Interreg France (Channel Manche) England
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COBBAUGE

A GUIDE FOR DESIGNERS

www.cobbauge.eu

Photo: Plymouth University, CobBauge project

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 type of wall construction is created entirely out of natural materials - clay subsoil and plant fibres. It contains two layers with 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).

*Watch **FILM 1:** **Introduction to CobBauge***

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. This guide develops as the CobBauge research project progresses, until it's closure in March 2023. This information partners with the *CobBauge - Guide for Builders,* and *CobBauge – Standard Details Package*.

Whilst 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.

Watch FILM 34: What a designer needs to know

1.3 What does the guide cover?

This guide provides a summary 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 follow. These processes range from the sourcing of raw materials and the mixing and testing (Sections 2-4) of CobBauge, to plinth, formwork, drying, openings, potential problems and scaffolding construction (Sections 5-11). 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.

*For supporting training videos, watch **FILM SERIES:** **CobBauge Training Videos***

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)

The INTERREG VA France (Channel) and England co-funded by the European Regional Development Fund (ERDF) through the Specific Objective 2.1: Low carbon technologies.

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

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 designers specifying 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 to use for CobBauge is an important part of the process as this significantly contributes to the new construction system's low embodied carbon objective (see Subsection 2.6). 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 of minimizing the project's embodied carbon output. Whilst the site's subsoils might not have 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 to make it useable (see Section 2.2.1 for more information).

Watch ***FILM 2: Sourcing Soils***

2.2 Subsoil requirements – structural layer

The earth needed to create the structural layer of CobBauge is the same as that needed for traditional cob. This is comprised of a subsoil with a clay content of 12 - 20%, to act as an adhesive for the other parts of the mix, which also needs to be 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 the CobBauge structural layer 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 as 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. Conversely, pure clay can be added to the subsoil to raise the total clay content of the cob mix.

*Watch **FILM 8**: **Sourcing Aggregate***

2.3 Subsoil requirements – thermal layer

The earth needed to create the thermal layer of CobBauge is the same as that needed for traditional light earth. This is comprised of a clay rich subsoil with a clay content of 60% or more, which is illustrated in Figure 2. This is used to create pourable clay slip which will adhere to the mix's natural fibres. Results show that the richer and higher strength of the clay, the lower the u-values of the CobBauge thermal layer (see Section 17). This is due to the light earth mix requiring less slip 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 (See Section 21 for recommended product).

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.

*Watch **FILM 7**: **Sourcing Fibres***

2.6 CobBauge Embodied Carbon

Due to CobBauge being a new construction system, its embodied carbon data is not yet finalised. Therefore, currently the data from rammed earth is used from the Bath ICE database due to its comparable materials. Table 1 shows both the density kg/m3 and an estimated total KgCO2/M3 of the CobBauge material.

Table 1 Embodied carbon data estimation of CobBauge

		MODULES															TOTAL/KG	TOTAL/M3	NOTES
		PRODUCT			CONSTRUCTION		IN USE									BEYOND			
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D			
		RAW MATERIAL	TRANSPORT (km)	MANUFACTURING	TRANSPORT (km)	CONSTRUCTION & INSTALLATION	USE	MAINTENANCE	REPAIR	REFURBISHMENT	REPLACEMENT	DECONSTRUCTION & DEMOLITION	TRANSPORT	WASTE PROCESSING	DISPOSAL	REUSE, RECOVERY & RECYCLING			RIBA Climate Challenge says not include module D
	Density (kg/m3)	KgCO2/Kg																**KgCO2/M3**	
CobBauge Structural Mix	1300	0.024			0.005	0.0048	0.0012			0	0	0.00096					0.03596	46.748	A1-A3- Data taken from Bath ICE database
CobBauge Thermal Mix	300	0.024			0.005	0.0048	0.0012			0	0	0.00096					0.03596	10.788	A1-A3- Data taken from Bath ICE database

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, or builder, to be able to access the subsoil for its clay presence and therefore potential to be used for one of the mixes (refer to Subsection 4.1 & 4.2 & to the *CobBauge – Guide for Builders* Document). 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 (Stage 2 & Subsection 4.3). 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 if so, how much of it, to make it suitable 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 (Subsection 4.3).

Stage 3: Tailor-made material recipes

Designers can then use this information to form the tailor-made material mix recipes for the CobBauge project (Subsection 3.3).

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 then be sourced for the build. It is advantageous to source all the subsoil needed for the build at one time. This will avoid inconsistencies that ordering different batches could cause which could in turn could affect the subsoil's characteristics.

Once the subsoils are construction ready - meaning that their ratios of ballast/clay are now correct - the following shows an example of the material ratios (in volume) used 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 be roughly 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 off-site, differ due to the density of the material in each case. As both cob and light earth are used in traditional construction techniques the following procedures for preparing the mixes should be familiar for builders with previous earth building experience.

*Watch **FILM 9**:* ***Preparing Cob Materials***
*Watch **FILM 13**:* ***Cob Mixing Method***

3.2.1 Mixing the structural layer

Materials required:
Structural clay
Straw
Water
Ballast with a grading range of 20mm – dust (potentially required)

Tools required:
A digger (minimum 4.5 tonne)
Skip(s) for storage
Tarpaulin or plywood for covering

*Watch **FILM 12:*** ***Cob Mixing Machinery***

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 3 & 4). Although, the machinery method makes CobBauge construction more viable due to the increased ease, speed, and ability by which 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 4)
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 3)

Whilst these methods differ on where the mixing of the material takes place, all require a minimum of a 4.5 tonne digger to have enough power for the mixing. 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 3.4). It is therefore important that the designer discusses these options with the contractor to decide which method would be the most appropriate for the project.

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.

Figure 3. Mixing the structural CobBauge mix by machine or foot. Photo: Plymouth University, CobBauge project (2021) (left), François Streiff (right).

Figure 4. Mixing the structural cob mix in a skip with a digger bucket. Photo: Katey Oven.

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 of the ingredients are added and fully mixed, to assess if the CobBauge 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 CobBauge mix, 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 CobBauge mix 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

Materials required:
Thermal clay
Hemp Shiv
Water

Tools required:
Skip or pit & damp-proof membrane to soak clay in
Plastic containers,
Paddle mixer
Measuring jug
Baron or cement mixer

Watch ***FILM 14****:* ***Preparing Light Earth Material***
Watch ***FILM 16****:* ***Measuring Light Earth Materials***
Watch ***FILM 17****:* ***Mixing Light Earth***

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 Subsection 4.4.3. 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 5) or using a skip.

Figure 5. 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 Subsection 4.4.2. It is advised to carry out this test on a

smaller sample of the chosen subsoil prior to mixing the slip in bulk, in order to more easily calculate 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 6). 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 6. 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 7). 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 7. 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. 8mm holes to remove any large stones and other large pieces of material (Figure 8). Ideally, the slip is sieved into several smaller buckets for ease of further use.

Figure 8. Sieving the slip. Photo: François Streiff.

Stage 6. Adding the slip to the hemp fibre

Once the slip is of the correct 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 9), or by using a machine, such as a cement, baron or plaster mixer (Figure 10). It is advised to add the slip gradually, a little at a time, to the hemp shiv to avoid oversaturating the mix.

Figure 9. Mixing of light earth mix on site using a cement mixer (left) and by hand (right). Photos: François Streiff (left) & Anthony Hudson (right).

Figure 10. Mixing of the clay slip and hemp shiv fibres off site using a baron mixer. Photos: Plymouth University.

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 11). 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.

Figure 11. 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 CobBauge mix's material volumes can then be calculated from this. It is important to remember that the water needed in the material mix should <u>not</u> be included when calculating the volume of the finished CobBauge wall layer. This is because the water will evaporate and therefore, will not form part of the finished wall. The estimated density of 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:

$50m^3 \times 1650kg/m^3 = 82{,}500kg$

In the case of Table 2, for this specific CobBauge 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 2 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 3 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 3, for this specific clay slip mix, a ratio of 1:1 clay-subsoil to water (by volume) was determined from the puddle test (Subsection 4.4.2). These volume quantities were then transferred into weight to give the ratio of 58:42 clay-subsoil to water (by weight). Just like the CobBauge mix, it is important to remember that all the water required for the light earth mix should not 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 3 also correspond to the 1:3 clay slip to hemp shiv ratio (by volume) rule of thumb as explained in Subsection 3.1.

Table 3 Thermal CobBauge ingredient quantities example

Ingredients	**Weight total of total build 55m^3**
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.)**

3.4 Storing the mixes

Materials required:
Tarpaulin sheets (or equivalent covering)

If the structural and thermal mixtures are being prepared prior to their use in construction, the storage of these is important, as is the storage duration, as it is difficult to retain the same moisture content of the materials when exposed to the elements. Whilst the sun and wind could alter the mix to become too dry, precipitation could cause it to be too wet. If either of these scenarios occur, regaining the optimal moisture contents for material mixtures is difficult to achieve accurately. Therefore, it is recommended that all pre-prepared CobBauge materials are stored and covered appropriately e.g., by covering with a tarpaulin sheet (Figure 12). Whilst for experienced cob builders it is possible to store a mix for a period of time, it is recommended that inexperienced cob builders use the mix while it is fresh. This avoids challenges such as the straw rotting, and therefore the mix loosing structural integrity or not being able to achieve a workable consistency.

Figure 12. Tarpaulin sheet covering the cob material mix. Photo: Katey Oven.

3.5 Additional materials required for CobBauge walls

Additional material required:
Hemp straw

Between each CobBauge sub-lift, hemp straw is placed perpendicularly to the run of the wall, at approx. 600mm centres to act as a binder and provide reinforcement between the layers (see Subsection 7.3).

4 TESTING OF COBBAUGE MATERIALS

4.1 Early subsoil testing

When considering a site for a CobBauge project, it is encouraged that the site's subsoil is also considered so it can be used in the construction process where possible. This is due to the increased financial and carbon cost of transporting a large amount of subsoil to the site, and compounded by the savings gained, financially and environmentally, of not sending any of the site's subsoil to landfill when clearing and digging the foundations.

When checking whether the 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 in Subsection 4.3. However, as these tests take time and have a financial cost, 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 Subsection 4.2 and 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.

Watch ***FILM 2: Sourcing Soils***

4.2 Field Tests for Earths

There are many kinds of field tests for subsoils, and it is the combination of the results that can gauge subsoil suitability for the two CobBauge materials.

Testing equipment
Shrinkage box (wood and screws)
PVC pipe (cut into 5cm rings)
Gloves
Tape measure
Ruler

4.2.1 Sensory Tests

- Smell – to detect organic material, reject topsoil with an organic, musty odour.
- Visual - to discern the presence of large elements, stone, pebbles or gravel.
- Touch – to indicate the presence of clay, sand and silt. A golf ball sized piece of soft damp subsoil (plastic state) can be squashed to see if it cracks (sand/silt dominate) or flattens smoothly (fines and clay dominate). A smooth bladed knife can be passed over the sample to leave a shiny surface indicating clay content. A fine silty soil will have a duller finish. It is also more difficult to wash clay from the hands after handling a sticky clay rich wet mix compared to a siltier one.

Watch ***FILM 3: Sensory Soil Tests***

4.2.2 Cigar Test

To establish clay type and content (cohesiveness).

Plastic earth is shaped into a long even cylinder 3 to 4cm in diameter, up to 1m in length. If there are stones or large amounts of grit present these should be removed first, by hand or sieving.

The end of the cigar is slowly pushed over the edge of a table until a piece breaks off. This is repeated several times to give a number of similar sized pieces which are measured to find the average length (Figure 13).

An average length of less than 5 cm indicates very low clay content (needs extra clay). A cigar of 10 to 20cm may be used for CobBauge. Beyond 20cm, the soil is likely to be clay rich and usable for light earth, but needs correction for CobBauge

*Watch **FILM 4: Cigar Test***

Figure 13 Results for Cigar test methodology, for two different earths, to establish clay type and cohesiveness. Photos: Olivia Elsey.

4.2.3 Shrinkage Test

To assess the risks of cracking during drying.

A: The Strip Test - a quick preliminary test that works for fine or sieved subsoils without coarse aggregates. These tests can also be done with the final mix of soil and fibres for CobBauge.

Make a 12cm long flattened length of plastic soil 1 cm wide and mark with a straight line with lines scored across it at the end of the 10cm line (Figure 14).

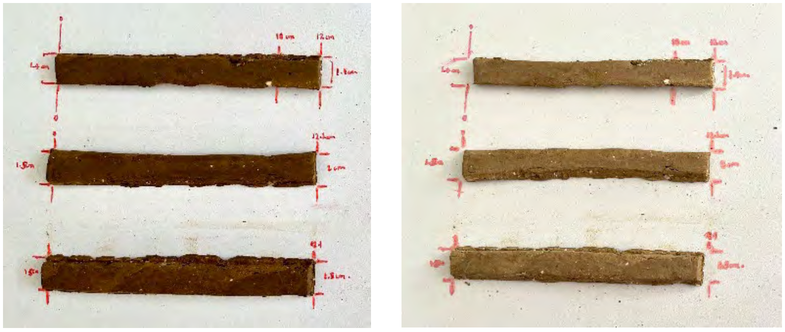


Figure 14 Strip test on day 1 (left) vs final strip test results (right).

B: The Box Test - will give a more accurate result using a larger sample and can be achieved with a coarser soil sample but stones should still be removed first.

Create a wooden shrinkage box (e.g. 50cm long, 5cm square in section) and fill to the top with plastic soil (this box is also useful to measure shrinkage of CobBauge mixes).

In both cases, shrinkage can be measured when the soil is dry. Strong shrinkage indicates fine soil, high in silt and clay which will crack significantly during drying. For CobBauge, such soils require gauging with gravel, sand or fibre to achieve the target shrinkage of 1%. For light earth, this sort of soil maybe suitable (Figure 15).

Watch ***FILM 5: Soil Shrinkage Test***

Figure 15 Results for the Shrinkage Box test methodology, for two different earths, to establish clay type and cohesiveness.

4.2.3 Breakage Test

To assess strength and clay content.

Mould a simple disc of plastic earth (remove larger aggregate first) in a PVC ring 5cm in diameter and 1cm thick. Once dry, the disc can be broken using the fingers. Easy to break means a low proportion of clay and/or a less strong clay type, hard to break, means clay rich soil or a strong clay type (Figure 16).

