a subsoil suitable for a CobBauge thermal layer. Photos: Katey Oven.

2.4 Requirements of natural fibres – for structural layer

Wheat straw is the recommended natural fibre for the cob mix that forms the structural layer of CobBauge. This fibre is accessible worldwide and has been proven to be successful for the CobBauge construction system. For best practice, it is important to ensure that the straw is fresh and kept dry. Before use, to check that the straw is in good condition, the straw bale should be opened and examined for mould, rotting or brittleness. The straw strands should be 150mm – 300mm in length and should not need to be cut before use. It is important to note that short lengths of straw will not make the structural layer as strong.

2.5 Requirements of natural fibres – for thermal layer

Hemp shiv is the recommended natural fibre for the light earth mix that forms the thermal layer of CobBauge. This fibre has been proven to be successful for the CobBauge construction system as it is good at resisting over compaction. The hemp shiv should be pre-cut to lengths of around 30-80mm and sold as a product for building purposes.

Chopped reed has been explored for use as the light earth's natural fibre, however this was less effective as it required more care to be given during its installation into the formwork. It was found that the reed could be over compacted and permanently deformed, diminishing the insulative properties of the thermal layer.

2.6 Internal plaster & paint

As the CobBauge wall system is breathable and hygroscopic, it is important that the internal plaster also follows these vapour permeable characteristics. This lends itself to natural plasters such as lime or clay. Whilst both are effective, environmentally, it is recommended that clay plaster is used as it is likely that this can be made from the same subsoil as the structural cob mix, therefore saving on embodied carbon. This also adheres to the monolithic wall construction approach of the CobBauge innovation as well as having similar traditional routes. To create the clay plaster, a specialist can be hired, or the designer can carry out in-house testing to get the right mix. The application of the plaster requires skills unique to this craft, therefore it is important to consider who will be contracted to complete this task. The same breathable qualities are also required for any paint finishes e.g., a clay-based paint. It is important to note that an impermeable finish would cause detrimental implications to the CobBauge wall, structurally and thermal performance wise, due to moisture and mould problems.

The limitation of clay plaster is that it is not waterproof, and therefore weatherproof, making it only appropriate for internal application. While it is possible to leave the internal face of the CobBauge exposed, without a plaster or paint finish, care would need to be given to the surface to make this method practical and appropriate e.g., applying a clear glaze coating to reduce potential dustiness. The structural layer's grid-textured finish would also need to be visually welcomed or investigated to see if it could be gently sanded down without affecting its structural integrity.

2.7 External renders

Like the internal plaster, it is also mandatory that the external render is breathable, sharing the characteristics of the natural CobBauge wall, however, with the addition of it to be waterproof and weather resistant. This makes lime the most appropriate render mix (Figure 3). While contracting firms should have a basic understanding of lime render, often specialist firms are used in these occasions. Unlike the internal face, the external face of a CobBauge wall cannot be left un-rendered as the thermal, light earth, layer is not durable enough and needs to be protected. Therefore, the application of a breathable paint alone is not enough.

Figure 3. Example of lime render being applied to a CobBauge wall. Photo: Raphaël Rattier.

3. MIXING COBBAUGE MATERIALS

3.1 Mix ratios

Both thermal and structural CobBauge materials are to be either mixed on site, close to site or imported from an external supplier. In each case, the following procedures should be followed to ensure the soil and mixture is suitable for use in a CobBauge building:

Stage 1. Initial in-house testing
Initial testing is completed by the designer in-house, to be able to access the subsoil for its clay presence and therefore potential to be used for one of the mixes (refer to the *CobBauge – Guide for Builders* Document for the tests). This is also a great opportunity to develop in-house understanding on the range of different subsoils, their characteristics and clay quantities. Once a prospective subsoil for use is found, a 1kg sample is to be extracted and sent to a suitable testing facility. Researchers on the CobBauge project at Plymouth University can assist with conducting the testing or finding a suitable facility. Contact details for this laboratory are: cobbauge@plymouth.ac.uk

Stage 2: Lab analysis
Lab analysis of the subsoil is conducted at the testing facility to determine its clay content, grading and cob and light earth mix viability. This will also help to determine if the subsoil needs additional ballast or additional clay, and how much of it, to make it appropriate for one of the CobBauge material mixes. This laboratory research will also help to determine the percentage of fibre needed for each of the CobBauge layers.

Stage 3: Tailor-made material recipes
Designers can then use this information, to form the tailor-made material mix recipes for the CobBauge project.

Stage 4: Sourcing enough subsoil for the build
Once a suitable subsoil has been thoroughly tested and chosen for both the cob and light earth mixes, bulk quantities of them can be sourced for the build. It is advantageous to source all the subsoil, needed for the build, at one time to avoid inconsistencies that ordering different batches could have, which could in turn affect the subsoil's characteristics.

Once the subsoils are construction ready, meaning that their ratios of ballast/clay are now correct, the following gives an example of the material ratios (in volume) for the structural and thermal layers:

• **Cob mix** (structural layer): 1 bucket of construction ready subsoil mix to 1 bucket of wheat straw fibre.

• **Light earth mix** (thermal layer): 1 part of clay slip to 3 parts of hemp shiv fibre.

These ratios show that the cob mix has an approximate ratio of 1:1 subsoil to wheat straw, whereas the light earth has an approximate ratio of 1:3 clay slip to hemp shiv (by volume). These ratios can also roughly be translated to 2.5% fibre content by dry weight of soil for the cob mix and 50% fibre content by dry weight for light earth. It is important to note that the above ratios are not a rule, which is why designers need to complete stages 1 & 2 of the above so the material percentages can be tailored to the project before the mixing stages occur (Subsection 3.2).

3.2 Mix methods

The methods for mixing thermal and structural CobBauge materials, on or away from site, differ due to the density of the material in each case. As both cob and light earth are traditional construction techniques the following procedures for preparing the mixes should be familiar for builders with previous earth building experience.

3.2.1 Mixing the structural layer

Stage 1. Decide how the material will be mixed and stored

Mixing the subsoil with the wheat straw, at the ratio which has been tailored to the project, can be undertaken by the traditional method, by foot, or by utilising modern machinery (see Figures 4 & 5). Although, the machinery method makes CobBauge construction more viable due to the increased ease, speed, and ability to make the material mixes more consistent.

There are multiple methods to mechanically mix the subsoil, wheat straw, water & potential addition of ballast together, these include:

1. **Using a skip** as the container to mix within and a digger bucket to mix with (Figure 5)

2. **Digging a pit** in the ground (about the size of a skip) and using this as the container to mix within and a digger bucket to mix with

3. **Putting the materials on a concrete slab or flat surface equivalent** to mix on and using a digger to run over this to mix the material together (Figure 4)

All these methods require a minimum of a 4.5 tonne digger to have enough power for the mixing, whilst they differ on where the mixing of the material takes place. It is also important to consider what container will be used to store the material and how it will be covered after it is mixed (see Subsection 9.3). Therefore, it is important that the designer discusses these options with the contractor to decide which method would be the most appropriate for the project.

