Sustainable Sourcing and Innovative Use of Building Materials: Case Study of Energy Plus House, Hieron's Wood, Derbyshire UK

B. Ceranic, D. Latham, A. Dean

Abstract— In this paper research on sustainable sourcing and innovative use of building materials is explored, through the prism of a complex case study of real building project. In particular, a novel use of sycamore as a structural material is investigated and reported. This includes methods and standards of its grading and classification, service classes and resistance to decay, in addition to results of its laboratory and in situ testing. A research method of longitudinal study is adopted, concentrating on the monitoring and assessment of its structural performance and conditions in which it might deteriorate. The study comprised of extensive desktop research on the sycamore properties, its standards and classification, followed by laboratory testing of its mechanical properties, namely bending strength and compression parallel to grain. In addition, an experimental build with *half sycamore-half softwood* structural timber frame was designed and constructed and early monitoring and assessment results reported. Finally, the in situ testing on the main building was undertaken, including visual observations, measurements of moisture content and wood decay detection. The latter was undertaken using digital micro probe to identify potential *soft* wood and cavities in sycamore and determine the extent of problems. So far research has established that sycamore can be applied to the structural and constructional aspects of building design and assembly, as long as due attention is paid to its detailing and resistance to decay and insect attack, moisture control, ventilation provision and service class uses. However, it has to be noted that the research findings of this project cannot be statistically extrapolated to a broader geographical extents, due to the locality of sycamore sourcing limited to within the site boundaries.

Keywords— sustainable design, sycamore, decay, structural performance monitoring, assessment, case study.

I. Introduction

Acer Pseudoplanatus, commonly recognised in the UK as sycamore, is a naturalised but not native hardwood tree in British Isles. It is a deciduous tree with broad leaves, capable of germination and growth under most conditions. It grows copiously, often where not needed, considered by some as an invasive and referred to as a ”weed” of the woodland. It can grow to a height of up to 35m creating a broad crown, whose shade prevents other trees from germinating and creates a reason for its success in occupying large areas of woodlands, thus impacting its biodiversity. Furthermore, sycamore has a low ecological count and supports a very small variety of insect life, thereby attracting few birds and little other wildlife. As stated by [1], sycamore ecological count is less than 25, whilst for example oak has around 400. It thus supports a very few species and its planned but regular harvesting could generate space for other species to grow, improving the biodiversity of woodlands.

Today, sycamore can be found in 3,461 (89.7%) of hectads in Britain, more than any native tree species [2], [3]. It is considered invasive in environmentally sensitive locations in the United Kingdom with active woodland management policies in place limiting its proliferation, although there are opinions that its reputation as an aggressive proliferation tree with a low conservation value is not altogether correct [4].

In the UK, sycamore is not approved for structural use due to its perishable nature and its predisposition to the rot and insect attack [5]. Nevertheless, its structural and constructional potential considering its mechanical properties is comparable to most structural softwood and hardwood species, as stated in the literature and established through consultation with the Timber Research and Development Association (TRADA), [6]. Research into suitable methods and treatments for its structural and constructional application could pave the way for sycamore to be specified more readily on building projects as a novel and sustainable source, thus supplementing current timber supplies, majority of which are currently imported [7].

II. Case Study - Energy Plus House, Hieron's Wood, UK

Hieron’s Wood is a four bedroomed dwelling, presently being constructed in the garden of an existing 1920’s house, set in a former quarry and situated on the edge of the sustainable village settlement of Little Eaton, Derbyshire (see Fig. 1). The design concept was to produce a building related to its physical, historical and visual site context, adopting its character through a careful selection and use of materials and imposing a very low visual and environmental imprint on the site.

B. Ceranic is Senior Lecturer and Assistant Head of Department at the University of Derby, Derby, UK (corresponding author; phone: +441332 593136; e-mail: b.ceranic@derby.ac.uk).

D. Latham is an Architect, Urban Designer, Masterplanner and Landscape Architect, Honorary Professor (e-mail: derek@dereklatham.co.uk).

A. Dean is Head of Department at the University of Derby, Derby, UK (e-mail: a.m.dean@derby.ac.uk).

The project offers an exceptional opportunity to carry out long term research in three key areas; innovative use of materials and technology; detail design and construction; BIM enabled smart building performance monitoring of energy consumption, embodied carbons and health and wellbeing [7].

Fig. 1. Aerial View - Site Location;

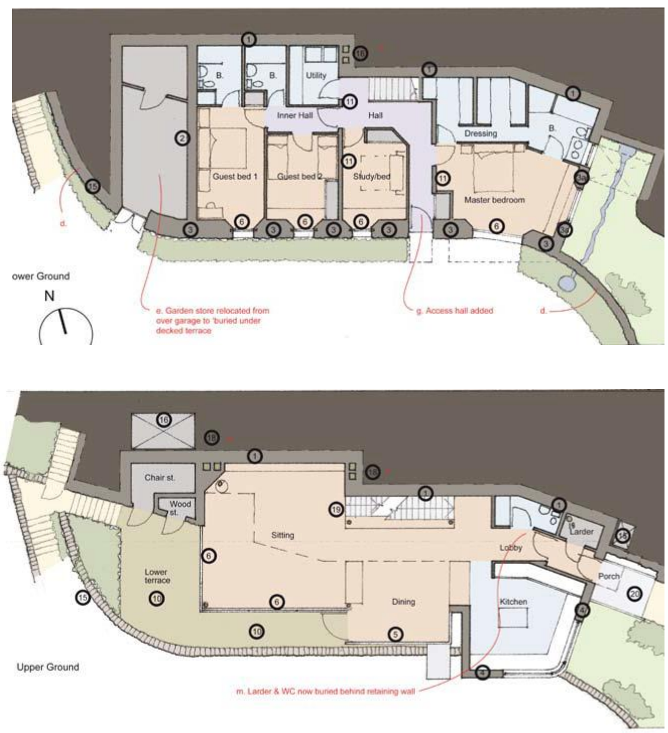


Fig. 2. (a) Lower Ground Floor ; (b) Upper Ground Floor

The proposed house is comprised of (see Fig. 2. a,b):