Watch ***FILM 6: Breakage Test***

Figure 16 Breakage Test methodology with two different clay types.

4.2.4 Dry Ball Drop Test on Soil

To assess clay content.

The plastic mixture used for testing the cigar can be used to form a ball 10 cm in diameter. This ball is left to dry for several days. Once dry, this ball is dropped from a meter high on a hard surface. If the ball does not break, the clay content is very high. If it breaks into a multitude of pieces, the earth lacks cohesion and therefore the proportion of clay is probably quite low.

Watch ***FILM 10: Drop Ball Test for Mix***

4.3 Laboratory testing methods

4.3.1 Structural layer laboratory testing methods

If 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 17 shows an example of laboratory results plotted onto a graph with the upper and lower grading limits for a suitable subsoil for CobBauge.

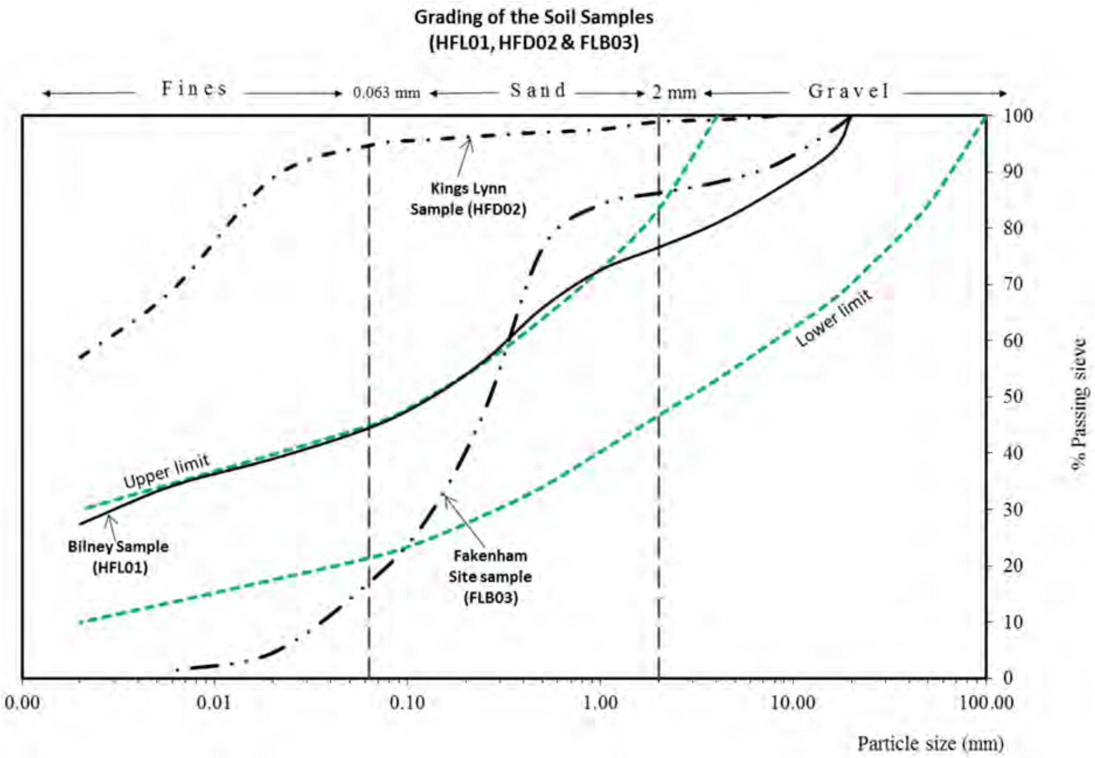


Figure 17. Laboratory grading results for three soils and recommended grading limits for structural CobBauge suitability. Completed by & sourced from David Clark.

In this example the ‘Bilney Sample’ can be seen to be close to the requirements for CobBauge 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 CobBauge 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 CobBauge 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 CobBauge.

The final important laboratory test to be conducted is the trial CobBauge 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 CobBauge mix in a calibrated apparatus. Throughout the duration of the build, it is recommended to send cylinders to be tested, across several lifts, to check the cob mixes are consistent structurally.

*Watch **FILM 11**: **Mix Shrinkage Test***

4.3.2 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 18 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 18. 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 CobBauge 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 CobBauge mixture has experienced increased wetting or drying after initial mix.**
   Designers should check that:
   a. 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.

4.4 Onsite testing

4.4.1 Structural layer onsite testing

To test if the structural CobBauge 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 CobBauge mix using a measuring jug (see far left image in Figure 19).
2. Form this quantity of material into a sphere by hand.
3. 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 CobBauge mix splat is 21cm, give or take 1cm.

Watch ***FILM 10:*** ***Ball Drop Test for Mix***

Figure 19. Ball drop test methodology for structural CobBauge mix. Photos: Katey Oven (2022).

4.4.2 Thermal layer onsite testing

To create the most suitable clay slip consistency for 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 20).

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).

Watch ***FILM 15****:* ***Slip Test***

Figure 20. Slip puddle test for thermal cob mix. Photos: Olivia Elsey (2022).

5. KEY DESIGN PRINCIPLES

5.1 Weather protection

The basic principles of designing with cob are still relevant to the CobBauge system such as the principle of ‘hat and boots’, which refers to having a generous roof overhang (e.g. 500mm) to prevent rain penetrating the top of the CobBauge wall, and a plinth up stand to raise the CobBauge wall up off the ground to protect from rain and snow (approx min 400mm).

5.2 Building heights

The pilot projects for CobBauge have focused on one and two storey buildings. In principle, additional storeys could be achieved, but this would be likely to require a thicker structural layer and subsequently larger foundations. The design of all CobBauge walls would need to be confirmed by a structural engineer.

5.3 Ground investigations

As with any other building project, ground investigations should be undertaken when using the CobBauge construction method. 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.

5.4 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.

5.5 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, to prevent the light earth material from falling into the gap, as well as providing a base for the thermal layer.

6. FORMWORK & TOOLS

Formwork equipment
Threaded bars and formwork clamps
Wood
Metal mesh

CobBauge Construction equipment
Scaffolding
Digging forks
Wheelbarrows
Buckets
Placement tool (wood to make)

Watch **FILM 18**: ***Formwork Systems***
Watch **FILM 19**: ***Mesh Formwork***
Watch **FILM 20**: ***Formwork Ties and Removal***
Watch **FILM 26**: ***Preparing & Finishing Surfaces***

6.1 Design and construction of formwork

CobBauge walls are constructed and shaped by using formwork (Figure 21). This comprises of two sections of framework, which are likely to be a combination of timber and metal. These are spaced over the thickness of the CobBauge wall, which is typically 600mm: 300mm structural layer and 300mm thermal layer (Figure 22). 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. These can be attached through the timber or the mesh. The mesh option can be more beneficial as it does not require any holes to be drilled, making it both easier to bolt and remove. However, builders need to be mindful that the mesh does not warp or bow. A large wooden 'washer' could be used to spread the pulling load of the bar on the mesh. 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.

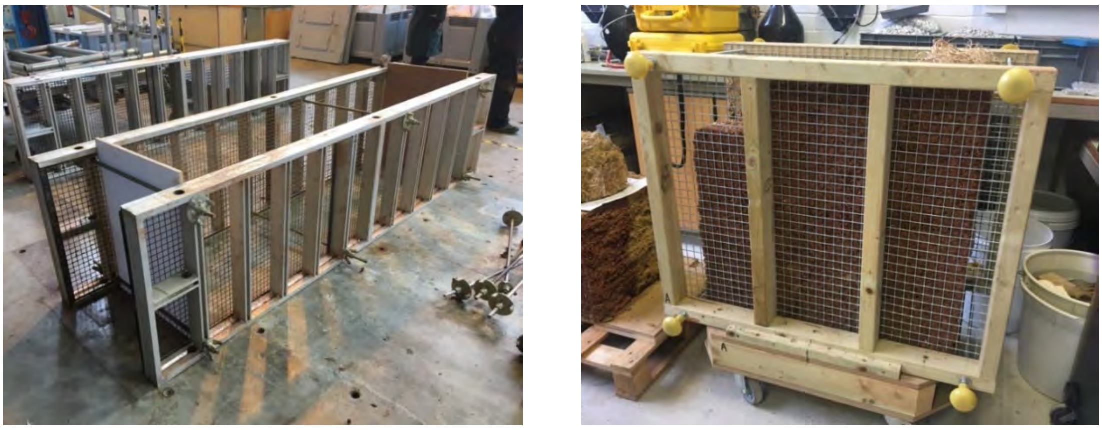


Figure 21. Metal (left) and timber (right) formwork examples. Photos: Esitc Caen (2022) (left), Plymouth University, CobBauge project (2021).

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 and provide a visual indicator of the material's compaction within the formwork, as well as 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.

Whilst CobBauge formwork does not have a prescribed length or height, 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 23). While it is possible to connect multiple short sections together, this makes getting the finished wall 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 that the width of formwork stays consistent, a pre-measured spacing block of wood could be used at the top of the timber frame (Figure 24). The bottom of the formwork should then stay at the consistent correct width as it is based on the top of the previous CobBauge lift, or plinth in the case of the first lift. To create openings within the CobBauge wall, formers need to be created using similar materials, see Section 9.

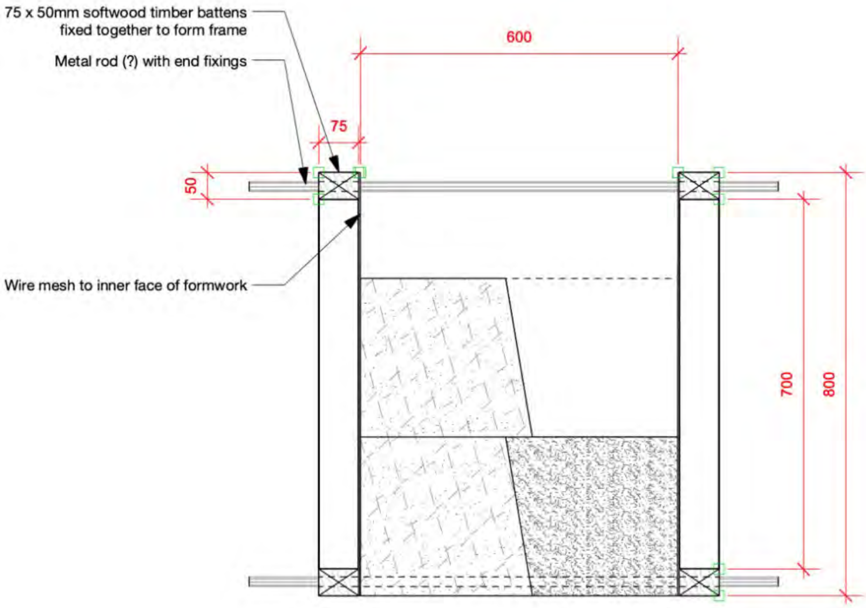


Figure 22. Section drawing of formwork and CobBauge material. Source: Fox Ecological Architects (2022).

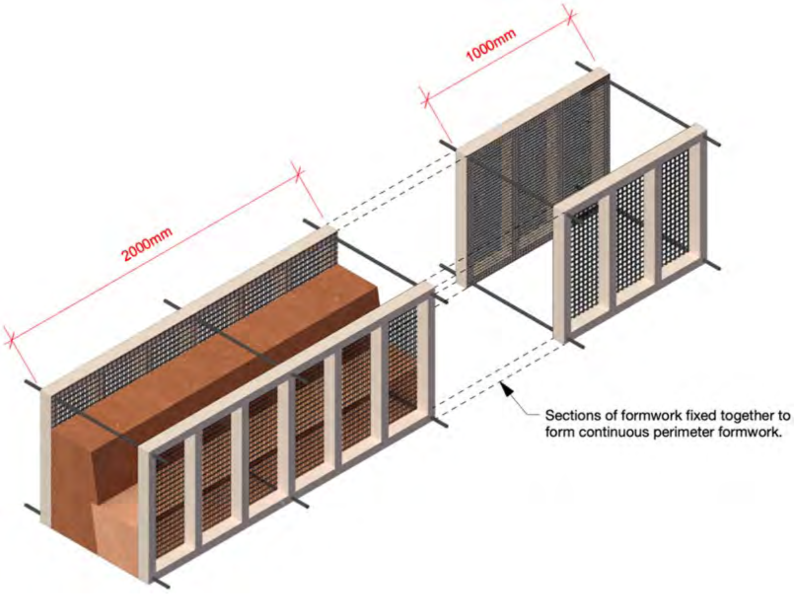


Figure 23. 3D diagram of formwork set-up & CobBauge material. Source: Fox Ecological Architects (2022).

Figure 24. Photo showing spacing of formwork using wooden spacing block. Photo: François Streiff.

6.2 CobBauge construction tools

For structural layer
Pickaxe handle

For thermal layer
Tamper tool (wood to make)

Additional tools
Trowel for scraping away excess material

6.2.1 Placement tool

Watch **FILM 22:** ***Using Falsework***

During construction, to separate the structural layer from the thermal layer within the formwork, a timber placement tool is used, which is comprised of two angled timber surfaces. Figures 25 & 26 illustrate what the generic tool looks like, although builders can optimise its construction to best suit their needs and preferences.

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 27). The angle of this tool also makes it easier 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.

6.2.2 Tamper tool

This is a simple hand tool used to compact the light earth. Figure 30 shows an example of a tamper tool, which comprises of a plywood plate fixed to the end of a mattock handle.