Figure 4. Mixing the structural cob mix by machine or foot. Photo: Plymouth University, CobBauge project (2021) (left), François Streiff (right).

 

Figure 5. Mixing the structural cob mix in a skip with a digger bucket. Photo: Katey Oven.

Stage 2. Weighing the materials to the desired ratio
The digger can also be a useful tool to measure the material quantities. To do this, the contractors can hire a digital scale that can be attached to the digger bucket, that will be used for measuring and adding the material to the mix, so that the weight of 1 digger bucket of each material can be calculated. From this, the specified material ratios can be converted into digger bucket volumes to make up the mix’s correct proportions.

Stage 3. Mixing the materials
Start by adding a weighed amount of the subsoil to the container. Next, use the digger bucket to gradually add the straw and water to form the specified mix ratio, thoroughly mixing the materials together throughout this process. It is recommended that the wheat straw and water are added a little at a time to aid the mixing process and to ensure that fibre is evenly mixed throughout.

Stage 4. Complete ball drop test
Once all the ingredients are added and fully mixed, to assess if the cob is of the right consistency to build with, the ball drop test needs to be carried out on the mix (see Subsection 4.3). If the material does not meet the desired output of the test, more materials will need to be added to the cob mix to get it to be right e.g., adding more water if the mix is too firm/dry or more subsoil and straw if it is too wet/loose. When the cob passes this test, the material can be stored ready for use (see Subsection 9.3) or added straight into the formwork of a CobBauge wall, as described in Section 6 of this document.

3.2.2 Mixing the thermal layer

The thermal layer is mixed using a clay slip. In summary the slip comprises of suitable subsoil that is then mixed with water until it meets the criteria set out for the puddle test in Section 4.3. The procedure for preparing the slip is as follows:

Stage 1: Soak the subsoil
It is recommended to leave the subsoil to soak for at least 3 days prior to mixing the slip. This will allow it to break down and become malleable. For any large solid chunks, the breakdown can be aided by using a hammer / crowbar etc. To complete this step, like the mixing of the

structural CobBauge, a container for the material needs to be sourced. This could be by digging a pit in the ground and lining it with an impermeable material, such as a damp proof membrane (see Figure 6) or using a skip.

Figure 6. The thermal mix subsoil soaking in a watertight pit. Photo: Tom Booen.

Stage 2. Estimating the slip ratio

There is an optimum viscosity for the slip. This is measured using a puddle test, which can be undertaken on site, and is explained in Section 4. It is advised to carry out this test on a smaller sample of the chosen subsoil, prior to mixing the slip in bulk, to be able to work out the ratio of subsoil to water to achieve the desired 14cm pool consistency.

Stage 3. Applying the slip ratio

Take a large container, such as a bucket, barrel (approx. 800ltrs in capacity) and fill it with the approximated project specific slip ratio (Figure 7). For instance, if the puddle test resulted in a ratio of 1:1 subsoil to water (by volume), then half of the bucket would be filled with the subsoil and the equivalent of the other half of the bucket would be the water.

Figure 7. Mixing the subsoil with water, in a large bucket, to form the clay slip. Photo: François Streiff.

Stage 4. Mixing the slip

Mix the subsoil and water together. While it is possible to complete this procedure by unmechanical handheld tools, it is recommended to use a motorised paddle mixer for ease, speed, and mixture consistency (Figure 8). It is also important to note that it is easier to add more water to the mixture than it is subsoil, to get the desired puddle consistency, therefore it is advised to add the water quantity to the subsoil gradually in small quantities.

Figure 8. The desired consistency of the clay slip. Photo: François Streiff.

Stage 5. Sieving the slip
Once the slip has been mixed, if there is aggregate present, this mixture is sieved using a mesh of approx. 8mm2 holes to remove any large stones and other large pieces of material (Figure 9). Ideally, the slip is sieved into several smaller buckets for ease of further use.

Figure 9. Sieving the slip. Photo: François Streiff.

Stage 6. Adding the slip to the hemp fibre
Once the slip is of the right consistency, and any larger particles have been removed, it can be added to the hemp shiv to form the light earth. The mixing of the light earth can be carried out traditionally, by hand (Figure 10), or by using a machine, such as a cement, baron or plaster mixer (Figure 11). It is advised to add the slip gradually, a little at a time, to the hemp shiv to avoid oversaturating the mix.

Stage 7. Assess the consistency
The light earth mixture should not be soggy but be wet and sticky enough so that all the hemp shiv is full coated in the slip and therefore is able to hold its shape when moulded in the palm of a hand (Figure 12). The characteristics of Light earth are often compared to a fibrous breakfast bar, such as a flapjack, while its mass is notably lightweight when lifted. Once the

mixture meets this description the light earth can be stored ready for use or added straight into the formwork of a CobBauge wall to form the thermal layer. Further information can be found in the Quality Assurance document, which partners this document.

Figure 10. Mixing of light earth mix on site using a cement mixer (left) and by hand (right). Photos: François Streiff (left) & Anthony Hudson (right).

Figure 11. Mixing of the clay slip and hemp shiv fibres off site using a baron mixer. Photo: Plymouth University.

Figure 12. Desired consistency of light earth mix. Photo: Katey Oven (2022).

3.3 Calculating CobBauge material volumes

The materials required for CobBauge construction should be calculated pre-construction to reduce site wastage. The volume of the structural and thermal layers should be calculated separately, as the outer thermal layer has a larger perimeter, and the method for working out the volumes will depend on the geometry of the specific building.

3.3.1 Structural layer material volume calculations

When the volume of the structural layer has been calculated, the cob mix's material volumes can then be calculated from this. It is important to remember that the water needed in the material mix should not be included when calculating the volumes of finished CobBauge wall layer. This is because the water will evaporate and therefore, will not form part of the finished wall. The estimated value for 1m³ of structural CobBauge is around 1,650kg/m³.

Worked example

As Table 1 shows, if a building requires 50m³ of structural CobBauge, then the total weight estimate of this would be:

50m³ x 1650kg = 82,500kg

In the case of Table 1, for this specific cob mix, the addition of 13% ballast and 10% clay are required for the mix. As an example, 100kg of raw earth would have 13kg of ballast and 10kg of clay added to create a total of 123kg to maintain the correct ratio. Once this subsoil mix has been created, this material comprises of 98.5% of the structural layer's total weight. The wheat straw accounts for the remaining 1.5% of the layer's weight, as the water is not included.