- Lower ground floor encompassing an ensuite master bedroom, two ensuite guest bedrooms and a bed/study room; lower entrance hall, utility and a garden store with external access.
- Upper ground floor with an open living/dining/ kitchen area, larder, cloakroom/wc and entrance hall.
- A mezzanine open study balcony incorporated within the upper living and dining area.
- A main staircase link between the upper and lower ground floors and a light, glass stair for accessing the mezzanine level.

Fig. 3 a,b show the recent progress of the build which currently is water tight and with the first fix completed.

Fig. 3. (a) Site build progress - March 2016

Fig. 3. (b) Sycamore Flitch Beam Fix - November 2015

Initial energy design calculations were based on eleven different scenarios, estimating that the dwelling will be capable of generating more renewable energy than it will need to consume, thus becoming both an *energy plus* and *carbon negative*, as demonstrated from the calculations in the Table I, scenarios 5-11.

Table I. Energy Demand, PV Generation and CO_2 emissions estimates (Scenarios 1 - 11)

Scenario	1	2	3	4	5
Heating demand [kWh/annum]	13389.0	13389.0	12103.0	12103.0	11778.0
Solar gains [kWh/annum]	0.0				
Internal gains [kWh/annum]	0.0	500.0	500.0	500.0	1500.0
Flow temperature [˚C]	40.0	40.0	35.0	35.0	35.0
Electricity for heating [kWh/annum]	3648.2	3512.0	2967.5	2967.5	2628.6
DHW demand [kWh/annum]	2585.0	2585.0	2010.0	2010.0	2010.0
Electricity for DHW [kWh/annum]	982.9	982.9	764.3	764.3	764.3
Electricity applicances & misc [kWh/annum]	3300.0	3050.0	2800.0	2550.0	2300.0
PV power generation [kWh/annum]	6092.7	6092.7	6092.7	6092.7	6092.7
Overall [kWh/annum]	1838.4	1452.1	439.0	189.0	-399.8
CO2 emissions [kg/annum]	964.4	761.8	230.3	99.2	-209.8

Scenario	6	7	8	9	10
Heating demand [kWh/annum]	11778.0	9266.0	9266.0	8451.0	8451.0
Solar gains [kWh/annum]					
Internal gains [kWh/annum]	1500.0	1500.0	3000.0	3000.0	3000.0
Flow temperature [˚C]	35.0	35.0	35.0	35.0	35.0
Electricity for heating [kWh/annum]	2628.6	1986.2	1602.6	1394.1	1394.1
DHW demand [kWh/annum]	2010.0	2010.0	2010.0	1800.0	1800.0
Electricity for DHW [kWh/annum]	764.3	764.3	764.3	684.4	684.4
Electricity applicances & misc [kWh/annum]	2050.0	1800.0	1700.0	1600.0	1500.0
PV power generation [kWh/annum]	6092.7	6092.7	6092.7	6092.7	6092.7
Overall [kWh/annum]	-649.8	-1542.3	-2025.9	-2414.2	-2514.2
CO2 emissions [kg/annum]	-340.9	-809.1	-1062.8	-1266.5	-1319.0

The design exemplifies the *fabric first* principles, proposing a highly insulated but breathable wall construction. The dry stone walling and sycamore are both sourced from the former quarry situated within the site compounds, facilitating the house to *blend in* with its surroundings (see Fig. 4).

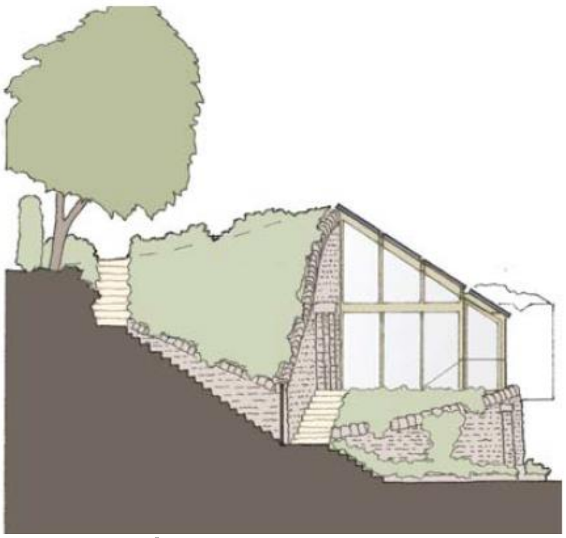


Fig. 4. West Elevation

The house benefits from the site's sloping southerly aspect using its perfect orientation to maximise PV energy generation. Building design utilises both proven and novel *green* technologies alongside passive energy saving measures, such as *upside down* design, zoning, solar gains, natural light, solar shading, high thermal mass, earth embankment on the northern side, passive stack, natural ventilation and earth tube as a passive earth to air heat exchange device (see Fig. 5).