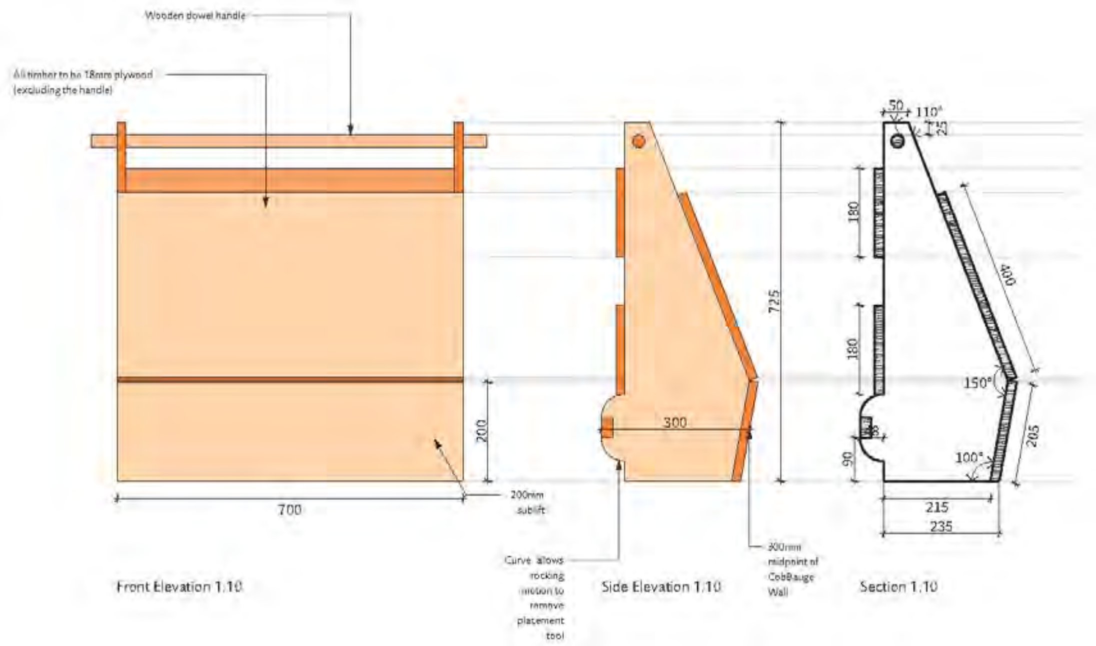


Figure 25. CobBauge placement tool elevation and section. Source: Hudson Architects (2022).

Figure 26. 3D views of CobBauge placement. Source: Hudson Architects (2022).

Figure 27. Angled saw toothed joint between thermal and structural layers. Photos: University of Plymouth, CobBauge project

7. METHOD OF CREATING A COBBAUGE SUB / FULL LIFT

7.1 Structural layer sub-lift

Watch **FILM 24**: ***Loading & Compacting CobBauge***

When laying 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 CobBauge mix can then be placed in the void between the placement tool and the formwork mesh, which will then become the inner layer of the wall. The CobBauge mix is typically lifted into the formwork by hand, using a pitchfork, and densely compacted using the handle of a pickaxe tool and by foot so that the structural layer has no voids (Figure 28). The recommended method consists of fully compacting small quantities of CobBauge at one time (e.g., a couple of pitchfork worths), using the pickaxe handle, particularly for the edges of the wall and feet to compact the wider area. Compacting the CobBauge in multiple thin layers makes the compaction process easier (requiring less force to be exerted), while reducing the risk of voids. The pickaxe handle has proved to be an essential tool in the process to provide a more focused compaction at the wall's edges, where feet can't get to so effectively.

Figure 28. Placement tool and stamping compression technique for structural layer. Photos: Tom Booen.

7.2 Thermal layer sub-lift

Watch **FILM 25:** ***Loading & compacting light earth***

Once this 200 - 250mm high section of CobBauge 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, so that it sits flush against the face of the structural CobBauge and the formwork and then compacting it using a hand tamper tool. The thermal layer requires much less force than the structural layer due to the lightweight qualities of the material. While over-compaction of the light earth shouldn't be an issue due to the nature of the hemp shiv, which will spring back, as well as the capabilities of tamper tool, it is important to remember that the purpose of this layer is for thermal performance. Therefore, it is important for this layer to be well adhered together yet retain air pockets for its insulative properties. The completion of the thermal layer laboratory testing, in Subsection 4.3.2, should help to guide the right force of material compaction.

7.3 Between sub-lifts

Watch **FILM 21**: ***Bond Strength Between Cob & Light Earth***

Once each full thermal and structural sub-lift is complete, hemp straw of between 300 - 450mm is placed perpendicularly to the run of the wall at approx. 600mm centres (Figure 29). This is to help tie both layers together and reduce the likelihood of cracking during the drying of the CobBauge wall. It is also recommended to moisten the previous sub-lift/full lift with water, before laying the next lift's material on top to help to improve the bond between layers.

Figure 29. Hemp straw placed, after each sub lift, perpendicular to the run of the CobBauge wall. Photos: Jim Carfrae.

7.4 Constructing multiple sub-lifts to form one full lift

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 CobBauge (Figures 30-32). 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. It is advisable for the sub-lifts to be a multiple of a full lift e.g., to have three 200mm sub-lifts to make one 600mm full sub-lift.

Figure 30. Tamper tool and technique for thermal layer. Photos: Tom Booen.

Stage 1. Insert placement tool into formwork. Hard up against mesh surface.

Stage 2. Fill structural cob and compact up to face of placement tool and mesh formwork.

Stage 3. Remove placement tool and fill void with thermal cob up to level of structural cob layer.

Stage 4. Position formation tool on next half lift (sub-lift) level (on top of thermal cob). Add structural cob as per stage 2.

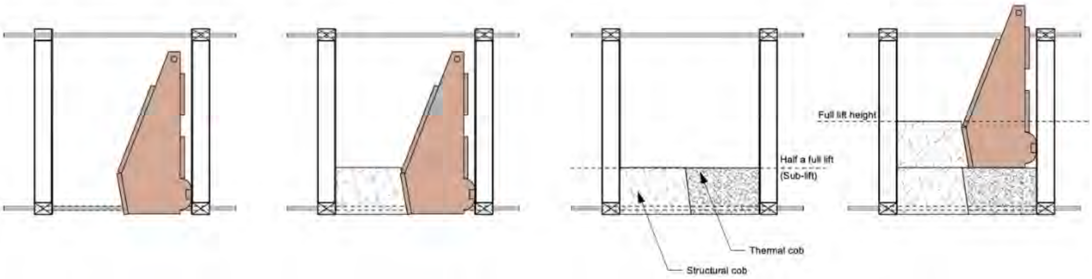


Figure 31. Illustrated placement tool and sub-lift methodology. Source: Fox Ecological Architects (2022).

Figure 32. Placement tool being used on site. Photo: François Streiff.

7.5 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 33). 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 33. Photo showing the compaction of the light earth viewed through mesh. Photo: Plymouth University, CobBauge project.

7.6 Formwork methods

When constructing lifts of CobBauge, contractors are to sit the connecting bolts on top of the previous lift before attaching the formwork frames (Figure 34). 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 walls. When the formwork is removed, there will be holes left by the threaded bar that supports the formwork. It is recommended to plug the wall’s face with the correct CobBauge material.

There are two formwork methods which can be used: the ‘leapfrog’ method (Figure 34) and the ‘full height inner leaf’ method (Figure 35). The full height inner leaf method has the advantage that it only requires the wall’s outer face formwork to be repositioned; therefore speeding up the construction process. On the other hand, it requires a larger upfront formwork cost and it makes the walls less straightforward to cover to protect from rain.

Following the completion of a lift of CobBauge, the formwork should be left in place to allow the CobBauge to dry for a period of time with consecutive dry weather, greater than 12°C, before being re-positioned. This time period will be dependent on several factors including temperature, humidity, wind, mix consistency etc. 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 for 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.

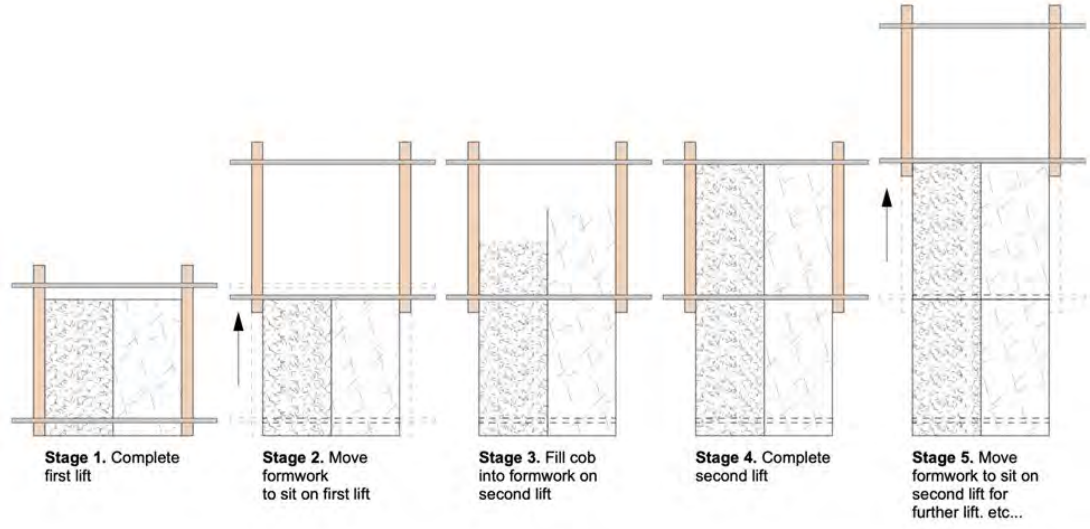


Figure 34. Illustrated 'leapfrog' method for raising formwork. Source: Fox Ecological Architects (2022).

1. Pour footings, construct plinth and floor deck

2. Erect inner leaf of formwork to full height, following profile of building

3. Complete first Cobbauge lift at lower plinth level

4. Complete subsequent Cobbauge lifts by constructing outer leaf of formwork as required - no downtime between lifts

5. Complete Cobbauge lifts to plate level

6. Strike formwork

Figure 35. 'Full height inner leaf' formwork methodology. Source: Hudson Architects (2022)

8. DRYING

Moisture measuring equipment
Ramin sensors (balsa wood & wires to make)
Wood moisture meter

Drying equipment
Large fans

Watch **FILM 30**: ***Managing Drying & Shrinkage***

8.1 Time between CobBauge lifts

Once a CobBauge lift has been completed, it is recommended that contractors wait around 2-3 weeks before laying the next lift if the 'leapfrog' method of formwork is used. During this time, contractors can prepare for the next lift by re-positioning the formwork and preparing the new material. Whereas, if the 'full height inner leaf' formwork method is used, contractors don't need to wait between lifts and can continue building by circulating around the build: 'chasing the tail of the previous lift'. As a rough guide, it takes approximately 3 days, using 3 workers, to construct one lift of 650mm CobBauge on a 30sqm square building. The speed of construction completely depends on the number of workers, the efficiency of the on-site construction method, competency of the builders, thickness of walls and size of building.

8.2 Maximum moisture levels for removing formwork

Ramin sensors can be made by the designer/builders and embedded within the CobBauge wall to assess how the moisture levels change over time (Figures 36 & 37). It is recommended to embed the ramin sensors in the first and last CobBauge lift and take readings weekly. This data can be used to create a curve of the wall's drying process and inform when the formwork can be removed or finishes to be applied. To take the moisture reading, the type of wood needs to be selected from the wood moisture metre and held onto the tab at the end of the wiring which sticks out from the wall. The figure is read from the wood itself, with no conversion needed.

8.3 CobBauge wall drying

If the CobBauge construction takes place over the period of spring/summer in the UK, the CobBauge walls are likely to be able to dry out naturally due to the dry and warm weather. However, if the construction takes place over Autumn/Winter, or the project want to increase the speed of the drying process, low-tech mechanical ventilation devices, such as large fans, may be appropriate to aid the drying process. Keeping the building well-ventilated and not fully enclosed is more effective than e.g., using heaters, due to the air flow circulation. Depending on the time of year the CobBauge was constructed, it is likely that a CobBauge building will take approximately a year to fully dry out. This is more than a traditional cob wall. Applying finishes too soon, can prolong the drying time length.

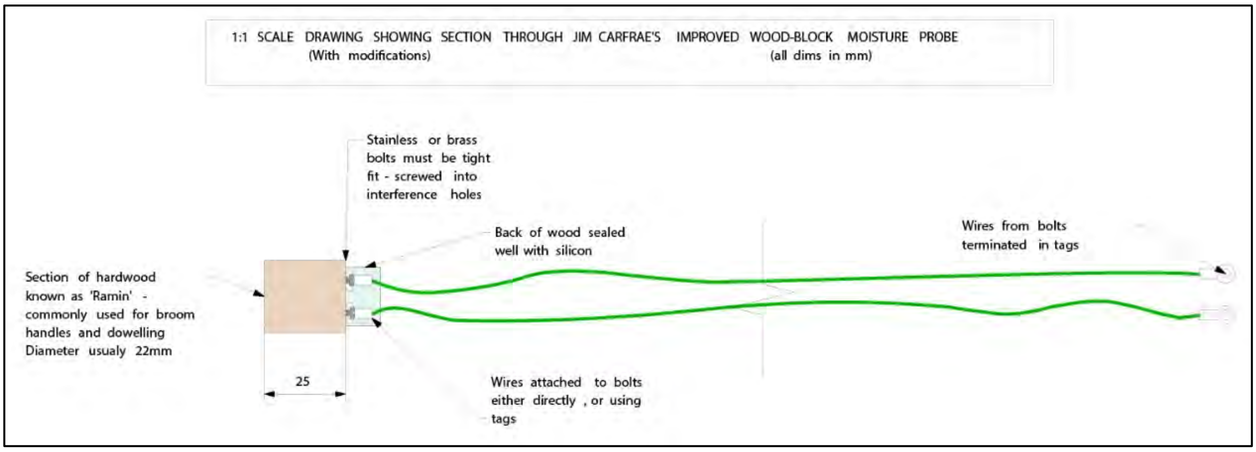


Figure 36. Diagram of Ramin Sensor. Source: Jim Carfrae.

Figure 37. Ramin Sensors laid in place, ready to be embedded into the final CobBauge lift. Source: Anthony Hudson.

9. OPENINGS

Watch **FILM 23**: ***Blocking Out Openings & Services***
Watch **FILM 28**: ***Door & window openings***
Watch **FILM 27**: ***Building in Lintols***
Watch **FILM 30**: ***Managing Drying & Shrinkage***

9.1 Window placement & support

It is recommended that windows are positioned within the thermal layer of a CobBauge wall to utilise the material's properties to minimise cold bridges. To support this, battens (50X50mm) can be set into the structural layer and across to the thermal layer to provide a fixing point for the windows. The thermal layer also includes a timber lintel fixed to plywood. However, if desired, windows can be placed within the structural layer and other insulating methods can be designed accordingly (see *CobBauge – Standard Details Package*).