Table 1 Structural CobBauge ingredient quantities example

Ingredients	**Weight total of total build 50m³**
Subsoil Mix (98.5%)	**81,262.5kg**
- *Subsoil (100%)*	- *66,066.5kg*
- *Ballast (13% of raw earth)*	- *8,589kg*
- *Clay (10% of raw earth)*	- *6,607kg*
Water	5,775kg (not included in dry weight)
Wheat Straw (1.5%)	1,237.5kg
Total Weight of Structural Layer	**82,500kg (est. after water evaporation)**

3.3.2 Thermal layer material volume calculations

When calculating the volume of the thermal layer, it is important to consider that it forms the outer half of the CobBauge wall, therefore it requires more material than the inner structural layer. In addition to this, the thermal light earth mix is often used more around building openings and the roof to reduce thermal bridging. The estimated value for 1m³ of thermal CobBauge is 350kg/m³.

Worked example

As Table 2 shows, if a building requires 55m³ of thermal CobBauge, then the total weight estimate of this would be:

55m³ x 350kg = 19,250kg

In the case of Table 2, for this specific clay slip mix, a ratio of 1:1 clay-subsoil to water (by volume) was determined from the puddle test (Subsection 4.3). These volume quantities were then transferred into weight to give the ratio of 58:42 clay-subsoil to water (by weight). Just like the cob mix, it is important to remember that all the water required for the light earth mix should <u>not</u> be included when calculating the volumes of the finished CobBauge wall layer. This is because the water will evaporate and therefore, will not form part of the finished wall. The values in Table 2 also correspond to the 1:3 clay slip to hemp shiv ratio (by volume) rule of thumb as explained in Subsection 3.1.

Table 2 Thermal CobBauge ingredient quantities example

Ingredients	**Weight total of total build 55m³**
Clay slip (wet)	24,053kg
- Clay rich subsoil (58% by weight)	*- 13,951kg*
- Water (42% by weight)	*- 10,102kg*
Hemp Shiv	5,298kg
Total Weight	**19,250kg (est.)**

4 TESTING OF COBBAUGE MATERIALS

4.1 Early subsoil testing

When considering a site for a CobBauge project, it is encouraged that site's subsoil is used where possible. This is due to the financial and carbon costs, of transporting a large amount of subsoil to the site, as well as the savings, financially and carbon wise, of not needing to send any of the site's subsoil to landfill when clearing and digging the foundations.

When checking whether subsoil can be used, it will be necessary to have laboratory tests conducted to be certain that the subsoil can be used for CobBauge, as outlined Subsection 3.1. However, as these tests take time and have a financial cost attached to them, it is beneficial to only send subsoils that have the potential to be suitable for laboratory testing. Therefore, it is recommended that the designer completes a series of initial in-house tests that are detailed in the *CobBauge – Guide for Builders* document. If the subsoil on site is not suitable, quarries and brickworks are good places to look for alternative local sources in addition to speaking with a local geologist to help with the search.

4.2 Laboratory testing methods

4.2.1 Structural layer laboratory testing methods

If the initial testing indicates that a subsoil may be a good candidate for either the structural or thermal CobBauge layer, then it is strongly advised to get a sample tested in a laboratory to confirm this and to propose the recommended material mix ratios.

As part of the lab testing, it is likely that the subsoils will be wet sieved, in accordance with BS1377, and analysed for 'fines' fraction (silt and clay) which is established through the pipette method. The grading of subsoils and determining of the particle size distribution are key elements of the lab testing. This will show the percentage of clay/silt, sand, and gravels, which can be compared to the distribution required for CobBauge. Figure 13 shows an example of laboratory results plotted onto a graph with the upper and lower grading limits for a suitable subsoil for cob.

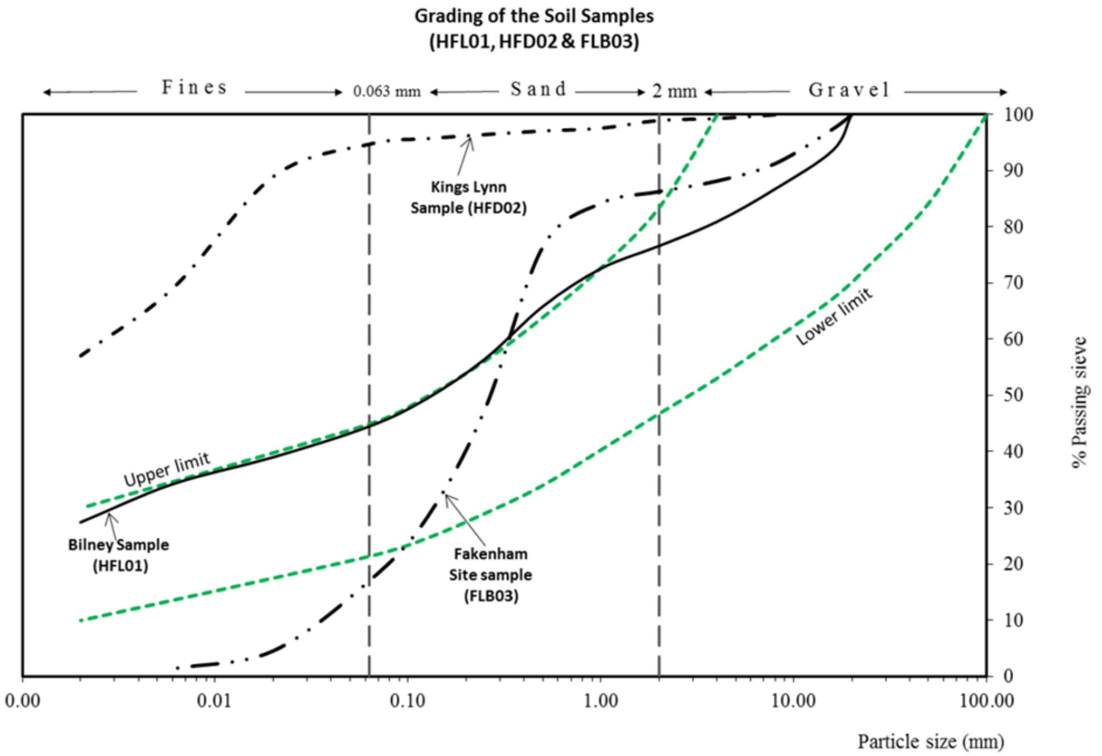

Figure 13. Laboratory grading results for three soils and recommended grading limits for structural cob suitability. Completed by & sourced from David Clark.

In this example the ‘Bilney Sample’ can be seen to be close to the requirements for cob construction as shown by the ‘upper limit’ and ‘lower limit’. It was recommended that the subsoil required approximately 13% ballast (20mm – dust aggregate) to fall within the suitable limits.