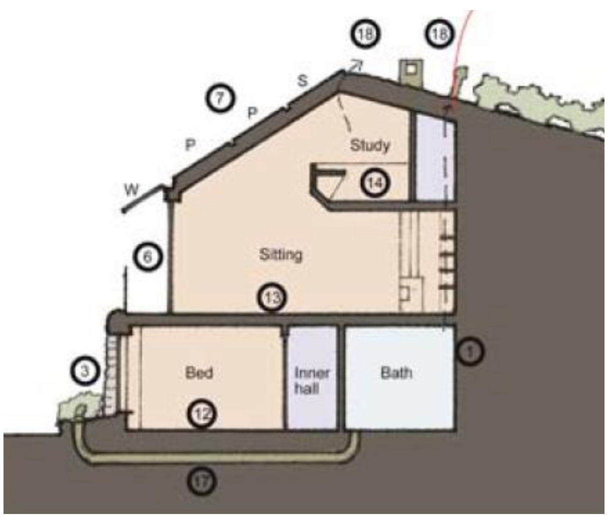


Fig. 5. Cross Section with the Earth Tube

III. Research Methodology

The fundamental reason for choosing a case study approach was to establish a longitudinal study through the prism of a complex and innovative real word project. This enables a detailed assessment of its novel aspects, including sycamore structural performance, within the framework of overall sustainable design and its integration with BIM and building performance monitoring [7]. Simons [8] explains the reasoning behind choice of a case study as a valid research method, stating that: "A case study is an in-depth exploration from multiple perspectives of the complexity and uniqueness of a particular project, policy, institution, programme or system in *real life* context. It is research based, inclusive of different methods and is evidence-led. The primary purpose is to generate in depth understanding of a specific topic".

To ascertain a concise realisation of the research project a single-case study holistic design method has been chosen. Yin [10] states that the holistic design approach is beneficial when the theory pertinent to the case study itself is of a holistic nature or where no logical sub-units can be identified. However, he further asserts the importance of access to the real world data stating that otherwise the case study may be an overly abstract, with a lack of suitably clear measures or data.

IV. Structural Use of Sycamore

Timber used structurally is strength graded either with machines (as is typical for most commercially produced softwoods) or by visual grading rules (as is typical for hardwood timbers). The Fig. 6 below shows sequence of actions required to determine hardwood structural design values, as per Eurocode 5: Design of timber structures [9].

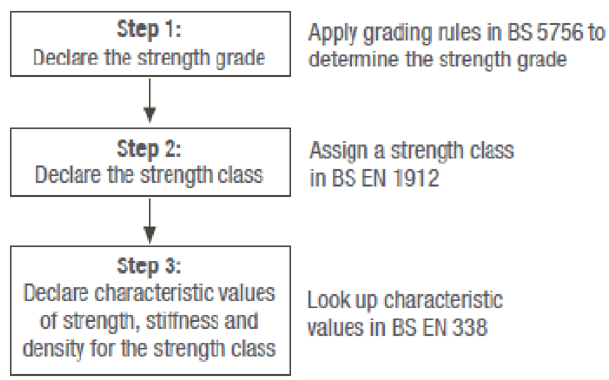


Fig. 6. Determination of Structural Design Values [9]

BS EN 5756 [10] states "a method of strength grading of tropical and temperate hardwood visually for structural use. For tropical hardwoods, the permissible limits of characteristics for a single visual strength grade of timber are specified, designated *Structural Tropical Hardwood* (HS) grade. For temperate hardwoods, the permissible limits of characteristics are specified for two visual strength grades for large size timber, designated *Heavy Structural Temperate Hardwood* (THA and THB), and two visual strength grades for smaller size timber, designated *General Structural Temperate Hardwood* (TH1 and TH2)."

There are a number of visual grading rules for hardwoods listed in BS EN 5756 but this standard does not cover sycamore. However, related to Step 2, the BS EN 1912:2012 Structural timber strength classes– assignment of visual grades and species [11], does list a German Standard DIN 4074 Teil 5 that gives grading rules for 'maple', but its botanical reference of 75 in Annex A refers to Acer pseudoplanatus. Also, according to TRADA the LS10 grading in Table II is comparable to the UK grading of TH1. It is considered that English sycamore should not differ significantly from the German sycamore (maple), given that they are the same species and that there are no large differences in climate, altitude or soil types. Hence, it is reasonable to use similar species data, as given by German standards, and provisionally allocate strength class of D30, as per Table II.

Table II. Assignment of visual grades and species [12]

D35	France	HS ST1	Jaboty	French Guyana	139	
	Germany	LS 10 and better; LS10K and better	Beech	Germany	119	
	UK	TH1	American white ash	USA	130	
D30	Germany	LS10 and better, LS10K and better	Oak	Germany	122, 123	
		LS10 and better	Maple	Germany	75	
		LS10K and better				
D 24	The Netherlands	C3 STH	Basralocus	Suriname	137	
	Italy	S	Sweet Chestnut	Italy	79	Maximum thickness 100 mm

NOTE The grades listed in this table are specified in the grading standards given in Annex A.