9.2 Boxing out openings

CobBauge wall openings are created by placing plywood boxing, surrounded by wire mesh (the same used for the formwork), into the desired wall locations within the formwork, ensuring that they are plumb and level with the wall formwork. The CobBauge is then constructed around these formers as normal (Figure 38). This boxing remains in place until the end of CobBauge construction and drying process.

Figure 38 The plywood & mesh window boxing (left), & boxing embedded within the CobBauge construction (right). Photos: Katey Oven (2022).

9.3 Window openings

Lintel designs for CobBauge walls can vary as the generic *CobBauge – Standard Details Package*, examples. The lintel design for the building is to follow the structural engineer's design and specification. For wider openings, such as double doors, the structural CobBauge may be too heavy to go across the opening and be adequately supported by timber lintel. Therefore, substitution with timber frame and light earth infill maybe considered.

9.4 Designing for shrinkage

When detailing windows, it is important to design for the shrinkage of the CobBauge wall, which generically is about 1-1.5%. A shrinkage approximation for a specific project can be gauged based on the laboratory shrinkage box result's percentage (see Subsection 4.2.3) combined with the height of the wall. For the CobBauge pilot builds, a 40mm shrinkage void was allowed at the window heads and filled with sheep wool insulation (see *CobBauge – Standard Details Package*). Other types of natural insulation with compressible qualities could be used.

9.5 Designing for weathering and waterproofing

Consideration should be given to preventing moisture from penetrating the CobBauge wall. At the window head, if lime render is used, bell mouth drips can be used to prevent water tracking back towards the window. At the sill, solutions will vary depending on the window system employed. The CobBauge pilot projects used sloped aluminium sills to direct water away from the building. The corners and junctions between the windowsill and rendered reveal also need to be carefully considered. Solutions could include a sill upstand or tape membrane to prevent ingress at this critical junction.

10.0 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.

10.1 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 in turn 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 (Figure 39). The use of plywood sheeting is the preferrable method as this still keeps the sides of the CobBauge wall well ventilated, which will help the drying process. Caution is advised if tarpaulin is used to protect the CobBauge walls from rain, to ensure that the walls are still well ventilated to aid the drying process and prevent cracking e.g., the inner structural layer is left exposed.

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.

Figure 39. Sheets of timber protecting the tops of the CobBauge wall. Photo: François Streiff.

10.2 Cracks within CobBauge layers

It is not uncommon to encounter some cracks in the CobBauge layers, so long as they are not too large or frequent. This can be due to a variety of reasons including differential drying. The extent and size of the crack should be considered before undertaking remediation action.

• **Small cracks** (see number 1 in Figure 40) in the wall can be filled with slip before starting a new sub-lift.

• **Large cracks** (see number 2 in Figure 40) should also be filled with slip or the relevant structural / thermal mix depending on its appropriateness for the location and type of crack present. 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.

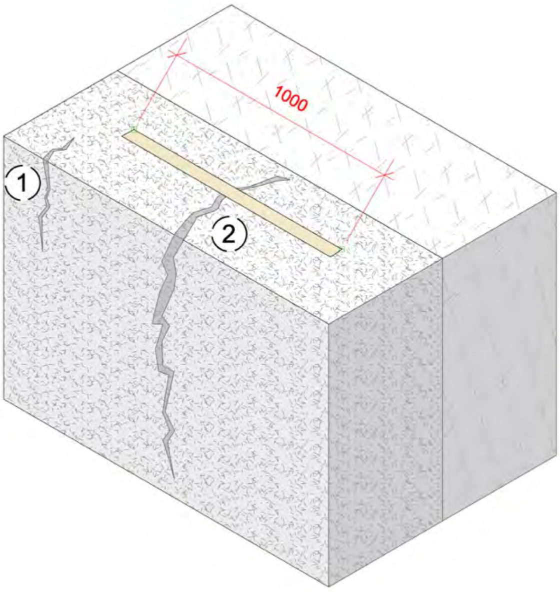


Figure 40. Illustration of types of cracks in a CobBauge wall and timber batten protection. Source: Fox Ecological Architects.

11.0 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.

11.1 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 41). This will enable contractors to have free movement around the site during the early stages of the build.

Figure 41. Using a small scaffold platform to aid low level construction.

11.2 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 42). 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 the scaffolding, moving formwork and material around on the scaffolding and when lifting material up to a higher level.

Figure 42. Scaffolding on the inner and outer sides of the CobBauge wall as it rises.

12.0 MOVING COBBAUGE MATERIALS AROUND ON SITE

12.1 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.

12.2 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.

13.0 COBBAUGE AT JUNCTIONS

13.1 CobBauge at first floor junctions

Intermediate floors can be supported on either cut in or cast in bearers (refer *CobBauge - Standard Details Package*). Floor joists can then be face fixed with joist hangers or bear directly onto the timber bearer. Generally, it is preferable to centre the bearer on the structural CobBauge.

Watch **FILM 29**: ***Connecting to other materials***

13.2 CobBauge at junction with non-loading bearing elements

Consideration should be given to junctions (plan & section) between CobBauge and non-load bearing partition walls due to differential shrinkage. This can be done using slotted metal channels fixed to the roof structure, which restrains the head of the partition wall, whilst allowing the structure supported on the CobBauge to sink downwards without bearing onto the partition wall. It is advisable to wait as long as possible between the completion of the CobBauge and installation of non-load bearing partitions to allow as much shrinkage as possible to take place. Note that consideration should be given to maintaining acoustic and fire separation at the deflection head detail. Shrinkage allowance should be calculated on a case-by-case basis, referring to the wall height and shrinkage capacity of the clay.

14.0 RUNNING SERVICES IN A COBBAUGE WALL

Watch **FILM 31**: ***Integrating Services***

For running M&E services in a CobBauge building, there are two main options: chasing and face-mounted conduits. If the electrical services are designed to be concealed within the CobBauge wall, they are to be “chased” into the inner structural layer prior to being plastered; just how one would a conventional solid wall. However, it is recommended to use non-ferrous (and galvanised) materials, to avoid a reaction (such as discolouration) occurring with the natural plaster. These alternative materials could consist of hessian to cover the chase and plastic fixings to attach it. The second main option for running services is to use face-mounted conduits, depending on its suitability to the function and desired aesthetic of the building’s interior. Due to the breathable nature and nonlinear form of the CobBauge wall, plasterboard is not a suitable option to conceal services.

For mechanical ventilation services there are also two main options: casting in the wall or through the roof. In the wall consists of casting in the plastic duct as the CobBauge wall is built up. This requires the building’s ventilation strategy to be considered during the design stage. The roof ventilation option can be strategized just like any conventional build would.

Underfloor heating is the recommended heating service type as it requires minimal wall interference, as well as its increased energy efficiency compared to conventional radiators. However, if radiators are desired, it is recommended to implement them on non-CobBauge walls e.g., internal timber or metal stud, as with all the building’s services. This means that the structural layer of CobBauge doesn’t need to be cut into.

Direct ontact with water on CobBauge walls should be considered in the design stage to minimise this, e.g., positioning the bath and shower perpendicularly or adjacent to the CobBauge wall. Due to the nature & size of clean and foul water pipes, it is not appropriate to pass these through any of the CobBauge walls, but for them to be fed underground.

15.0 FITTINGS & FIXTURES

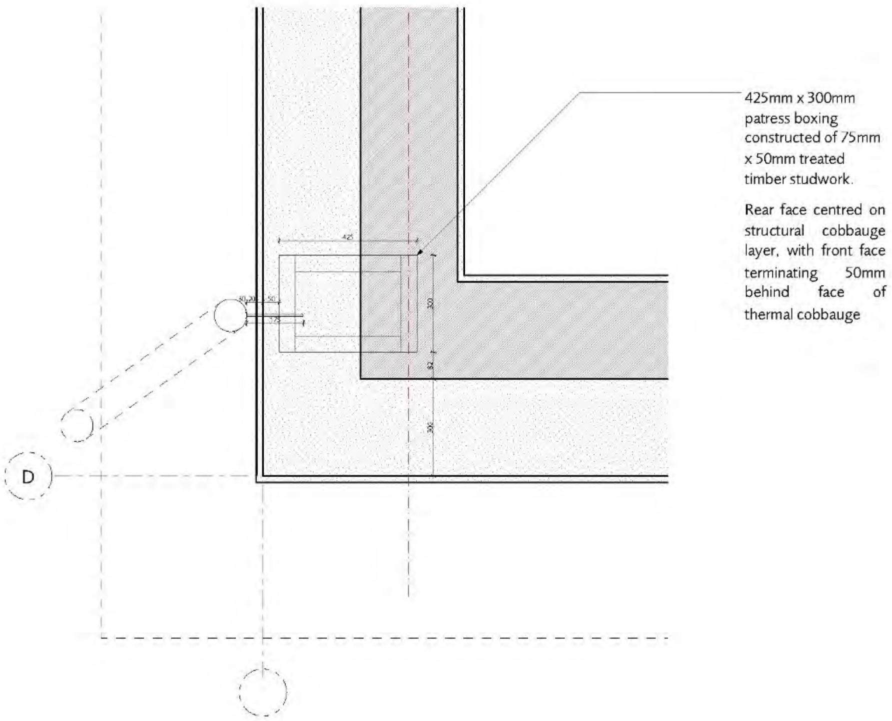
Watch **FILM 32**: ***Secondary Fixings***

Both interior and exterior fixtures and fittings need to consider the CobBauge wall’s structural integrity as well as its breathability. Overall, it is advised to design out the number of fixtures to the CobBauge walls where possible and apply them on the internal or timber stud instead.

On the internal face of the CobBauge wall, it is suitable to hang lightweight fixtures such as light fittings, pictures and small shelves onto the structural layer using screw fixings. It is advised that heavier items, such as vanity units, tv’s, heavy shelves, cabinets, and cooker hoods, should be placed onto non-CobBauge internal walls or be freestanding instead. Fitted furniture or placing furniture next to CobBauge walls, should also have a ventilation gap to prevent moisture build up.

On the external face of the building, due to the strength of the thermal layer, fixtures should be avoided and designed out. An example of this is utilising the building overhangs, required for CobBauge wall protection, for sofit-fixed lighting as opposed to wall-mounted. It is all about designing within the constraints and opportunities of the earth wall construction. However, for essential fixtures, such as downpipes, treated timber framing should be cast across the thermal and structural layers to accommodate downpipe fixing points (see Figure 43). This fixing strategy requires consideration during the design stage.

Whilst it is possible to finish the building with a rainscreen cladding to achieve a desired aesthetic, the pattressing would need to be carefully designed to not bear load onto the thermal layer, whilst still allowing breathability and ventilation. Due to the un-linear form of the CobBauge walls, a more versatile cladding option, such as timber shingles, could be more practical as well as accommodating with the natural wall materials option.



425mm x 300mm patress boxing constructed of 75mm x 50mm treated timber studwork.

Rear face centred on structural cobbauge layer, with front face terminating 50mm behind face of thermal cobbauge

Figure 43 Example pattressing detail for downpipe.

16.0 FINISHES & AIRTIGHTNESS

Watch **FILM 26**: ***Preparing & Finishing Surfaces***
Watch **FILM 33**: ***Finishes & Aftercare***

16.1 Internal plasters & paint types

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 CobBauge mix, therefore offering a saving on embodied carbon properties. 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. Alternatively, clay plaster can be bought off the shelf ready-made. 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 and what methodology is best followed. The clay plaster mix, that comprises of clay, chopped straw and some sand if needed, is usually created based upon the desired wall finish e.g., smooth, rough, floated, flat, wavy, abrasion resistance, painted or unpainted. The book “Earth Render”, by James Henderson (2013) is also a useful source of information.

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, both structurally and thermal performance wise, due to moisture and mould problems.

In terms of time frames, it is recommended that the walls are as dry as possible before applying the plaster or render (see Section 8 for CobBauge drying).

The limitation of clay plaster is that it is not waterproof, and therefore weatherproof, making it only appropriate for internal application. As discussed in Section 14 regarding external details, similarly, it is important to detail out any direct water contact with the clay plaster or CobBauge walls internally (i.e., use splashbacks etc). Steam in bathrooms & kitchens is not deemed to be a problem, in fact clay plaster and the CobBauge walls are good humidity regulators. This can be exemplified by the reduction of condensation on mirrors.

As mentioned in Section 14, it is important to note that ferrous materials can cause a reaction (such as decolourisation) with natural plasters and paints. Therefore, it is recommended to use non-ferrous materials instead. It is also important to consider the junction between the CobBauge wall and other materials, such as the block work plinth, and around corners. It is recommended to lay reinforcement mesh to prevent cracking in these areas.

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.

16.2 Airtightness

The CobBauge system is inherently reasonably airtight, but the internal plaster finishes should be taken as the airtightness line. Consideration should be given to maintaining airtightness at key junctions which can be done using membranes, with tape that can be plastered over.

16.3 External render

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 being waterproof and weather resistant. This makes lime the most appropriate render mix (Figure 44). Whilst 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. Due to the material composition of the light earth, it is advised to wet the surface of the thermal layer prior to the render application as is likely to absorb a lot of the moisture.

Figure 44. Example of lime render being applied to a CobBauge wall. Photo: Raphaël Rattier.

17.0 U-VALUES

17.1 U-value depth and density matrix

Table 4 shows a matrix of calculated U-values, for a completed CobBauge wall, at varying density and thickness of the thermal layer. These values are based on a wall build-up of:

Internal clay plaster	30mm
Structural Mix	300mm
Thermal Mix	250 – 350mm
External lime render	30mm

Table 4 Matrix showing U-values in red

	Depth of Thermal layer (mm)		
Density Kg/m3	250	300	350
200	0.24	0.21	0.18
250	0.26	0.23	0.20
300	0.28	0.25	0.22
350	0.30	0.27	0.24
400	0.32	0.28	0.25

The following Lambda (conductivity) value, calculated for each density (W/mK), are based on results of 34 conductivity measurements made at Plymouth University and ESITC (Caen) using a Netzsch HFM446 heat flow meter. These figures show that the lower the density of thermal mix, the better the conductivity.