Another key element of the lab testing is the subsoil’s shrinkage. This analysis is conducted by filling a shrinkage mould (of approx. 40mm x 40mm x 600mm) with a trial cob mix, using the subsoil sample, leaving it to dry out and then measuring the material’s new length. In the instance of the Bilney sample, the cob mix was also mixed with 10% and 15% ballast to compare how these material additions affected the results. The 15% ballast was found to give a 1% shrinkage rate which is an acceptable amount for cob.

The final important laboratory test to be conducted is the trial cob mix’s unconfined compressive strength. It is important to note that a structural engineer will require this value from the designer to be able to complete the building’s structural design. This value is obtained by compressing a dry 100mm cylinder of the trial cob mix in a calibrated apparatus.

4.2.2 Thermal layer laboratory testing methods

The thermal layer of CobBauge is not expected to perform a structural role in the wall. Instead, the purpose of this construction element is to provide the building’s thermal performance, which is critical for the building to meet building regulations. Therefore, thermal conductivity is the primary quality indicator for this material.

To assess the thermal conductivity of the thermal layer of CobBauge, designers are to form rectangular 300mm x 300mm x 70mm (Length X Width X Depth) samples of the light earth mix, using a mould, which are to be sent for laboratory thermal conductivity testing. These dimensions are critical for the preparation of samples that are suitable to be measured using Heat Flow monitoring apparatus. Figure 14 shows an example of an acceptable light earth sample mould, and alongside it an example of a light earth test sample next to the apparatus. This lab testing will involve the samples to be oven dried at 40°C until they reach an equilibrium weight. This means that 3 consecutive weighing’s at 24hour intervals are within 1% of each other.

Figure 14. An example of a heat flow monitoring apparatus & thermal cob test sample. Photo: Plymouth University, CobBauge project.

It is advised that this is completed with a trial light earth mix, using the tailored-made material ratios, before the light earth mix for the building is mixed up in bulk. If the designer is happy that the results fulfil the building’s thermal performance, the light earth for the building can be mixed up in a larger quantity.

Before the first lift of a CobBauge wall, it is advised that designers repeat the test, to produce an accurate thermal performance reading on the light earth mix that is going to be used for the building. This will ensure that the result is representative for the CobBauge wall. This will require the designer to produce at least three more rectangular samples to be sent away for the laboratory testing.

If the average thermal conductivity result for the samples is less than the value specified, possible reasons for this, and what the designer needs to investigate, include:

1. Components and or quantities of the mix are incorrect.

Designers should check the following:

a. Percentage of clay in the subsoil

b. Percentage of aggregate in the subsoil

c. Percentage of fibre in the mix

d. Percentage of water in the mix

2. The cob mixture has not been prepared or mixed correctly.

Designers should refer to Section 3 of this document for guidance on how to mix the thermal CobBauge and check the following:

a. The consistency and thoroughness of the materials mixed

b. The compaction of the samples e.g., if they are over or under compacted.

3. The cob mixture has experienced increased wetting or drying after initial mix.

Designers should check that:

a. That the material storage is appropriate e.g., the mixture has been stored with proper protection (tarpaulin) from sun, wind and rain.

b. The material has been transported appropriately e.g.; the mixture has been protected during transport.

4.3 Onsite testing

4.3.1 Structural layer onsite testing

To test if the structural cob mix (subsoil, fibre & water plus any specified material additions) is of a suitable consistency & plasticity to build with, a ball drop test needs to be carried out. This is likely to be completed by the builder or the person responsible for creating the mix. This method consists of:

1. Measure 2 litres of cob mix using a measuring jug (see far left image in Figure 15).

2. Form this quantity of material into a sphere by hand.

3. Next, drop this ball from a height of 1 metre onto a flat surface.

4. Measure the diameter of the ball’s ‘splat’. The desired diameter for the cob mix splat is 21cm, give or take 1cm.

Figure 15. Ball drop test methodology for structural cob mix. Photos: Katey Oven (2022).

4.3.2 Thermal layer onsite testing

To create the most suitable clay slip consistency for the use in the thermal layer, a puddle test needs to be undertaken. This method consists of:

1. Measure 100ml of clay slip (subsoil and water mixed together - no fibres), using a measuring jug. It is recommended to add the water to the earth gradually to form to slip, as adding additional water to achieve the desired viscosity is much easier than adding additional clay.

2. Pour the 100ml of clay slip from a 100mm height onto a flat surface (see far left image in Figure 16).

3. Measure the diameter of the slip's puddle on the surface. The desired diameter, for an optimal slip mixture, is exactly 14cm. More than 14cm will mean that the slip is too diluted, which would reduce the slip's adhesive and therefore structural properties. Less than 14cm, risks using more clay slip than necessary which will alter the desired insulation properties of the thermal mix.

4. Once this consistency is achieved, the slip is ready to be mixed with the fibres at a specified ratio (see Section 3).

Figure 16. Slip puddle test for thermal cob mix. Photos: Olivia Elsey (2022).

5. PLINTH

5.1 Ground investigations

For CobBauge construction, ground investigations should be undertaken, just like any other building project. As CobBauge is a heavyweight construction, it is vital that it is properly supported. Therefore, it is recommended that a suitable geotechnical engineer investigates the ground conditions of the site to inform the structural design of the foundations.

5.2 Suitable plinth support

The ground investigations may dictate the type and depth of the building's foundations. A range of potential foundation types are shown in the *CobBauge Standard Details* document. As the CobBauge project aims to reduce the embodied carbon of a building, it is recommended that the suitable foundation with the lowest embodied carbon is chosen.

5.3 Supporting the CobBauge

The design of the plinth must fully support the CobBauge wall across the entirety of its width. For a standard CobBauge wall this will be 600mm. This construction needs to provide full structural support for the structural layer of CobBauge, therefore it should not contain cavities or non-structural insulation. The materials used below the structural layer of CobBauge must have a load rating of greater than or equal to the structural CobBauge.

Insulation may be placed below the thermal layer of CobBauge, however, the outer 100mm of the layer must be supported. If this part of the plinth contains a cavity, it is recommended to detail a stainless-steel mesh with a geotextile membrane on top of this to prevent the light earth material from falling into the gap, as well as to provide a base for the thermal layer.

6. FORMWORK

6.1 Design and construction of formwork

CobBauge walls are constructed and shaped by using formwork (Figure 17). This comprises of two sections of framework, which are likely to be a combination of timber and metal, that are spaced over the thickness of the CobBauge wall, which is typically 600mm: 300mm structural layer and 300mm thermal layer (Figure 18). These are held in place with long bolted rods or threaded rebar at two or three locations along the length of the formwork, both top and bottom. It is important that these are easy to both bolt and remove. The length of the bars should be sized to allow for the formwork to be expanded or contracted depending on the thickness of the wall being constructed. A project's unique formwork design and methodology needs to be completed by the designer and constructed by the contractor.