Once strength class has been allocated, the characteristic strength and stiffness values required for the structural calculations can be taken from BS EN 338:2009 Structural timber — Strength classes [12]. However, to account for possible small variation in timber quality between German and English sycamore, the mechanical properties used in the structural design for this project have been assumed to be reduced by 15% from D30 strength class properties given in the BS EN 338 above.

V. SERVICE CLASSES AND RESISTANCE TO DECAY

In terms of its grading, timber can be visually graded as either *dry graded* or *wet graded* [13]. *Dry graded* is when the "fissures and distortion of a batch of timber are assessed once the batch has an average moisture content of 20% or less, with no reading exceeding 24% moisture content." *Wet graded* applies when there are difficulties in drying timber, i.e. with thickness of 100 mm or more, or for specification in contact with water or conditions that lead to timber moisture content exceeding 20% (corresponding to Service Class 3, as defined in BS 5268-2 and EN 1995-1-1, see Table III).

Wood absorbs or shed moisture until it reaches an equilibrium with its surroundings, and this is a key aspect to be considered in terms of its service classes and constructional use. According to [13], the key benefits of drying timber could be summarised as follows:

- preventing excessive shrinking post installation
- maximising timber strength
- reducing fungal decay susceptibility
- easier handling (green timber is heavier)
- increasing effectiveness of treatment by the preservatives (most specify requirement for reduced moisture content)
- effective gluing, painting, staining, filling and polishing
- preventing the metal fixings corrosion
- meeting structural timber legislation

Therefore the sycamore should ideally be installed with the moisture content as close as possible to its in-service conditions, as per Table III classification. It is worth pointing out that the structural application of the sycamore in Hierons Wood project is in service classes 1 and 2 and hence expected to maintain less than 20% moisture content. As such, it is unlikely to be susceptible to a substantial fungal decay [13].

Table III. Service Classes and Moisture Content [13]

Service Class	Examples of use in building	Typical upper moisture content in service
1	Warm roofs Intermediate floors Timber-frame walls, internal and party walls	12%
2	Cold roofs Ground floors Timber-frame walls, external walls External uses protected from direct wetting	20%
3	External uses, fully exposed	>20%

According to the Building Research Establishment (BRE), the resistance to fungal decay is the main criterion for assessing durability. The durability classes according to BS EN 350-1 as well as BRE classes are given in Table III below and are based on the performance of stakes driven into the soil and subjected to continuous ground contact for many years. Based on this classification sycamore is deemed as Class 5, i.e. non durable (or perishable).

Table III. Durability classes [13]

BS EN 350 Durability classes		BRE classes	
Class	Description	Description	Approx life of 50×50mm stakes in ground
1	Very durable	Very durable	More than 25 years
2	Durable	Durable	15 - 25 years
3	Moderately durable	Moderately durable	10 - 15 years
4	Slightly durable	Non durable	5 - 10 years
5	Not durable	Perishable	Less than 5 years

However, this experimentation is conducted in conditions much more severe than is likely to occur in modern building construction and certainly for structural use of sycamore in the Hierons Wood project.

VI. Mechanical Properties Testing

Although hardwoods are visually graded in practice [11], after consultation with TRADA it was decided in addition to test its mechanical properties, as per BS EN 408 [14]; namely local modulus of elasticity, bending and compression strength. The density and moisture content of sample specimens were also recorded. Whilst the beam testing facilities at the University are not certified for a commercial machine grading, they did enable for accurate testing to be undertaken, with the results for compression test shown in Fig. 7 and Table IV and for bending tests in Fig. 8 and Table V.

The results below are part of an initial phase of mechanical properties testing related to the bending and compression strength tests, as per BS EN 408:2010 requirements, undertaken on a 10 randomly chosen solid sycamore samples. Next phase will include the repetition of the same mechanical properties tests for laminated sycamore (at least 10 samples).

Table IV. Compression Test Results

Sample 50x50x300 (mm)	Density (kg/m³)	Moisture Content (%)	Compression strength ll to grain (N/mm²)
1	566.8	14%	33.1
2	572.3	14%	37.3
3	582.8	14%	38.6
4	585.9	14%	41.3
5	591.2	14%	42.1
6	587.4	14%	39.9
7	580.3	14%	38.8
8	577.4	14%	37.9
9	590.2	14%	41.3
10	578.6	14%	38.4
Avg	**581.3**	**14%**	**38.9**
SD	7.8	0.00	2.6

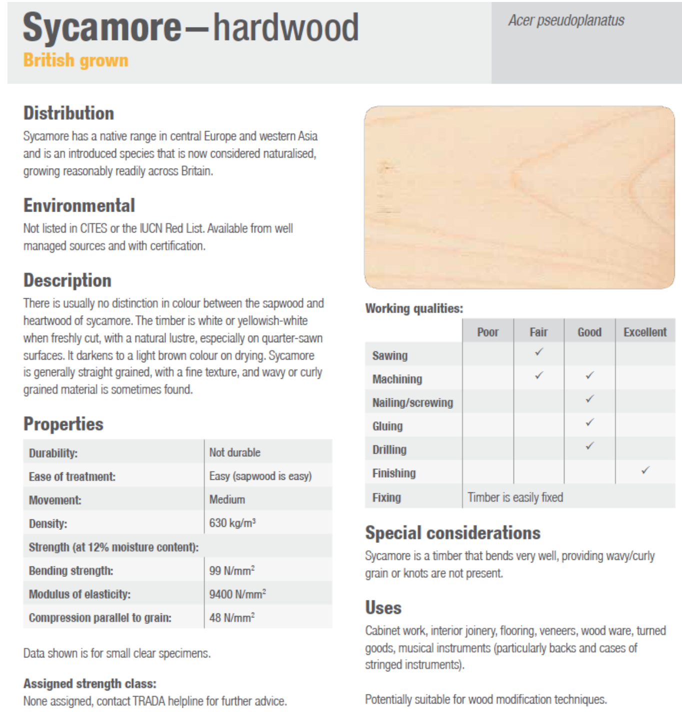
Fig. 7. Compression strength test (Source: Author)