200 = 0.078
250 = 0.088
300 = 0.098
350 = 0.108

17.1.2 Example U-value calculation

Table 5 shows an example U-value calculation for a wall with a 300mm thermal layer with a density of 300Kg/m^3 (please note: Thickness in this calculation expressed as metres).

Table 5 Example U-value calculation for a CobBauge wall with a 300mm, 300Kg/m3 thermal layer.

CobBauge + 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	0.440	0.07
Structural Mix	1503	0.300	0.430	0.70
Thermal Mix	300	0.300	0.098	3.06
Lime render		0.03	0.600	0.05
External Surface		n/a	n/a	0.06

Total Resistance	4.06
U-Value W/m2K	**0.25**

18.0 STRUCTURAL WARRANTY & FUNDING

As the CobBauge system is a non-standard construction typology, should lending be required to complete the project, it is advisable to check with the lender, prior to commencement of the build, to ascertain whether funding will be released. Additional surety in the form of a Council of Mortgage Lenders (CML) certificate may be needed to secure funding.

19.0 FURTHER INFORMATION

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).

20.0 REFERENCES

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EBUKI, Earth Building UK and Ireland (2022). Available at: http://ebuki.co/projectcobbauge.htm#sthash.v7sDkxob.dpbs

Esitc Caen, Graduate School of Construction Engineers of Caen (FR) (2022). Available at: https://www.esitc-caen.fr/en/cobbauge

Fox Ecological Architects, Devon (UK) (2022). Available at: http://www.foxecoarc.com/

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Plymouth University, Plymouth, Devon (UK): Lead partner of the CobBauge project (UK) (2022). Available at: 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).

21.0 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.

Form Ties

(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/

Moisture Reader

Protimeter Timbermaster BLD5609 Wood Moisture Meter: https://www.test-meter.co.uk/protimeter-timbermaster-bld5609-wood-moisture-meter

Earth Render Book

“Earth Render”, by James Henderson (2013)

22. APPENDIX A – GEOLOGY REPORT

CLAY WORKS

Geological and geocultural information to support development of earth building in Norfolk and beyond.

Tim Holt-Wilson

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1) Introduction

A variety of raw earth materials have been used for architecture in Britain. These include rammed earth (pisé de terre), cob, clay blocks, chalk and rammed chalk (chalk pisé) (Williams-Ellis & Eastwick-Field, 1947, pp.2, 14, 15). This account focuses on the geological availability of these materials, focusing on cob, known as bauge or torchis in France.

Different material lend themselves to different usages. For example, the "*soils suitable for rammed earth houses are broad and include sands with sufficient clay and silt, clayey silts, clayey gravels and gravel-sand-clay mixtures*". (Maniatidis & Walker, 2003, p 23) "*Cob walls are built of a mixture of clay, straw and water... A mixture of crushed chalk and straw has also been used... In Hampshire a cob-type all is made of three parts chalk to one of clay*". (Williams-Ellis & Eastwick-Field, ibid, p.82) Key physical properties determining suitability of the material include particle size distribution (on the textural scale clay-silt-sand-gravel), plasticity, dry density, mechanical strength, durability and shrinkage. (Maniatidis & Walker, ibid, pp.59-63)

Deposits containing a substantial proportion of fine-grained materials (clays, silts and fine sands) tempered with a smaller proportion of coarser materials (e.g. grit and pebbles) are most likely to be useful for cob architectural purposes. "*A great many types of earth can be used for making components out of cob by adjusting the working practices and architectural conceptualisation with a view to the structure intended. Silty and clayey earths are particularly suitable for making cob, although investigation of our built heritage shows that all sorts of earths may be suitable with due consideration given to adjusting material mixtures and working practices. The only earths to avoid are those in which the presence of organic matter can be detected by visual or olfactory assessment, and they do not make for cohesion"*. (CTA, 2018, p.11; translated).

Raw materials for cob need to be in a plastic or mouldable state. Clays and earths may need to be pre-processed by weathering: "*Construction earth* [la terre à bâtir] *is worked while in a plastic state. For this, it must be exposed outdoors so that bad weather can supply the water necessary for hydration. Exposing it in winter time allows frost to break up clods of earth. Breaking down the clods promotes water penetration through the material in cases where the construction earth is dry and/or very clayey, or where old cob being recycled".*

The presence of minerals salts may in some cases be deleterious to cob: *"In cases where earth from old walls is being recycled particular attention should be paid to the potential presence of mineral salts* [sels] *arising from the use of the old building".* (CTA, ibid, p.12). However, this text does not specify which mineral salts are referred to, nor what uses might lead to adverse mineralisation.

Two samples of clay from Norfolk have been tested for their suitability for cob construction purposes (Hudson Architects, undated).

- Sample 1 – Middleton Aggregates East Bilney quarry (Rawhall Lane, East Bilney, East Dereham NR20 4HH).
- Sample 2 – Middleton Aggregates Setch Road quarry (Setch Road, Blackborough End, King's Lynn PE33 0FB).

Given that the physical properties of these samples have been assessed as suitable for construction (Anthony Hudson, pers comm), this account provides a short review of geological and geocultural information surrounding these materials which can be used to support development of earth building in Norfolk and beyond, whether rammed earth, cob, clay lump or wattle and daub. (Photos 1, 2 and 3)

>>> Photo 1. Restoring a 16th century barn at Dairy Farm, Newton Flotman, Norfolk, 1992, with wattle and daub technique using Lowestoft Till puddled with chopped straw. Photo TD Holt-Wilson.

>>> Photo 2. A damaged farm yard wall at Finningham, Suffolk, showing crudely layered, cob construction, probably 18th or early 19th century. It is made of Lowestoft Till puddled with straw, set on brick footings and is faced with tar-painted plaster. Photo TD Holt-Wilson.

>>> Photo 3. Rammed earth walls in a shelter on a recreation ground at Letham, Angus. Constructed using glacial till derived from local Devonian bedrock and designed by Arc Architects Ltd. Photo TD Holt-Wilson.

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2) Geological background of the samples

Sample 1 – 'East Bilney clay'

❖ Brown, crumbly-textured, stony clay.

East Bilney quarry (Beetley, Norfolk) is extracting glacial sands and gravels from beneath an overburden of glacial till. Till is a deposit of glacial origin comprising a mixture of stony materials amassed from the land surface over which an ice sheet travelled it is transported then dumped on the surface as a kind of ground moraine. Tills of various kinds are often found wherever ice sheets have passed; in some places they may be tens of metres thick, and in others less than a metre. They typically consist in a variety of pebbles, cobbles and boulders in a fine-grained clayey or sand matrix – hence their traditional name of 'boulder clay'. It is an example of a superficial ('drift') geological deposit.
The till at East Bilney was deposited about 440,000 years ago during the Anglian stage of the Pleistocene period, and is attributed to the passage of an ice sheet from the northwest which deposited a geological unit known as the Lowestoft Till Member, part of the Lowestoft Formation. The Lowestoft Till occupies a large part of the land area of central Norfolk and Suffolk (Map 1), and shapes the undulating 'boulder clay plateau' landscape. (Photo 4) When fresh, the clay is typically a blue-grey colour, due to a higher percentage of Jurassic clays amassed when the ice sheet passed over the clays and mudrocks of the Fenland basin. It also contains a notable percentage of chalk fragments, eroded from the Chalk hills of west Norfolk.

>>> Photo 4. Clay-rich till of the Lowestoft Formation outcropping in the walls of a ditch at Mendham, Suffolk. The unweathered till is blue-grey in colour; the weathered and decalcified is brown. Photo TD Holt-Wilson.

>>> Map 1. The Lowestoft Till at outcrop in Norfolk and Suffolk. Image courtesy British Geological Survey.

The sample was taken from a long-term stockpile of clay-rich overburden, in occasional use for backfilling quarry voids, lining farm reservoirs or for general landscaping purposes (Peter Lemon (Middleton Aggregates), pers comm). It is considered to have low economic value. It is brown in colour, as the original blue-grey clay content has been exposed to weathering (sun, rain, frost), calcium carbonate has dissolved and iron minerals have oxidised.

Since it is such an abundant material in East Anglia, the Lowestoft Till has been used widely for building purposes over many centuries. It was used as far back as Saxon times for making wattle-and-daub (Tipping, 2010). It was fired From the Middle Ages onwards to make a variety of bricks, both red and cream in colour, depending on the relative percentages of water, iron and chalk in the clay. "*White bricks are made from the stiff blue clay and red bricks from the brown sandy clay*" (Bennett, 1884, p.6). Most parishes located on Lowestoft Till had their own local brickworks; a notable example was Somerleyton (Suffolk) which supplied reds and whites for building Liverpool Street Station (Butler, 1980). A variety of sandy clays or clayey sands (termed loam or brickearth in 19th century geological literature) were widely available for exploitation. In the period 1790 to 1860, raw boulder clay was compressed to make clay lump bricks for houses and farm buildings (Tipping, ibid). "*The clay is used for bricks and 'lumps' (air-dried rectangular blocks of clay well worked-up with straw, and used for rough building, with moist clay as setting).*" (Whitaker & Dalton, 1887, p.24).

Analysis of the physical properties of the clay from East Bilney suggests that it falls mostly within the optimal grading zone for raw cob usage provided that it is admixed with a 10% proportion of coarser components (Clark, 2022, p.3).

Sample 2 – 'King's Lynn clay'

- Blue-grey, cohesive, plastic, pasty-textured clay.

Setch Road quarry (Middleton, Norfolk) is an active quarry extracting fine-grained, calcareous mudstone or shale from beneath a thin layer of superficial deposits including till and periglacial head (subsoil mobilised by freeze-thaw processes active on slopes during ice age conditions). The rock is blue-grey in colour and contains a high percentage of silt and frequent fossil shell fragments (Photo 5). It is an example of a bedrock ('solid') deposit laid down in marine conditions in the Late Jurassic period, about 155 million years ago, known as the Kimmeridge Clay Formation. The formation contains a variety of seams with different physical properties, depending on ancient sea-bed conditions, with variations in colour and texture reflecting differing percentages of clay minerals, quartz, calcium carbonate and hydrocarbons (Gallois, 1994, p.37). The bedding layers near the surface show evidence of having been fragmented by weathering and periglacial freeze-thaw processes, producing the plastic clay seen in the sample. They contain the mineral selenite (a crystalline form of gypsum, calcium sulphate) which results from weathering of the mineral pyrite (iron sulphide) diffused through the rock. Kimmeridge Clay bedrock underlies the eastern side of the Fenland basin in Norfolk, however it is mostly buried by superficial deposits (peat and alluvial silt) and only outcrops in patches near West Winch and Downham Market. (Map 2) The formation is present elsewhere in England, and contains marker horizons which can be matched as far away as Surrey and Dorset (Gallois, ibid).

>>> Photo 5. The margin of a partly vegetated lagoon exposing silty mudstone bedrock of the Kimmeridge Clay Formation at Setch Road quarry, Middleton, Norfolk – NGR TF646149. The pale colour is likely to be due to the presence of calcium carbonate and/or calcium sulphate. Photo TD Holt-Wilson.

>>> Map 2. The Kimmeridge Clay Formation at outcrop in Norfolk, Suffolk and Cambridgeshire. Image courtesy British Geological Survey.

The Kimmeridge Clay has some commercial uses. It contains a high percentage of clay, so it is extracted at Setch Road for lining farm reservoirs and landfill sites, and for making water-retentive embankments (Peter Lemon, ibid). In the past it was used, among other local clays, for making 'common bricks', as at nearby West Winch (Gallois, ibid, p.178; Whitaker et al, 1893, p.144), though its patchy outcrop no doubt reduced its usefulness for this purpose. Some horizons contain a high percentage of hydrocarbons, and an abortive oil shale industry was set up at West Winch in the 1920s.

Analysis of the physical properties of the clay from Setch Road suggests that it has a very high proportion of fines (<0.063 mm grade), which means it falls outside the optimal grading zone for raw cob usage (Clark, ibid, p.2). However, its plastic qualities make it a suitable material for admixing (Katey Oven, pers comm) and for making clay slip (Hudson Architects, ibid, p.28).

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3) Potential cob materials in Britain

3.1 The variety of deposits

The two Norfolk samples are drawn from contrasting geological categories: superficial ('drift' geology), and bedrock ('solid' geology). Both categories are found in all parts of the UK:

Superficial deposits

Including a wide variety of unconsolidated materials lying close to the surface:
- subsoil layers formed from weathered bedrock.
- glacial deposits (tills, sands and gravels);
- colluvium, head, coombe rock and brickearth (mixed deposits resulting from processes on slopes);
- clay-with-flints (a residual deposit formed by in-situ weathering of strata overlying chalk);
- windblown deposits (dune sand, also fine-grained loess and coverloam deposited by dust-storms);
- peat (partly decayed organic matter),
- alluvium (materials deposited by running water, as in rivers, estuaries and tidal flats).

For our purposes, we may also categorise some artificial, anthropogenic deposits (for example heaps of mining spoil) as 'superficial'.

Bedrock deposits

Including all kinds of cemented rocks underlying the landscape:
- igneous (crystalline rocks such as granite and basalt);
- sedimentary (derived from the breakdown of existing rocks, for example sandstone; from biogenic processes, e.g. reef limestone; from chemical processes, e.g. precipitated salt);
- metamorphic (crystalline rocks produced by the effects of temperature, pressure and stress on any kind of rock).