Figure 17. Metal (left) and timber (right) formwork examples. Photos: Esitc Caen (2022) (left), Plymouth University, CobBauge project (2021).

A wire mesh, with square gaps of around 25mm², is located on the inner edges of the timber formwork frame. The purpose of the mesh is to: aid the drying process of the wall, provide a visual indicator of the material's compaction within the formwork, as well as to ease the removal of the formwork after a lift of CobBauge wall is completed. Material that gets compressed through the wire mesh should be scraped away while it is still wet and added back into the mix. This procedure reduces material waste, and further eases the removal of the formwork.

CobBauge formwork does not have a prescribed length or height however, both the designer and contractor should be mindful of its weight and manoeuvrability. A generic CobBauge formwork section can have a length of between 1 and 3 metres; with 1m being the easiest to move and 3m becoming heavier and more difficult (Figure 19). While it is possible to connect multiple short sections together, this makes getting the finished wall to be straight and plumb more challenging. The height of the formwork should be sufficient for one lift of CobBauge, which can vary from approximately 500 - 650mm in height. A generic CobBauge formwork has a section of 750mm high to ensure that the material is fully contained.

It is important that the formwork remains straight and plumb. To ensure the width of formwork stays consistent, a pre-measured spacing block of wood could be used at the top of the timber frame (Figure 20). The bottom of the formwork should then stay at the consistent correct width as it based on the top of the previous CobBauge lift, or plinth in the case of the first lift.

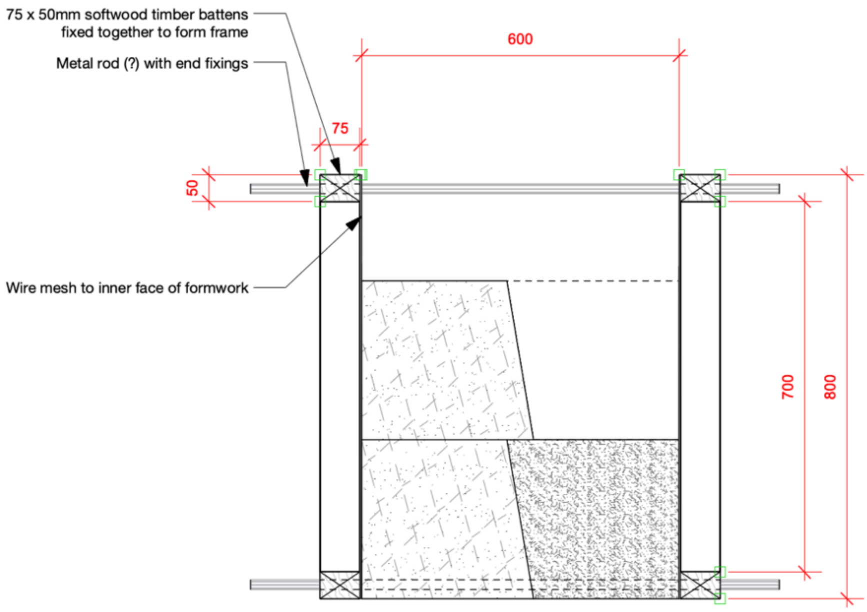

Figure 18. Section drawing of formwork and CobBauge material. Source: Fox Ecological Architects (2022).

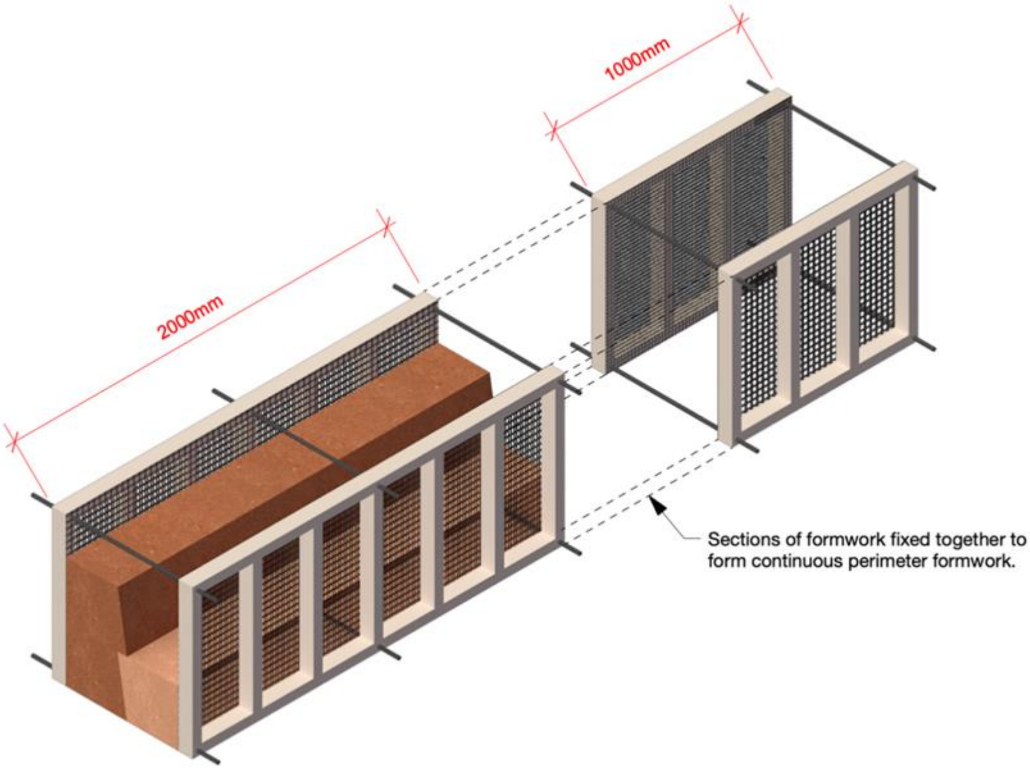

Figure 19. 3D diagram of formwork set-up & CobBauge material. Source: Fox Ecological Architects (2022).

Figure 20. Photo showing spacing of formwork using wooden spacing block. Photo: François Streiff.

6.2 Creating a CobBauge lift and CobBauge tools

During construction, to separate the structural layer from the thermal layer within the formwork a timber placement tool is used, which comprises of two angled timber surfaces (Figures 21 & 22).

This tool enables one sub-lift, which is typically 200 - 250mm high, to be formed. The slight angle of the timber (approx. 10°) is what gives the CobBauge wall its interlocking ‘zig-zag’ section between the two layers of material (see Figure 23). The angle of this tool also makes it easier for it to be removed after the material has been compacted. The measurements of placement tool need to be tailored to the project’s structural layer’s width and sub-lift height by the designer and then constructed by the contractor. It is advised that multiple placement tools are made so that more builders can work on the CobBauge lift at one time and speed up its construction.