Table V. Bending Strength Test Results

Sample 50x50x1000 (mm)	Density (kg/m³)	Moisture Content (%)	Local Modulus of Elasticity (N/mm²)	Bending Strength ll to grain (N/mm²)
1	566.8	14%	9785	123.7
2	582.8	14%	9677	96.9
3	571.2	14%	9406	96.7
4	575.6	14%	9529	108.6
5	583.9	14%	9590	91.5
6	575.2	14%	9350	92.6
7	578.3	14%	9370	93.7
8	585.5	14%	9610	97.5
9	579.1	14%	9512	98.6
10	580.2	14%	9570	99.2
Avg	**577.9**	**14%**	**9540**	**99.9**
SD	5.8	0	137.8	9.6

Fig. 8. Bending strength test (Source: Author)

Although the size of sample is relatively small and the sycamore was sourced within the narrow confines of the site, the test results are comparable to the published data such as TRADA, with sycamore bending strength reported to be 99 N/mm^2, modulus of elasticity 9400 N/mm^2, density 630 kg/m^3 and compression parallel to grain 48 N/mm^2, see Fig. 9 [6].



Sycamore – hardwood
British grown
Acer pseudoplanatus

Distribution
Sycamore has a native range in central Europe and western Asia and is an introduced species that is now considered naturalised, growing reasonably readily across Britain.

Environmental
Not listed in CITES or the IUCN Red List. Available from well managed sources and with certification.

Description
There is usually no distinction in colour between the sapwood and heartwood of sycamore. The timber is white or yellowish-white when freshly cut, with a natural lustre, especially on quarter-sawn surfaces. It darkens to a light brown colour on drying. Sycamore is generally straight grained, with a fine texture, and wavy or curly grained material is sometimes found.

Properties

Durability:	Not durable
Ease of treatment:	Easy (sapwood is easy)
Movement:	Medium
Density:	630 kg/m³
Strength (at 12% moisture content):	
Bending strength:	99 N/mm²
Modulus of elasticity:	9400 N/mm²
Compression parallel to grain:	48 N/mm²

Data shown is for small clear specimens.

Assigned strength class:
None assigned, contact TRADA helpline for further advice.

Working qualities:

	Poor	Fair	Good	Excellent
Sawing		✓		
Machining		✓	✓	
Nailing/screwing			✓	
Gluing			✓	
Drilling			✓	
Finishing				✓
Fixing	Timber is easily fixed			

Special considerations
Sycamore is a timber that bends very well, providing wavy/curly grain or knots are not present.

Uses
Cabinet work, interior joinery, flooring, veneers, wood ware, turned goods, musical instruments (particularly backs and cases of stringed instruments).

Potentially suitable for wood modification techniques.

Fig. 9. Sycamore TRADA Data Sheet [6]

VII. Performance Monitoring and in Situ Measurements

The strategy for performance monitoring included designing and constructing an experimental build at the Hill Holt Wood, Lincoln. The structural frame for this small scale timber building was made of half sycamore and half softwood timber, with hempcrete infill insulation, forming a wall thickness of 450mm (see Fig. 10). No preservative were used for this construction and an oriented strand board (OSB) formed the initial shuttering for the wall construction. After the hempcrete setting period the OSB board was *struck off* from the exterior side of the wall (see Fig, 11), which was later finished with lime render. However, the OSB board was kept on the interior side of the external wall and painted with a non-breathable paint.

Fig. 10. Hemp wall construction 450mm, with *half sycamore half softwood* structural timber frame within

Fig. 11. OSB board struck off at the exterior face of the wall, ready to receive lime rendering

The Ethernet manager and sensors for wireless monitoring of temperature, relative humidity and moisture content were installed and monitored remotely. The Fig.12 below shows the temperature and moisture content reading of a NW sycamore corner post in a typical week, giving a concern regarding its high moisture (> 20%), which persisted over a period of time, regardless of the weather conditions. The conclusion was that retaining the non-breathable OSB board on the interior side of the external wall has limited moisture movement through the wall, as the hempcrete passes through its intermittent periods of wetting and drying. It thus kept sycamore in unnecessarily high humid conditions for prolonged periods of time.