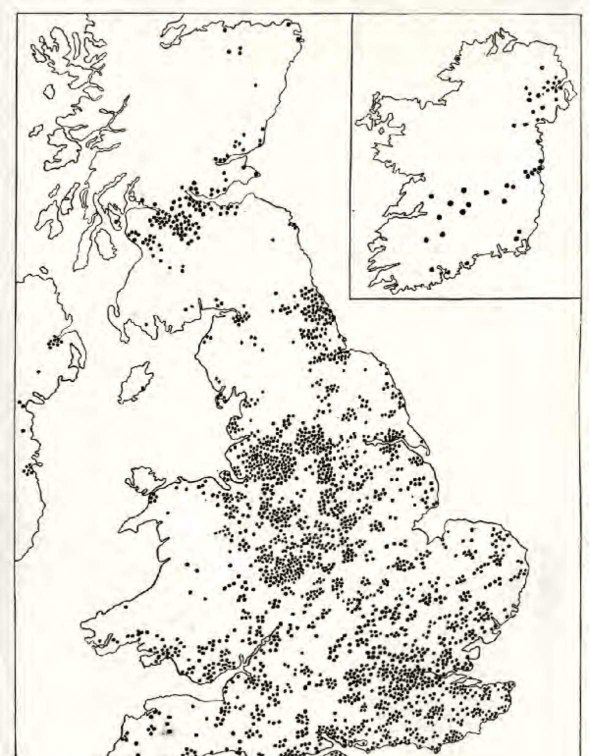
Igneous and metamorphic rocks are too hard to form raw geological materials for cob/bauge. As we have seen, the best are materials are mixtures of sandy and gravelly silts and clays of sedimentary origin from which raw organic matter and deleterious mineral salts are absent.

3.2 Raw materials

A great abundance and variety of cob/bauge resources are present in the UK. These include bedrock clays, shales and mudstones as well as superficial clay-rich tills and a variety of Quaternary periglacial and colluvial slope deposits with varying degrees of stony content. It is worth noting that tills are not found south of a line running roughly from London to Bristol, as the ice sheets never reached beyond it. These resources have been exploited for making common bricks, firebricks, pipes, tiles, pottery, cob, daub and clay lump, with the material obtained directly from the ground by excavation or indirectly from spoil heaps, and sometimes tempered with other materials to obtain the right physical properties.

In general, enormous reserves of these resources exist: *"The mudstones in the Coal Measures around Leeds have been dug for bricks, and there are unlimited quantities of this material*". (Edwards et al, 1950, p.71), and *"Resources of brick clay within the Mercia Mudstone and Bromsgrove Sandstone sequences are extremely large"* (Worssam & Old, 1988, p.128). "*Great Britain is wonderfully rich in fireclays, thanks to the great development of the Carboniferous rocks. … There are great reserves of the known high grade clays in each of the important areas in Yorkshire, South Staffordshire and Worcestershire, the Central Valley of Scotland, also in North and South Wales*". (Geological Survey, 1920, pp.1, 2)

The historical distribution of 'clayworks' in Britain gives a clear indication of the former geographical extent of clay-related industries and is a proxy for the availability of clays in the landscape. (Map 3)



The Chief Clayworks in Great Britain.

>>> Map 3. 'The Chief Clayworks in Great Britain'.
From 'An Introduction to British Clays, Shales and Sands' by AB Searle; Charles Griffin & Co Ltd, London, 1912.

Some superficial deposits may be more localised and finite, for example those in glacial lakes and other hollows: *"Brickworks in Luton at Eaton Old Green … may have exploited brickearth in a solution collapse feature"* (Hopson et al, 1996, p.119). Material sourced from coal industry spoil heaps may also be finite: "*The refuse-tip of Duck Pit, which worked the Supra-Pennant coals … forms the raw material for brickmaking at Cinderford"* (Trotter, 1964, p.78) – this industry had ceased production by 1970.

Old coal mining spoil is rich in clayey material. Well-weathered shale was recovered in the past from old mine-tips for brick-making at Coalbrookdale (Geological Survey, 1920, p.154). Weathering was necessary to ensure that iron sulphides and other unstable minerals were oxidised and leached out. At Stourbridge: “*The clays are weathered at least nine months, and in favourable circumstances for 3 years or more. To assist the weathering the dumps are sprayed with water”* (ibid, p.134). Weathering is still employed during brick and tile making. (Photo 7)

A variety of grog materials can be used for blending and tempering raw clay and silt to reduce shrinkage. Historical examples from the brick industry include old colliery waste at Tilmanstone (Bloodworth et al, 2002), fly-ash from power stations at Benfleet (BCA, undated), and brickdust and siliceous sandstones and sands of Carboniferous, Triassic and Pleistocene origin in Staffordshire (Geological Survey, 1920, p.118).

3.3 Where to find suitable materials

We may use the distribution and variety of clayey materials (bedrock and superficial) as a proxy guide to the likely presence of raw materials suitable for mixing to make cob/bauge. (Maps 4 and 5) However, it should be noted that the general local availability of these materials has been substantially reduced over the past 100 years, due to the reduction in local brick and pottery making and the closure of collieries.

>>> Map 4a – Bedrock formations used for sourcing clays. UK North. Image courtesy British Geological Survey.
Map 4b – ditto. UK South. Image courtesy British Geological Survey.

>>> Map 5a – Superficial formations used for sourcing clays. UK North. Image courtesy British Geological Survey.
Map 5b – ditto. UK South. Image courtesy British Geological Survey.

Materials used for brick and tile

Historically, brick and tile making has taken place wherever suitable clays, shales and mudstones are found. A variety of local clays gave rise to very localised manufacture of a wide range of products. (Hammond, 1998) For instance: *“In the past all the argillaceous formations and superficial deposits which crop out in Central England have been used in the local manufacture of bricks, tiles, etc.”* (Hains & Horton, 1969, p.105) *“At Long Waste near Rodington a brick and tile works was producing common red bricks and drain pipes ... The raw material in both cases is a chocolate brown, stoneless, laminated silt. The boulder clay, usually stony, has been worked for bricks at various places*” (Pocock, RW, et al, 1938, p222). All these materials are likely to be useful for cob/bauge purposes when weathered and tempered.

Today, brick production is currently concentrated in a few large factories exploiting a restricted range of strata:

Bricks are produced in all the countries of the UK, but England accounts for more than 90% of production. Although other clays are used on a small-scale, the location of the industry tends to reflect the distribution of the principal bricks clay resources:

- *Carboniferous mudstone is in northern England and Central Scotland: variable in quality, with only a small portion suitable for brick manufacture (most are too high in carbon and sulphur). Despite this, they are the most important resource, accounting for almost 30% of consumption in England and over 90% of consumption in Scotland. ...*
- *Etruria Formation or 'Etruria Marl' (Carboniferous age): high quality clays close in composition to the 'ideal' brick clay. Extracted and used mainly within Staffordshire and other parts of the west Midlands.... Often used to sweeten poorer quality clays. ...*
- *Mercia Mudstone Group or 'Keuper Marl' (Triassic age) in the Midlands: extraction and use clays confined to the Midlands. The mineralogy of parts of the resource gives rise to distinctive pale-bodied bricks due to the presence of carbonate minerals. ...*

- *Peterborough Member or Lower Oxford Clay (Jurassic age): extraction of these clays is confined to Cambridgeshire and Bedfordshire where they are used in the manufacture of 'fletton' bricks. ... Their carbon content requires an unusual manufacturing process. ...*
- *Weald and Wadhurst clays (Cretaceous age): principal brick clay resource in South East England. ...*
- *Fireclays (from Carboniferous coalfields in the Midlands and the North): associated with coal seams and produced mainly as a by-product of opencast coal extraction. ...*
- *Minor brick clay resources are locally important and include brickearth in Kent and Essex; the Reading Formation in Hampshire and the Chilterns; the Gault Clay in Kent, West Sussex and Hampshire; the Thanet Formation in Essex; Carboniferous and Devonian mudstones in South West England, the Skiddaw group near Barrow-in-Furness and alluvial clays on Humberside.*

(British Geological Survey, 2007, pp.7, 8)
Heaps of spoil from this industry may be a ready, low-cost source of cob/bauge raw material.

>>> Photo 6. Digging clay from the Lower Coal Measures at Clough Green Pipe Works, Cawthorne, West Yorkshire, 1928. Fireclay is being extracted from beneath a shallow coal seam.
Photograph courtesy British Geological Survey P204533.

With the contraction of the coal industry since 1980, brick clays are less readily available from Carboniferous sources. Fireclays in particular are much less accessible than they once were. (Photo 6) Currently their extraction centres on open-cast coal pits, and stockpiling is taking place to serve as strategic reserve, for example at the ‘Donington Island’ site at Swadlincote. (British Geological Survey, 2006; Leicestershire CC, 2016)

The composition of brick and tile clays varies according to the various percentages of clay minerals (particularly illite and kaolinite) and quartz (sand and silt). Clays can be blended to improve their physical properties, (Searle, 1912, 149) and the ‘Etruria Marl’ is particularly useful for this purpose. (Photo 7) Accessory calcium, iron, sulphur and carbon minerals influence the quality and firing properties of the clay. The presence of mineral salts, notably (pyrite) iron sulphide and gypsum (calcium sulphate), can be deleterious to quality, as can coarse-grained carbonates such as chalk which spall the brick. These risks are mitigated by carefully choosing the clay and ‘souring’ (weathering) it. (British Geological Survey, ibid, pp.6, 7) While the presence of raw organic matter in alluvial clays can produce gases (Firman and Firman, 1967, p.306), ancient carbonaceous inclusions in some clays (notably the Oxford Clay) produce partially self-firing bricks (Horton, 1989, p34).

See Appendix for examples of locations of brick and tile clays.

<u>Materials used for pottery</u>
Like brick and tiles clays, pottery clays are drawn from a wide variety of geological sources. They include kaolin and ball clays, derived from the deep weathering of granites (British Geological Survey,

2009; 2011). They need to be fine-grained, without inclusions such as limestone or chalk particles or raw organic materials which produce gases during firing. Tempering and weathering can modify their physical properties. They may be suitable for making cob/bauge slips. Examples of deposits include:

- Middle Coal Measures clay at Benthall, Shropshire (SAP, undated) and fireclay at Moira, near Ashby-de-la-Zouch (Worssam & Old, 1988, p.127).
- Clays of the Permian Edlington Formation at Littlethorpe, Ripon (Littlethorpe Potteries, undated).
- Lower Jurassic clay of the Saltwick and Cloughton Formations at the Commondale Brick, Pipe and Pottery Company Ltd, North Yorks (British Museum, undated).
- Carboniferous clays of the Etruria Formation at Stoke on Trent (Rees et al, 1998).
- Post-Permian kaolin / china clay at St Austell, Cornwall (British Geological Survey, 2009).
- Weald Clay Fm at Dicker Potteries, near Hailsham, East Sussex (Lake et al 1987 p.93).
- Lambeth Group (Reading and Woolwich Beds) at Ewell, Surrey (Geological Survey, 1920, p162, 3).
- Eocene ball clays (Poole Formation) at Wareham, Dorset (British Geological Survey 2011).
- Oligocene ball clays (Bovey Formation) at Heathfield, Devon (Edmonds et al, 1969, p100).
- Pleistocene marine clays at Watson's Potteries, Wattisfield, Suffolk (Spencer, 1972; Craven, 2006).
- Pleistocene glacial clays at Barvas, Isle of Lewis (HFM, undated).

>>> Photo 7. Heaps of clay being weathered before use at a flooring tile factory. The grey clay was sourced from Jurassic Kimmeridge Clay at Setch Road, Middleton, and the purplish clay in the background is pottery clay from Triassic Keuper Marl deposits near Stoke on Trent.
Photo courtesy Norfolk Pamments Ltd.

<u>Other clayey materials</u>

Superficial deposits usually include a range of clayey materials of diamictic (mixed-source) origin, including till, head and alluvium. As well as providing raw material for bricks, they were used in the past for cob and clay lump architecture. For instance, in the Okehampton area of Devon: *"Many of our and cottages of the district show low stone walls continued upwards by solid cob. This material is made from a mixture of (commonly stony) clay, straw and water ... Both Culm and head clays have been used, and the colours of such walls reflect those of the local surface geology - red for Permian-derived clayey head and yellowish brown for Culm clay and Culm-derived head."* (Edmonds, 1968, p.210) (Photo 8) In South Norfolk: "*In the neighbourhood of Hardwick, Tivetshall, etc, bricks are made … out of chalky boulder clay. The material dug is mixed with chopped straw and then puddled and dragged about in a mill by horses, after which it is put in moulds ... and then dried in the sun*". (Woodward, 1881, p.117). (Photo 9) These kinds of vernacular architecture are another proxy for the likely presence of raw materials suitable for making cob/bauge.

Photo 8. A cob wall with stone footings at Bolberry, Devon, made from local head deposits derived from Devonian bedrock. The material is exposed to rainwash and freeze-thaw erosion where a sheltering roof is missing. Photo courtesy Google StreetView Oct. 2016 © Google 2022.

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Photo 9. Renovations to an early 20th century clay lump house at Blo' Norton, Norfolk. The blocks were made from locally-sourced Lowestoft Till mixed with chopped straw. Photograph TD Holt-Wilson.

Tempering materials

A range of materials have been used to temper clays for brick and pottery production to reduce shrinkage (Wikipedia, 2020). Examples include:

- Ground flint (PHS, 2022).
- Calcined, ground animal bone (IGMT, undated)
- Brick-dust (grog) (Searle, 1912, 15; Geological Survey, 1920, pp.118, 197).
- Ground sandstone (ibid, p140).
- Sand (ibid).

Tempering materials can be sourced for cob/bauge making purposes from quarries and industrial waste heaps. The pottery industry has used ground pottery waste and also mollusc shells sourced from shellfish processing businesses. Chopped straw once served the same purpose in clay lump bricks.

Sources of information

There are many books and websites devoted to the history of the brick industry in the UK, though rather fewer devoted to the pottery industry. These provide information about localities likely to yield suitable clays and 'brickearths'. British Geological Survey publications from the 19th century to the present day yield invaluable information about locally available resources. A great many regional guides are available to view online at https://webapps.bgs.ac.uk/data/publications/pubs.cfc?method=viewHome. See the references in Appendix for examples. The best general overview of the usage of clays in the historic brick and pottery industries, their varieties, geographical distribution, physical and chemical properties and processing techniques, is probably Searle (1912). It brings together much valuable information about British clays not readily accessible today.

4) Conclusion

Two clay samples in Norfolk have been tested and found potentially useful for cob/bauge purposes. They are drawn from bedrock and superficial deposits with a high percentage of fine-grained material. Such deposits are widely found in all parts of the UK, as mudstones, shales, clays, silts, tills and head spanning periods from the Palaeozoic Epoch to the present day. Historically, they have been fired to make many kinds of brick, tile and pottery, with modification by tempering and weathering, and have been used in raw form to make cob, clay lump and daub. They represent a varied resource available for cob/bauge research and building construction across the country today, supported by an extensive geological research literature.