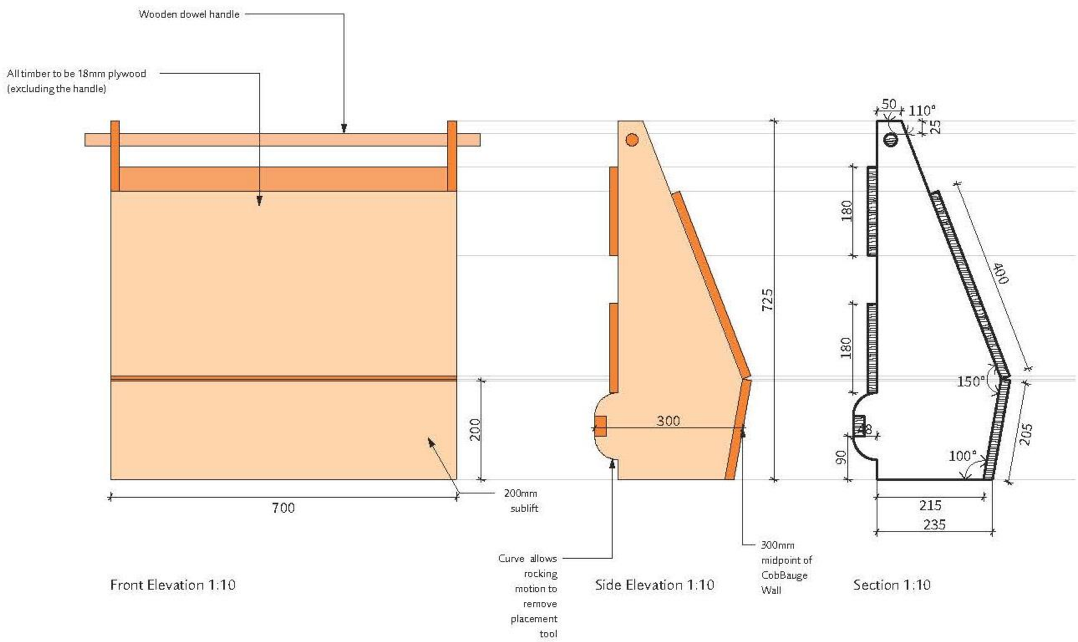

Figure 21. CobBauge placement tool elevation and section. Source: Hudson Architects (2022).

Figure 22. 3D views of CobBauge placement. Source: Hudson Architects (2022).

Figure 23. Angled saw toothed joint between thermal and structural layers. Photos: University of Plymouth, CobBauge project

To lay the CobBauge materials, the placement tool needs to be butted up to the side, of what will be the external face of the wall, within the formwork with the angled side facing towards the centre. This is so the structural cob mix is then placed in the void, between the placement tool and the formwork mesh, that will become the inner layer of the wall. The cob mix is typically lifted into the formwork by hand, using pitchfork, and densely compacted by foot so that the structural layer has no voids (Figure 24).

Figure 24. Placement tool and stamping compression technique for structural layer. Photos: Tom Booen.

Once this 200 - 250mm high section of cob has been laid, along the walls of the entire building, the placement tool is removed, and the thermal layer’s equal sub-lift can be constructed. This comprises of placing the light earth mix in the void, it so that it sits right up against the face of the structural cob and the formwork and compacting it using a hand tamper tool. Figure 25 shows an example of a hand tamper tool, which comprises of a plywood plate fixed to the end of a mattock handle. The thermal layer requires much less force than the structural layer. It is important to take care not to over compact this material as this will reduce its thermal performance. The aim of the tampering technique is to adhere the light earth together and remove large inconsistent voids, rather than to compress it.

After each sub-lift of both the thermal and structural layers has been laid into the formwork, hemp straw of between 300 - 450mm is placed perpendicular to the run of the wall at approx. 600mm centres (Figure 26). This should also be done before the first sub-lift of a new lift. This intends to help tie both layers together and reduce the likelihood of cracking during the drying of the CobBauge wall. It is also recommended to lightly moisten the previous lift with water to help improve the bond between layers.

To begin the next sub-lift, the placement tool is laid on top of the first sub-lift of the thermal layer, ready to build up the next sub-lift layer of structural cob (Figures 27 & 28). This above-described process, of alternating the laying of one material at a time, is then repeated until there are two or three sub-lifts, which make up the height of one full CobBauge lift (500 - 650mm in height). This should be signified by the CobBauge wall build up reaching near to the top of the formwork.

Figure 25. Tamper tool and technique for thermal layer. Photos: Tom Booen.

Figure 26. Hemp straw placed, after each sub lift, perpendicular to the run of the CobBauge wall. Photos: Jim Carfrae.

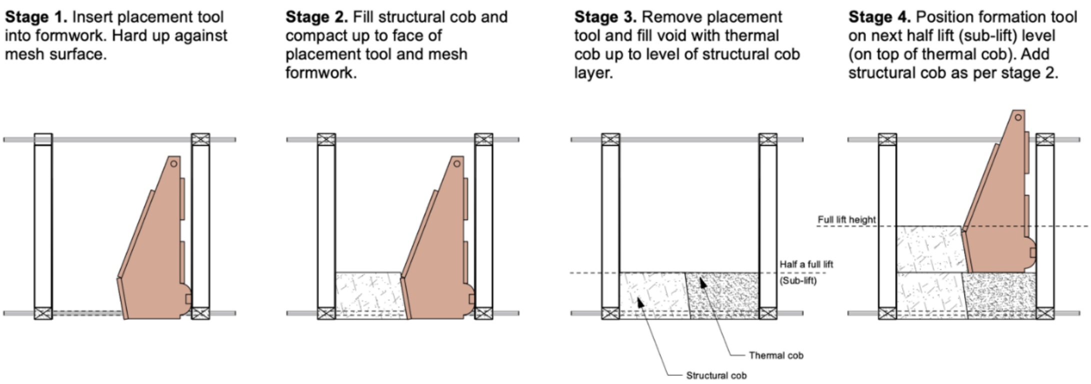

Figure 27. Illustrated placement tool and sub-lift methodology. Source: Fox Ecological Architects (2022).

Figure 28. Placement tool being used on site. Photo: François Streiff.

6.3 Checking the compaction of CobBauge in formwork

To check the quality of the material compaction, it is advisable to look through the mesh as the layers of material are added to the formwork (Figure 29). This will give a visual indication of compaction or if there are any voids in the material. By regular inspection, if any air pocket gaps are detected they can be remediated before the next sub-lift takes place. At this point, it is also advisable to remove the excess material (e.g., with a trowel), that has pressed through the mesh (as described in Subsection 6.1).