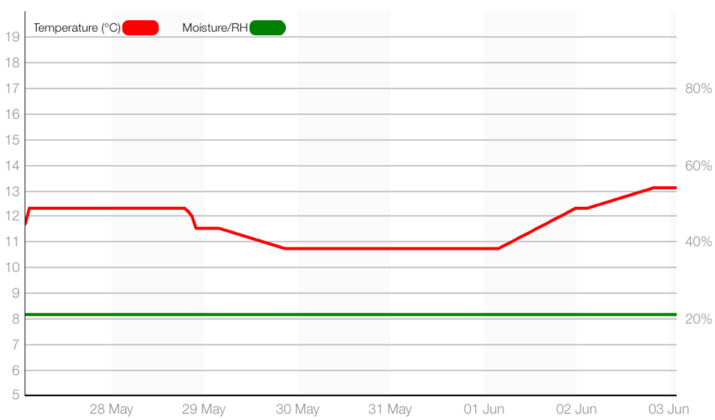


Fig. 12. Temperature and moisture content reading of NW sycamore corner post, 28 May-03 June 2015

The lesson learnt for the main build was to provide for a construction free of any materials that could limit the *breathability* of the wall, with the application of a breathable vapour barrier on the outer face of the hemp. Thus the construction of the external wall, from outside in, is composed of 150mm dry stone walling (with a partial bed of lime mortar for stability but with random air gaps), 10mm air gap, 450mm hempcrete infill with 150x100mm sycamore frame and lime render on the inside (see Fig 13). It provides for uninterrupted moisture movement as the hempcrete goes through its intermittent periods of wetting and drying.

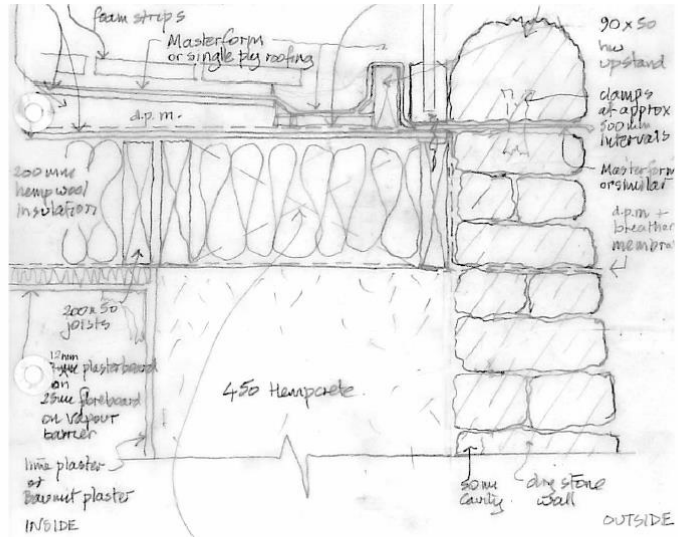


Fig. 13. Construction detail of exterior wall, including balcony decking, gutter and balustrade

Regarding the main building, a long term performance monitoring (at least five years) of the Hierons Wood development is proposed [15].

The performance strategy shown in Fig. 15 will include regular testing of the moisture content, condition and integrity of the sycamore structural frame, including measuring the temperature and relative humidity of its immediate environment. A digital micro probe (DmP) has been used to detect and analyse wood decay [16], see Fig 14. Cavities or *soft* wood generated as a result of decay are detected by the DmP as an abrupt decrease in the penetration resistance. This resistance to penetration is then recorded graphically and digitally, to a high level of accuracy.

Fig. 14. Digital Microprobe

The monitoring parameters for earth tube system are humidity, temperature, CO_2 and VOCs in relation to air quality, but also monitoring of air speed and the pressure [17]. The performance monitoring of hempcrete encompasses temperature, relative humidity and water vapour transfer rate; including gSKIN U-Value equipment for measurement of heat flux and dynamic changes of U-values, as the hempcrete goes through its weather dependent periods of change in regards to the moisture content.