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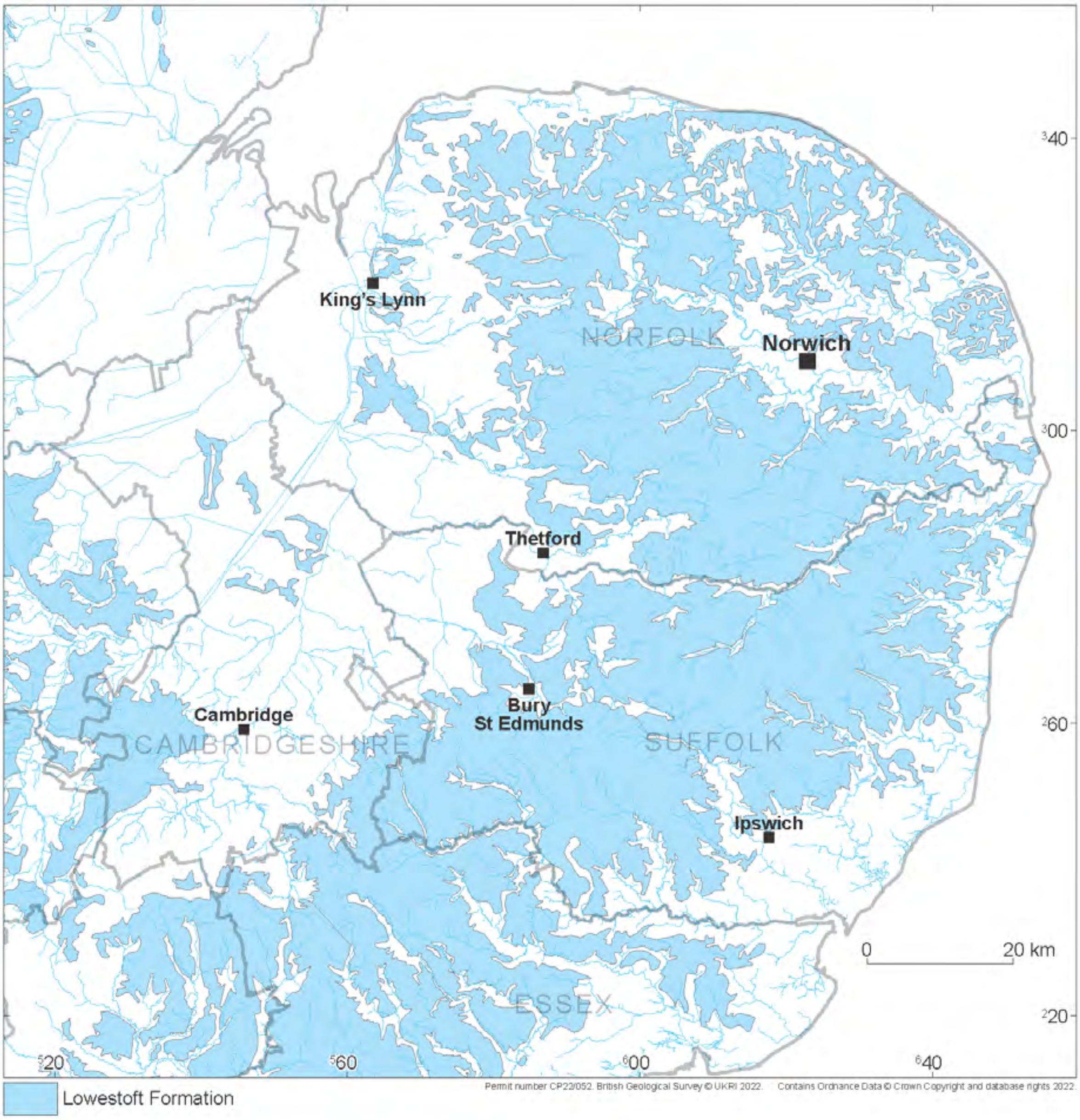
T.D. Holt-Wilson
Norfolk Geodiversity Partnership
September 2022

23.0 APPENDIX B – GEOLOGY REPORT MAPS



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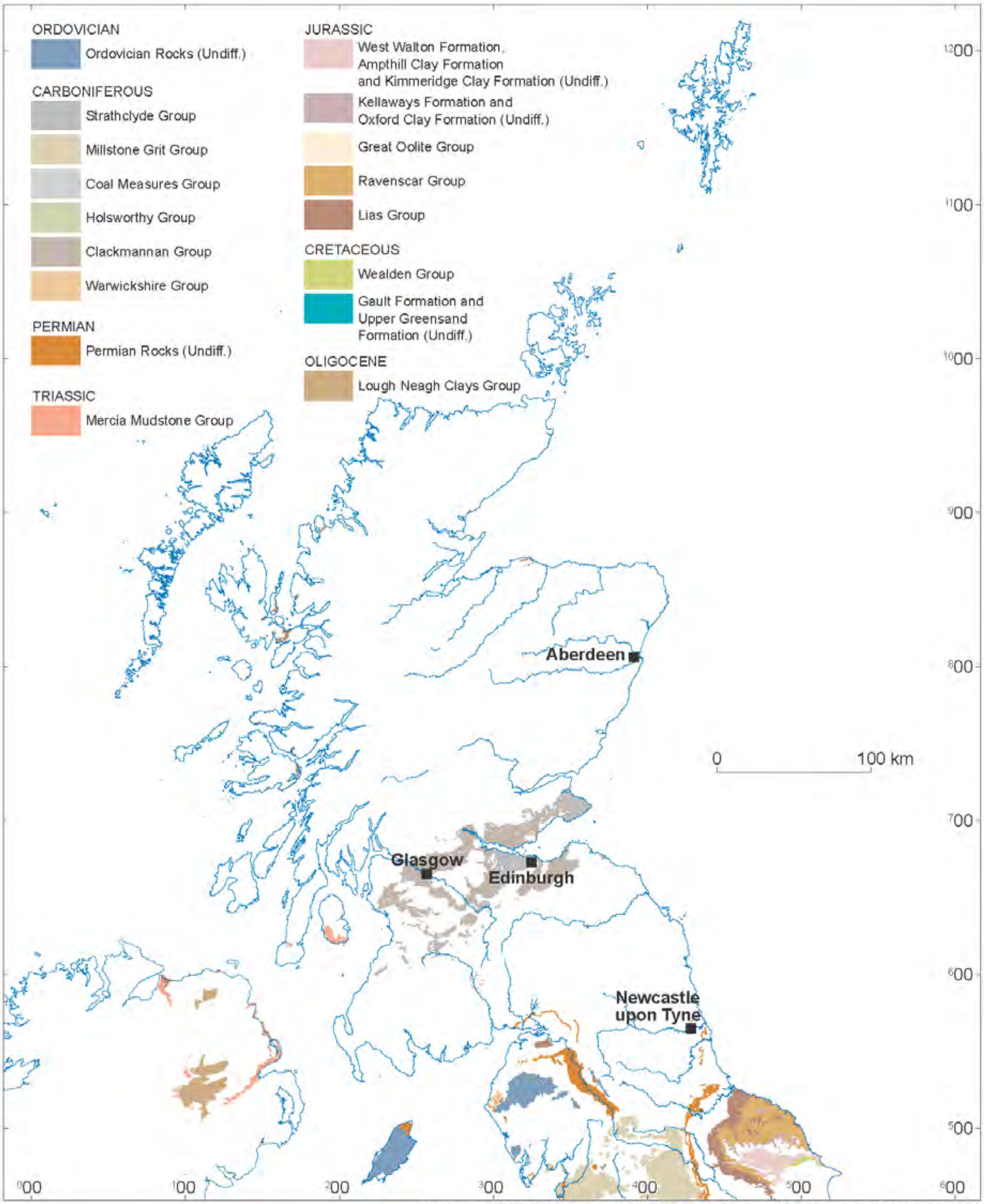
Map 1. The Lowestoft Till at outcrop in Norfolk and Suffolk. Image courtesy British Geological Survey.

Map 2. The Kimmeridge Clay Formation at outcrop in Norfolk, Suffolk and Cambridgeshire. *Image courtesy British Geological Survey.*



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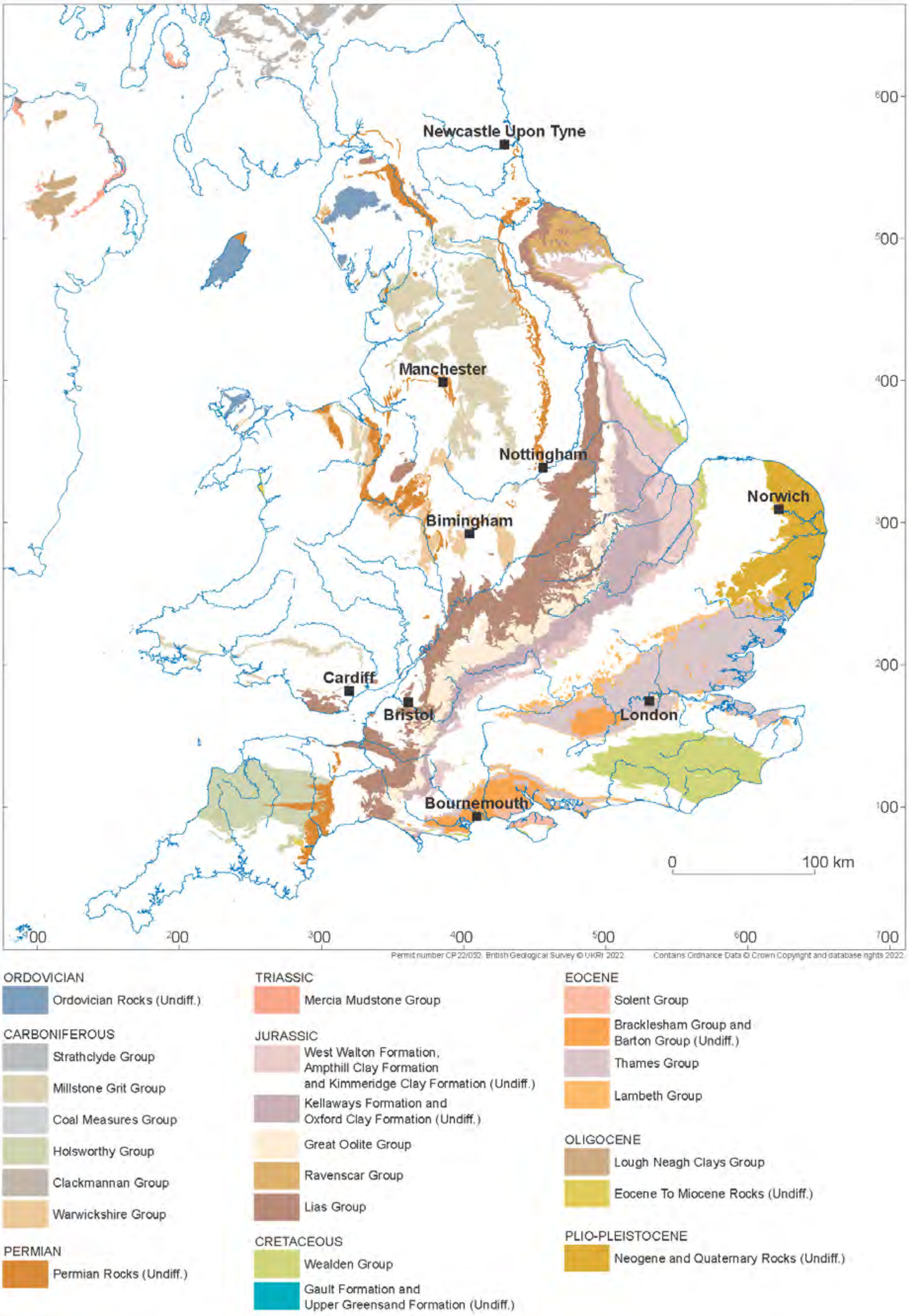
Map 4a – Bedrock formations used for sourcing clays. UK North. Image courtesy British Geological Survey.



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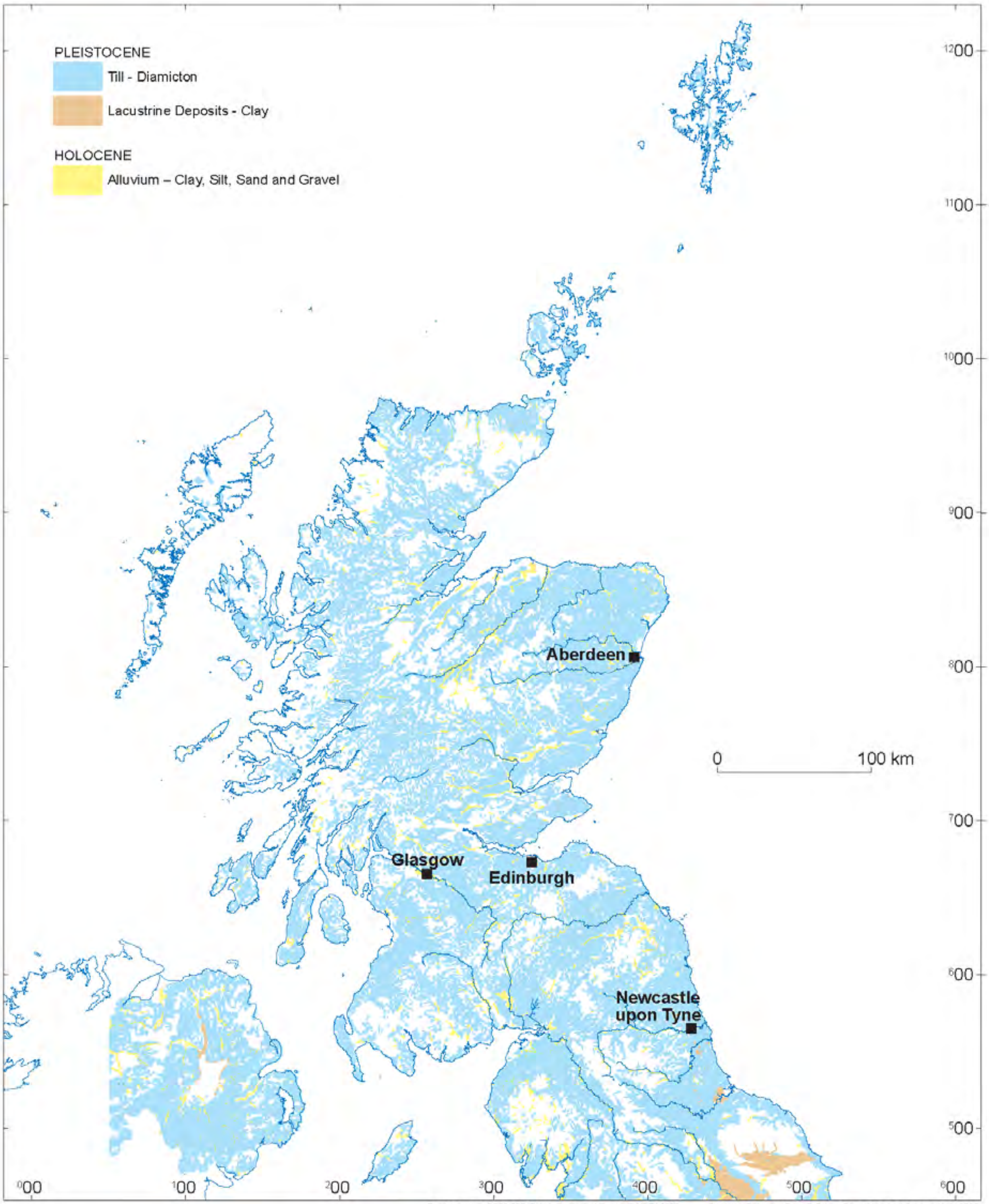
Map 4b – ditto. UK South. Image courtesy British Geological Survey.