Figure 29. Photo showing the compaction of the light earth viewed through mesh. Photo: Plymouth University, CobBauge project.

6.4 Re-positioning the formwork

When constructing lifts of CobBauge, contractors are to sit the connecting bolts on top of the previous lift before attaching the formwork frames (Figure 30). This helps to support the formwork for the new lift. It is important to carefully, but forcefully, remove the buried rods from the CobBauge wall, while it is still wet. Using lengths of bar that are threaded along the entire length will aid the removal by un-screwing them from the wall if necessary.

Designers and contractors will need to carefully plan the construction of the formwork, as there should be enough formwork in place to completely construct one entire lift of the external walls. When the formwork is removed, there will holes left by the threaded bar that supports the formwork. It is recommended that these can be filled in with sheep's wool and then plugged at the wall's face with the correct CobBauge material.

Following the completion of a lift of CobBauge, the formwork should be left in place to dry for a minimum of 3 days of consecutive dry weather, greater than 12°C, before being re-positioned. To allow the CobBauge lift to remain supported for as long as possible, it is recommended to have two complete sets of formwork. This minimises the risk of the lower lift deforming from the weight of a subsequent lift. Therefore, the formwork must be designed to stack on top of each other to allow this. This also allows the previous layer of formwork to be removed and reinstalled, while the intermediate layer is still drying, to give flexibility to the build.

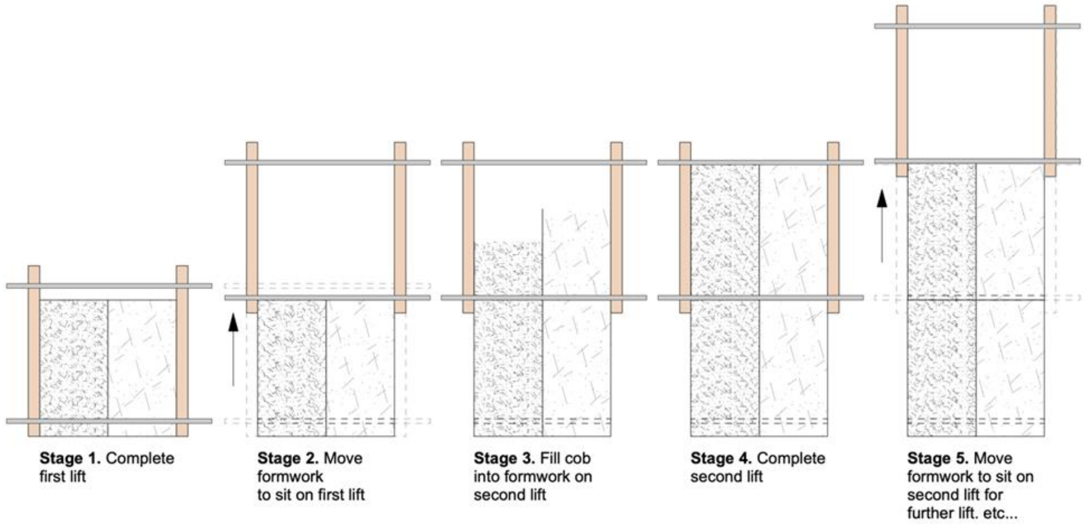

Figure 30. Illustrated method for raising formwork. Source: Fox Ecological Architects (2022).

6.5 Openings

CobBauge should be filled into the wall formwork, as normal, to the level of insertion of the additional infill box formwork needed for the opening. These infill boxes can be fixed to the formwork, ensuring that they remain plumb and level with the wall formwork. CobBauge lifts are then placed as normal at either side of the formwork for the opening, and it remains in place until the end of construction.

7. DRYING

7.1 Time between CobBauge lifts

Once a CobBauge lift has been completed, contractors should wait around 2-3 weeks before laying the next lift. During this time, contractors can prepare for the next lift by re-positioning the formwork and preparing the new material. As a guide, it takes approximately 3 days, using 3 workers, to construct one lift of 650mm CobBauge on a 30sqm square building.

7.2 Maximum moisture levels for removing formwork

Ramin sensors can be made by the designer and embedded within the CobBauge wall to assess how the moisture levels change over time (Figures 31 & 32). These readings can be used inform when the formwork can be removed or finished to be applied.

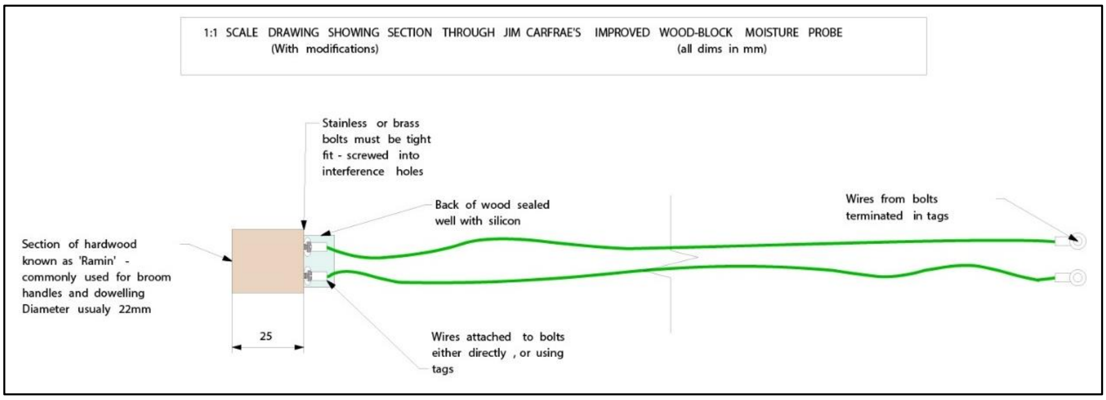

Figure 31. Diagram of Ramin Sensor. Source: Jim Carfrae.

Figure 32. Ramin Sensors installed into the first CobBauge lift. Source: François Streiff.

8. OPENINGS

8.1 Door Openings

To be complete.

8.2 Window Openings

To be complete.

8.3 Larger Openings

To be complete.

9.0 POTENTIAL ISSUES ENCOUNTERED ON SITE

This section discusses some of the possible issues a contractor might be faced with on site in relation to the construction of a CobBauge wall.

9.1 Precipitation during construction.

The impact of rain on CobBauge, during construction, depends on the severity of the weather.

• **For light rain** showers that are not prolonged, both the structural and thermal layers can be left unprotected, and construction can continue.

• **For heavy rain**, a prolonged light shower or if wet weather is forecasted during the construction of CobBauge, the walls and material mixes need to be covered for protection.