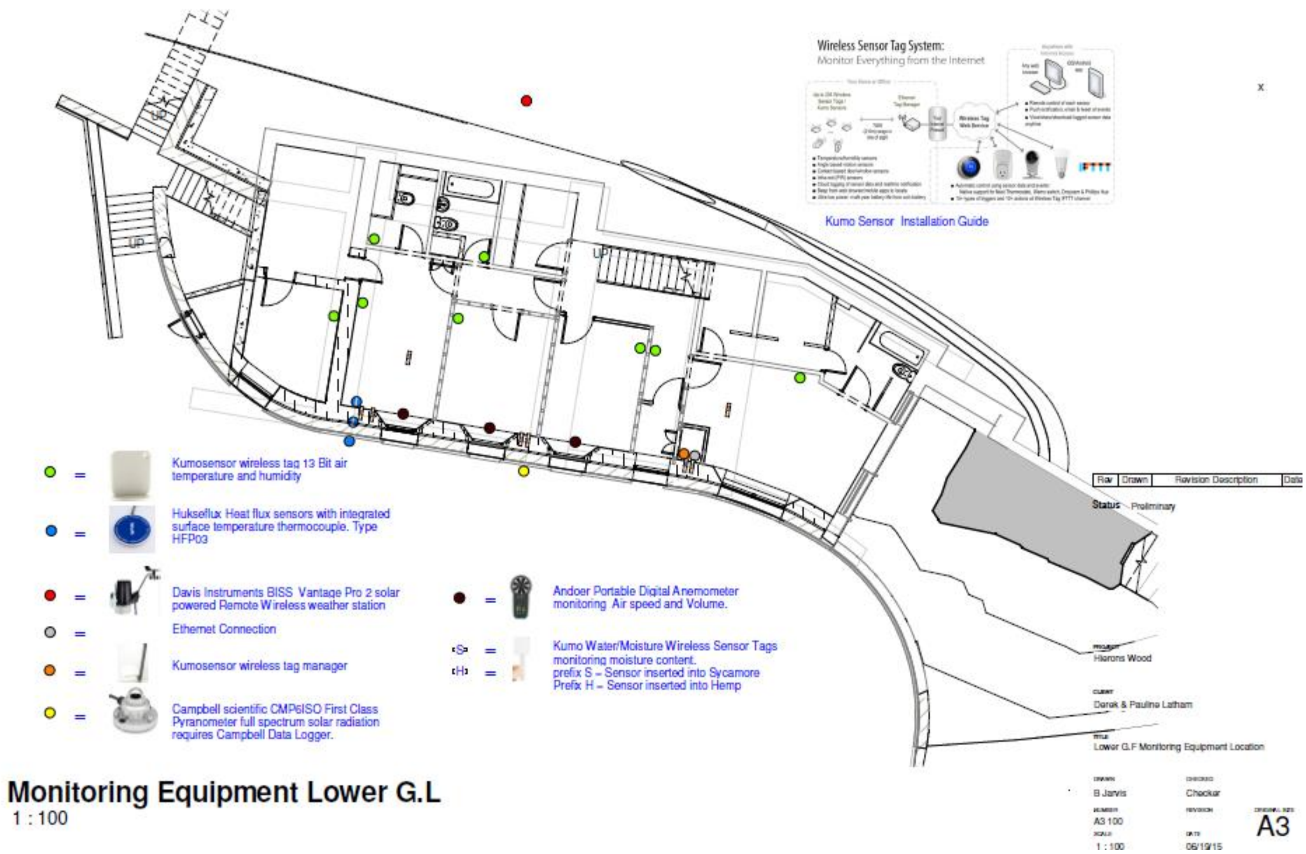


Fig. 15. Building Performance Monitoring Strategy – Lower Ground Floor

The initial sycamore moisture content measurements in situ have started, with the readings for characteristic *weak* points of construction recorded and shown in Table VI.

Table VI. Sycamore Moisture Content Measurements In situ

SYCAMORE MOISTURE CONTENT MEASUREMENTS INSITU	
DATE	19.04.16 T=15^{0}C RH=60%
Position	moisture content (%)
master bedroom stud	12.2%
master bedroom sole plate	16.3%
GF entrance lobby stud	14.5%
GF entrance lobby sole plate	15.3%
GF plant room stud	12.0%
GF plant room sole plate	12.3%
FF west side column to flitch beam	9.5%
FF south side column to balcony door	9.9%
FF west side sycamore floor joist	8.7%

It is noted that whilst all timber is within its service class 1 and 2 limits (see Table III), there is a significant variation in its moisture content depending on its location. In particular and as expected, there is a notable difference between the moisture content of the sycamore within the hempcrete lower ground external wall construction (ranging from 12% to 16.3% - see Fig. 16) in comparison to the upper ground internally exposed sycamore (ranging from 8.7% to 9.9% - see Fig.17).

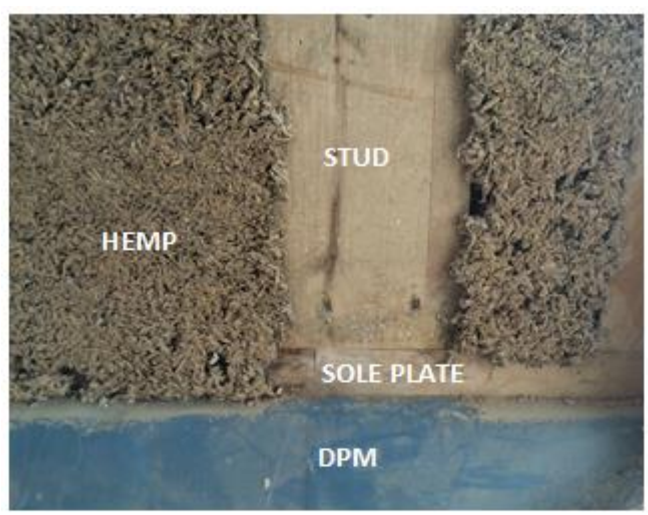


Fig. 16. Master Bedroom Stud and Sole Plate Junction

Given that all sycamore was kiln dried prior to construction to 14% MC, it is evident that its location impacts on its moisture content variations.

Fig. 17. Flitch Beam – Upper Ground Floor MC =9.5%

The final and ultimate test of sycamore performance is the rate of decay of sycamore, in particular related to *weak* spots on the junctions between the studs and base plate in the external hemcrete wall. Fig. 18 below shows the *hardness* of master bedroom stud and base plate, measured in the number of rotations required by DmP probe to penetrate every 0.1mm. Whilst there are no abrupt decreases in the penetration resistance between the stud and base plate, the latter has some *soft* wood between 10 and 30mm depth, with a potential cavity discovered between 80 and 90 mm. This, as well as other junctions reported in the Table VI, will be further monitored on a monthly basis.