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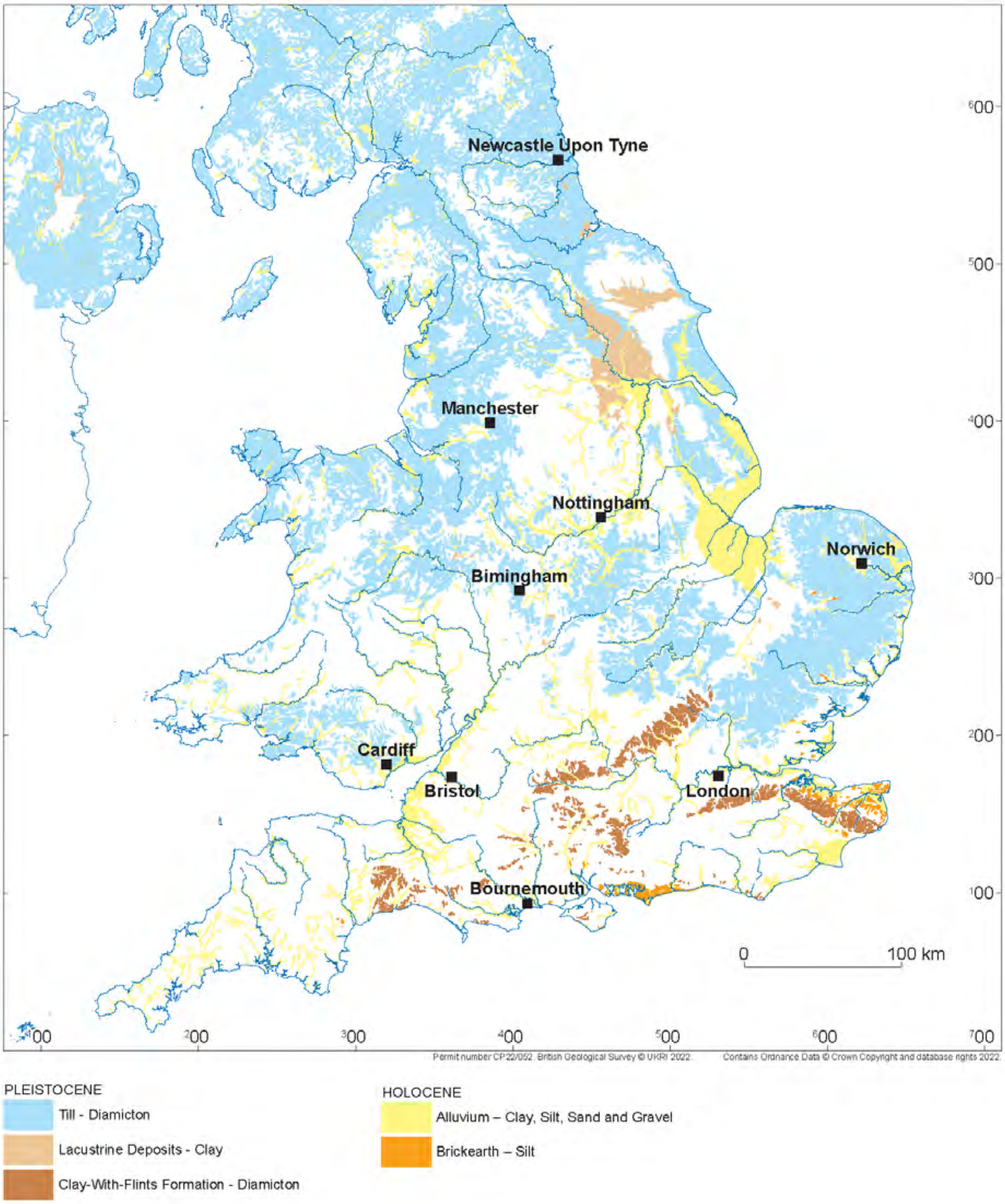
Map 5a – Superficial formations used for sourcing clays. UK North. Image courtesy British Geological Survey.



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Map 5b – ditto. UK South. Image courtesy British Geological Survey.

24.0 APPENDIX C – GEOLOGY REPORT APPENDIX

Examples of clay-rich geological materials suitable for making cob/bauge, drawn from historical and contemporary information about brick- and tile-making industries.

Regions and areas	Bedrock formations	Superficial deposits	References
South-west England	▪ Carboniferous Crackington Fm mudstones near Holsworthy and North Tawton ▪ China clay (kaolin) near St Austell and Shaugh Prior. ▪ Oligocene Bovey Fm clays near Bovey Tracey.	▪ Head deposits developed on a variety of bedrocks, including Devonian and Permian.	Edmonds et al, 1968, 1969; Geological Survey, 1920.
Isle of Wight	▪ Cretaceous Wealden Group shales near Sandown; Gault Fm clay near Shanklin. ▪ Eocene Hamstead Mbr clays (Bouldnor Fm) at West Medina.	▪ Pleistocene 'brickearths' at Carisbrooke and Bembridge.	Osborne White, 1921.
Bristol and Gloucester area	▪ Devonian mudstones of the Brownstones Formation at Mitcheldean. ▪ Carboniferous clays of the Trenchard Formation in the Forest of Dean. ▪ Carboniferous South Wales Lower and Middle Coal Measures clays at Almondsbury (Cattypool)	▪ River alluvium used to make 'bath bricks' near Bridgwater.	Green, 1992; Trotter, 1964;
Hampshire Basin and Dorset	▪ Jurassic Fullers Earth and Oxford Clay at Bridport. ▪ Cretaceous Wealden Clay at Swanage and Gault Clay at Shaftesbury. ▪ Eocene Reading Fm at Fareham; London Clay at Bursledon; Bracklesham Beds at Bitterne,	▪ Periglacial sandy loam at Southampton and Gosport. ▪ River alluvium of the R. Frome at Frampton and R. Stour at Blandford.	BGS, 2011; Smith, 2012; White, 1971.

	Bournemouth and Wareham; Headon Beds at Beaulieu.		
Sussex and Kent	▪ Cretaceous Wealden Group – Weald Clay Fm at Crowborough and Hamsey; Ashdown Fm siltstones at Warnham and clays at Fairlight; Wadhurst Clay Fm at Horam. ▪ Eocene Reading Fm at Epsom.	▪ Pleistocene brickearths at Alfriston and Sittingbourne. ▪ Holocene floodplain alluvium at Piddinghoe.	Beswick, 1993; Bloodworth et al, 2002; Gallois, 1965; Geological Survey, 1920; Lake et al 1987;
The London Basin	▪ Eocene Reading Fm at Chesham, Colliers End Ewell and Maidenhead; Claygate Member at Rettendon; London Clay Fm at Great Wakering and South Woodham Ferrers.	▪ Pleistocene lacustrine clays at Mark's Tey. ▪ Pleistocene river terrace silts / brickearths at North Shoebury and Rochford. ▪ Pleistocene loess at Great Wakering.	Lake et al, 1986; Geological Survey, 1920; Hopson et al, 1996; Mercer & Mercer,2022; Sumbler, 1996.
East Anglia	▪ Jurassic Kimmeridge Fm at Downham Market, Ely and Littleport. ▪ Cretaceous Snettisham Clay Mbr at Heacham; Gault Clay at Burwell. ▪ Pleistocene clays of the Norwich Crag at Chillesford, Rockland, Wattisfield and Wrentham. ▪ Pleistocene clays of the Happisburgh and Lowestoft formations at Norwich, Somerleyton and Woolpit.	▪ Chalky clays of the Lowestoft Formation for bricks at King's Lynn and Diss and clay lump at Hockwold and Tivetshall. ▪ Pleistocene lacustrine clays at Hoxne. ▪ Alluvial silty clays of the Breydon Formation at Burgh Castle and the Fenland Formation at Walsoken,	Arthurton et al, 1994; Bristow, 1990; Craven, 2006; Gallois, 1988; Gallois, 1994; Mathers et al, 1993; Moorlock et al, 2000; Tolley, 2011; Whitaker et al, 1893 Woodward, 1881; Worssam & Taylor, 1969.
South Midlands	▪ Jurassic Ampthill Clay Fm at Ampthill; Oxford Clay Fm at Fletton, Whittlesey, and Stewartby; Kimmeridge Clay	▪ Neogene clay-with-flints at Luton and Rableyheath.	Dodsworth, 1976; Hopson et al, 1996; Horton, 1989;

	Fm at Aylesbury, Cumnor, Stewkley and Swindon. ▪ Cretaceous Gault Clay at Arlesey.	▪ Pleistocene till at Stotfold and glacial lake deposits at Walkern. ▪ Holocene alluvial silts at Terrington.	Shepherd-Thorn et al, 1994; Sumbler, 1996.
Eastern England	▪ Triassic Mercia Mudstone Group at Bishop Wilton. ▪ Jurassic Middle Lias clays of the Charmouth Mudstone Fm at Lincoln. ▪ Middle Jurassic Blisworth Clay Fm in North Lincs. ▪ Upper Jurassic Kimmeridge Clay Fm at Fulletby and Market Rasen.	▪ “Thick deposits of boulder clay are actively worked in some localities”. ▪ Estuarine alluvium at Barton on Humber.	East Midlands Named Bricks, undated; Kent et al, 1980; Swinnerton & Kent, 1981.
Wales	▪ Ordovician shales of the Stone House Shale Fm at Buttington, Powys. ▪ Carboniferous Coal Measures shales at Llanelli, Pontypool, Port Talbot and Dowlais. ▪ Carboniferous Lower and Middle Coal Measures fireclays at Buckley, Trevor and Ruabon. ▪ Carboniferous mudstone of the Etruria Formation at Buckley, Flintshire.	▪ Colliery waste ▪ Glaci al till	Geological Survey, 1920; Howells, 2007; Jenkins, undated;
Central England and the Midlands	▪ Silurian Raglan Mudstone Fm at Ledbury. ▪ Carboniferous Middle Coal Measures fireclays at Benthall, Moira, Stourbridge and Swadlincote; pottery clays of the Etruria Fm at Stoke on Trent. ▪ Triassic Mercia Mudstone Group at Colwich, Desford, Ibstock and Arnold; mudstones of the Helsby Sandstone Fm at Measham; mudstones of the Bollin	▪ Pleistocene till of the Devensian glaciation at Longsight, Manchester and at Poynton, Stockport. ▪ Pleistocene glacial clays at Morrillow Heath. ▪ Pleistocene glaciolacustrine silts and clays at Long Waste.	Aitkenhead et al, 2002; Ford & Ambrose, 2014; Geological Survey, 1920; Hains & Horton, 1969 Manchester History, undated; Rees, 1998; Pocock et al, 1938; Stephenson & Mitchell, 1955; Worssam & Old, 1988;

	Mudstone Mbr at Warrington. ▪ Jurassic Rutland Fm at Stamford.		
Northern England and the Pennines	▪ Carboniferous Lower Coal Measures fireclays at Accrington, Shibden near Halifax and Wigan ▪ Carboniferous Lower and Middle Coal Measures clays at Swillington near Leeds; fireclays at West Hunwick and Crook, Co. Durham; laminated clays at Birtley near Gateshead. ▪ Permian Eden Shales Formation at Colehill near Carlisle.	▪ “Glacial till, laminated lacustrine lacustrine clays, alluvial and marine clays and silts” were used.	Aitkenhead et al. 2002; Edwards, 1950; Geological Survey, 1920; SRCA, undated; Stone, 2010.
Northern Ireland	▪ Permian Belfast Group clays at Annadale, Belfast. ▪ Triassic Mercia Mudstone Group at Limestone Road, Belfast.	▪ Glacial boulder clays at Aghadowey, Ardoyne, Killough and Irvinestown. ▪ Glacial lacustrine clays at Mullaghmore, near Agivey.	Department for Communities, 1976; Kitching, undated; Wilson, 1972;
Scotland	▪ Carboniferous fireclays of the Lawmuir Fm at Paisley. ▪ Carboniferous Millstone Grit fireclay horizons in the Midland Valley including Glenboig, Roughcastle and Saltcoats. ▪ Carboniferous Lower Coal Measures at Falkirk. ▪ Upper Jurassic shales at Brora, Sutherland.	▪ “Superficial deposits [were] worked in widespread areas of coastal Aberdenshire, Banffshire and Morayshire”, including boulder clay, glaciolacustrine deposits, raised marine deposits and alluvium.	Geological Survey, 1920; Stephenson & Gould, 1995;

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