Failure to protect the walls and material mixes from heavy rain will alter the water content of the CobBauge wall, which can cause detrimental moisture impacts regarding drying times and structural stability. Therefore, it is advised to protect the walls and material mixes as much as possible during the construction process.

This can be completed by using tarpaulin or timber sheets laid over the top of the formwork. In both cases the coverings should be weighed down to ensure that they stay in place (Figures 33 & 34). The use of plywood sheeting is the preferrable method as this keeps the sides of the CobBauge wall still well ventilated, which will help its drying process.

Protection of the unused material mixes should also be a priority. This can be completed by placing polythene or tarpaulin sheets over the material. This type of protection should be used anyway, to prevent the material mixes from drying out through wind and solar exposure (see Subsection 9.3).

Figure 33. Sheets of timber protecting the tops of the CobBauge wall. Photo: François Streiff.

Figure 34. Tarpaulin sheet covering the cob material mix. Photo: Katey Oven.

9.2 Cracks within CobBauge layers

It is not uncommon to encounter cracks in the CobBauge layers. This can be due to a variety of reasons, such as differential drying. The extent and size of the crack should be considered before undertaking remediation action.

• **Small cracks** (see number 1 in Figure 35) in the wall can be filled with slip before starting a new sub-lift.

• **Large cracks** (see number 2 in Figure 35) should also be filled with slip or the relevant structural / thermal mix depending on its appropriateness for the location and type of crack present in. Large cracks should also be protected at the top of its opening with a long timber batten, which should be pressed into the material over the length of the wall, with the crack in the mid-point of this batten. This should help to prevent the crack from travelling further through subsequent layers.

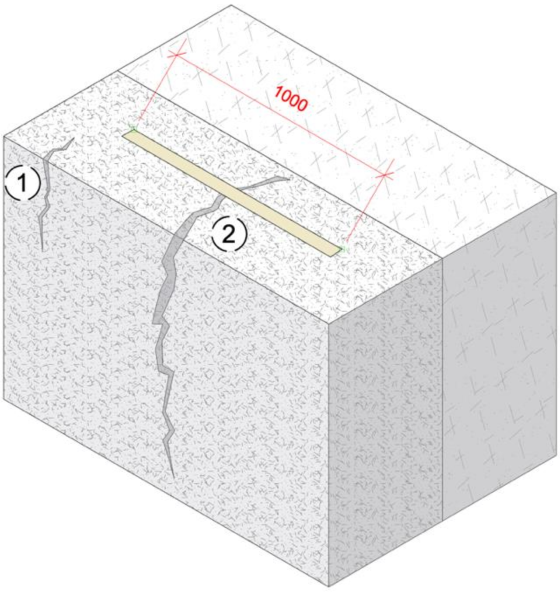

Figure 35. Illustration of types of cracks in a CobBauge wall and timber batten protection. Source: Fox Ecological Architects.

9.3 Storage onsite

If the structural and thermal mixtures are being prepared prior to their use in construction, the storage of these important, as it is difficult to retain the moisture content of the materials when exposed to the elements. While the sun and wind could alter the mix to become too dry, precipitation could cause it to be too wet. If these scenarios occur, to regain the optimal moisture contents for material mixtures is difficult to achieve accurately. Therefore, it is recommended that all pre-prepared CobBauge materials are stored appropriately (see Subsection 9.1).

10.0 SCAFFOLD FOR A COBBAUGE BUILDING

It is highly likely that scaffolding will be required for the construction of a CobBauge wall or building. It is advisable that there are two stages to the erection of scaffolding on a CobBauge project.

10.1 Stage 1: Working from the ground

When working on the first or second lift of a CobBauge wall, contractors might find it relatively easy to work from ground level or from a simple platform (Figure 36). This will enable contractors to have free movement around the site during the early stages of the build.

Figure 36. Using a small scaffold platform to aid low level construction.

10.2 Stage 2: Erecting a scaffold

Once the wall rises beyond two lifts, it becomes difficult to form further CobBauge lifts safely. Therefore, scaffolding should be erected (Figure 37). The contractors should decide whether to add scaffolding to the inner or outer sides of the CobBauge wall or both. If it is decided to only use scaffolding on one side, extra care should be taken when manoeuvring the formwork panels. The contractors should ensure that the typical standards of health and safety are carried out, while working on scaffolding, moving formwork and material around on the scaffolding, and when lifting material up to a higher level.

Figure 37. Scaffolding on the inner and outer sides of the CobBauge wall as it rises.

To protect the CobBauge walls from weathering during construction, contractors might consider a full scaffold with tarpaulin to cover the entire building area. Such measures might also lower the risk of differential drying, and therefore shrinkage, due to solar exposure in warmer months.

11.0 MOVING COBBAUGE MATERIALS AROUND ON SITE

11.1 By hand

At a very basic level, both the structural and thermal mixes can be moved around on-site using wheelbarrows or trolleys and hand shovelled into the formwork using spades and forks. To avoid injury, care should be taken not to overload the barrows and to shovel the material in manageably sized loads.

11.2 By machine

Machinery can be used to ease the transportation of the material mixes on site and into the formwork. Mechanised CobBauge construction includes the use of telehandlers (front loader), with a fork and sack or a bucket and forklifts. These machines can also be used to lift material to high levels on scaffolding, where contractors can move the material around by hand once laid down at a higher level, or they can be used to directly lower and tip the material into the formwork. Other mechanical aids that could be used include a mobile crane, cherry picker or an electric lift on the scaffold system.

12.0 RUNNING SERVICES IN A COBBAUGE WALL

Electrical, data and water services that are designed to be concealed within the inner structural layer of CobBauge are to be "chased" into the material prior to being plastered.

13.0 FURTHER INFORMATION

Further information can be found in the Quality Assurance document, which partners this document.

In addition, should the designer 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).

14.0 REFERENCES

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https://www.plymouth.ac.uk/research/cornerstone-heritage/cobbauge-project

PnrMCB, Regional Nature Park of the Marshes of Cotentin and Bessin, (2022). Available at: https://parc-cotentin-bessin.fr/cobbauge

LUSAC Laboratory, University of Caen Normandy, (FR) (2022).

15.0 EXAMPLE MATERIAL SOURCES

Threaded bar

(FR) TAM Mandelli – Setra: https://www.mandelli-setra.fr/produits/materiels-de-coffrage/tiges-accessoires/ Where the following products have been used with good success:

Bars ref 007549 and nuts ref 007810.

(UK) DY.CO DYWIDAG Form Ties: https://www.dywidag-formties.com/products/threadbars/ where a similar thread bar and nut can be sourced.

Hemp Shiv

East Yorkshire Hemp Company: https://eastyorkshirehemp.co.uk/products/building-products/

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