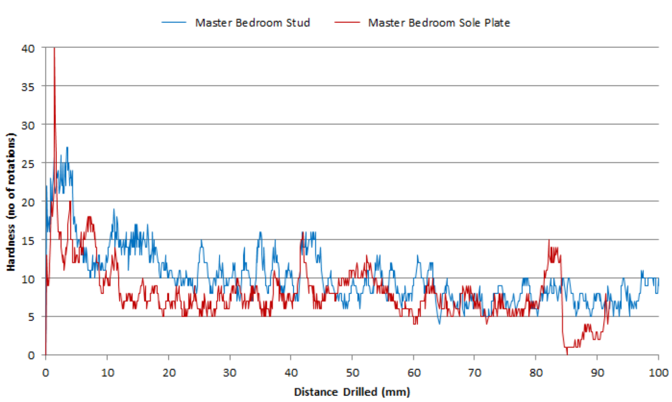


Fig. 18. Master Bedroom Stud and Sole Plate Hardness

VIII. CONCLUSIONS AND FURTHER RESEARCH

In the Hierons Wood project sycamore will only be structurally used in the service classes 1 and 2. This, in conjunction with the *first line* of defence through a high quality construction detailing and workmanship on the site, including the use of natural preservatives as a *second line* of defence, should protect sycamore against perishability.

The key findings are summarised below as follows:

- The assignment of visual grades and species in the BS EN 1912:2012 lists a German Standard DIN 4074 Teil 5 which gives grading rules for Acer Pseudoplanatus, ordinarily referred to in the UK as sycamore.
- The mechanical properties of sycamore used within the project have been tested and proven to be comparable to published data, albeit on a small sample of solid wood specimens.
- It is essential to keep sycamore maintained at a moisture content of less than 20%, thus making it significantly less likely to be susceptible to a substantial fungal decay.
- The extensive desktop research and testing thus far has established that the sycamore can indeed be used for the structural and constructional applications, as long as due care is taken in regards to its detailing and resistance to decay and insect attack, moisture control, ventilation provision and service class uses.
- The breathability of walls has to be protected to ensure an unhibited moisture movement and thus prevent sycamore to being exposed to prolonged periods of high humidity within its immediate surroundings.
- Evidence of potential rate of decay and local issues with the moisture content and *hardness* of timber can still be encountered, in particular in *weak* areas on the junctions between the studs and base plate. It is important that their moisture content and *hardness* is measured regularly.

Furthermore, similar to other timbers, sycamore is a natural material and its property testing results can often differ significantly between individual specimens. Hence, due to the relatively small sample size and narrow locality of its sourcing the results of this research cannot be statistically extrapolated for other building applications. The above however was expected, given the bespoke nature of Hierons Wood case study and it does not undermine the importance of this project serving a useful learning precedent with the lessons of a "one off" innovative design case study. The building has evolved from a unique design concept, including a sustainable approach and site conditions, with design and build undertaken by a dedicated team of practitioners and researches. The aim of producing a contextually sensitive *energy plus*, *carbon negative* and *autonomous* house was agreed at the early inception stage, including local materials sourcing, breathable wall constructions and maximising passive design approaches. The usual limitations imposed by restricted budgets have been avoided by the fact that the owner and client was also the project architect.

ACKNOWLEDGMENT

Price & Myers - Structural Engineers, ARUP – Building Services Consultancy, Derek Latham – Architect and Home Owner.

REFERENCES

[1] T.R.E. Southwood 'The Number of Species of Inspect associated with various trees', *Journal of Animal Ecology*, 1961, 30:1-8

[2] C.A. Stace, and M.J. Crawley, *Alien Plants*, London: Harper Collins, 2015

[3] *BSBI Distribution map Acer Pseudoplatanus*, Botanical Society of Britain and Ireland (BSBI).[Online] http://bsbidb.org.uk/maps/?taxonid=2cd4p9h.etk

[4] M. Townsend, Sycamore - Acer pseudoplatanus, Birchanger Wood Trust, [Online] http://www.birchangerwoodtrust.org/sycamore-paper-ext-version.pdf

[5] BS EN 350:1994, Durability of wood and wood-based products, *BSI Copyright* 2013

[6] TRADA, 'Specifying British-grown timbers', WIS 2/3-67, *TRADA Technology Ltd*. 2013

[7] B. Ceranic, D. Latham and A. Dean, Sustainable Design and Building Information Modelling: Case Study of Hieron's Wood, Derbyshire, UK', *Proc. of International Conference on Sustainability and Energy in Buildings* 2015, SEB- 2015, 1 - 3 July, 2015, Lisbon, Portugal

[8] H. Simons, *Case Study Research in Practice*, pp. 21-25, Sage Publ. Ltd 2009

[9] Eurocode 5: *Design of timber structures*, 2008

[10] BS 5756:2007 +A1 2011, *Visual strength grading of hardwood,* BSI Copyright 2013

[11] BS EN 1912:2012, *Structural Timber Strength Classes — Assignment of visual grades and species*, BSI Copyright 2013

[12] BS EN 338:2009 *Structural timber -Strength classes*, BSI Copyright 2013

[13] TRADA, 'Structural use of hardwoods', WIS 1-17, TRADA Technology Ltd. 2013

[14] BS EN 408:2010+A1:2012, *Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties*, BSI Copyright 2013

[15] P. Tse and M. Colmer, Building Performance Evaluation: Overview of Programme Portfolio, 2014, *Innovate UK* https://connect.innovateuk.org/documents/3270542/19792080/BPE_Overview%20of%20the%20programme%20portfolio_Nov%202014

[16]SIBTEC DmP, http://www.sibtec.com/digitalmicroprobe.html, [last accessed March 2015]

[17] Lee, K. & Strand, R., The cooling and heating potential of an earth tube system in buildings. *Energy and Buildings*, 2008, Vol 40, pp. 486