Reducing the Environmental Impact of Construction by Using Renewable Materials

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ABSTRACT: The relative importance of embodied energy and operational energy on the environmental impact of construction are examined in this article. It highlights the fact that the targets set by the Kyoto Protocol are primarily being met by the reduction of in-use energy, and that the implications of that are that the energy embodied in buildings will increase in significance from its current 17% level to 50% by 2050. The article describes how the use of bio-based renewable materials can make a significant contribution to reducing not only the embodied energy of buildings by using the sequestration of CO_2 through photosynthesis, but also in-use energy demand through passive environmental control. Case studies are presented showing ways in which this has been achieved.

KEYWORDS: Bio-based materials, vapour-active materials, embodied energy, transient thermal performance, hemp-lime, straw bale, carbon sequestration, life-cycle assessment, environmental impact

1 INTRODUCTION

In 1979, in response to gathering evidence of anthropogenic climate change, the first World Climate Conference (WCC) took place. The Intergovernmental Panel on Climate Change (IPCC) was set up in 1988, and in 1990 the United Nations called for a global treaty on climate change. The United Nations Framework Convention on Climate Change (UNFCCC) came into force in 1994, and in 1997 the Kyoto Protocol (KP) was adopted. The KP is designed to put the UNFCCC into operation through a series of reporting and verification procedures; flexible market-based mechanisms, which have their own governance procedures; and a compliance system. The KP sets binding emission targets for 37 industrialised countries. In the first commitment period from 2008 to 2012 these targets added up to an average five percent emission reduction compared with 1990 levels. At Doha, Qatar, on 8 December 2012 the Doha Amendment was adopted, launching the second commitment period from 2013 to 2020.

Globally, buildings are responsible for more than 40% of global energy consumption and as much as 33% of carbon dioxide equivalent emissions (CO_2e) [1], which amounts to about 8.1 Gt annually [2]. This IEA baseline scenario for the building sector in 2050 predicts global emissions of 15.2 Gt annually without any corrective action, but identifies potential reductions of as much as 12.6 Gt through adoption of their proposed ‘Blue Map’ strategies, driven by aggressive policy action.

In the UK, the responsibility of the building sector is even more significant, where it is considered to be responsible for over 50% of total UK carbon emissions [3]. The Climate Change Act of 2008 [4] was the UK Government’s response to the Kyoto Protocol agreement, setting a target reduction of the net UK carbon account for the year 2050 to at least 80% lower than the 1990 baseline. The act provided for a series of 5 year carbon budgets up to 2022, requiring the reduction against the 1990 baseline to be at least 26% by 2020. Legislation referring to the construction sector includes the Code for Sustainable Homes [5], the 2016 Zero Carbon Policy [6] and the Low Carbon Construction Action Plan [7], all of which demand reductions in the embodied carbon of the fabric of buildings since this represents 15% of the amount of carbon emissions that the construction industry has the ability to influence [8].

This article seeks to identify a strategy to reduce the environmental impact of construction by using bio-based renewable materials. Recent literature in the field is reviewed and the potential of bio-based materials to achieve this is illustrated through case studies.

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2 ENVIRONMENTAL IMPACT OF CONSTRUCTION

A number of strategies have been developed to reduce carbon emissions, including improved thermal insulation for both new build and retro-fit (e.g. the Green Deal); better building design (e.g. PassivHaus); improved efficiency of heating, ventilation and air conditioning (HVAC) systems; reduction in the carbon emissions of energy production through the use of nuclear energy, renewable energy sources (hydro, wind, tidal, photovoltaic, bio-mass, etc.); but less emphasis appears to be placed on reducing the embodied energy within buildings.

Embodied energy is the energy cost of constructing a building, and since this is a fixed cost which makes up ~10% of total global carbon emissions, it is a significant factor which is worthy of addressing with great urgency.

Traditionally, building materials were sourced locally, and it is the range and variety of local materials which created the character of the historic built environment. Vernacular buildings rely on small-scale craftsman led construction technologies, and such technologies are not suitable for the high volume, mass-produced built environment need to service the large and every growing global population. Industrialisation brought financially efficient technologies to the built environment such as mass-produced bricks, concrete and steel. Such materials are low cost to produce and require low skill levels to convert into buildings. They all, however, share a common high energy cost in areas such as extraction, processing and transportation. In addition, these materials all come from finite (if large) resources. Once extracted and converted, the raw material is gone forever, and with low historic levels of recycling, much of this material is lost to future generations who will have to rely on increasingly depleted resources.

Life-cycle assessment (LCA) has become an important tool in the design of future construction. This is a vast area of study, with many variants as defined by the various practitioners. All variants share a common approach as defined by ISO14040 [9]. There are three phases to any life-cycle assessment: Goal and Scope Definition; Inventory Analysis; and Impact Assessment. These phases are all subject to interpretation, and it is vital that transparency is maintained throughout the process. It is only through this transparency that the validity of any LCA can be assured.

Figure 1 shows a schematic of the LCA process that is followed for buildings.

The schematic deconstructs the various elements that are involved in the construction, use, maintenance and deconstruction of a building and adds clarity to our understanding of how it is possible to reduce the environmental impact of construction.

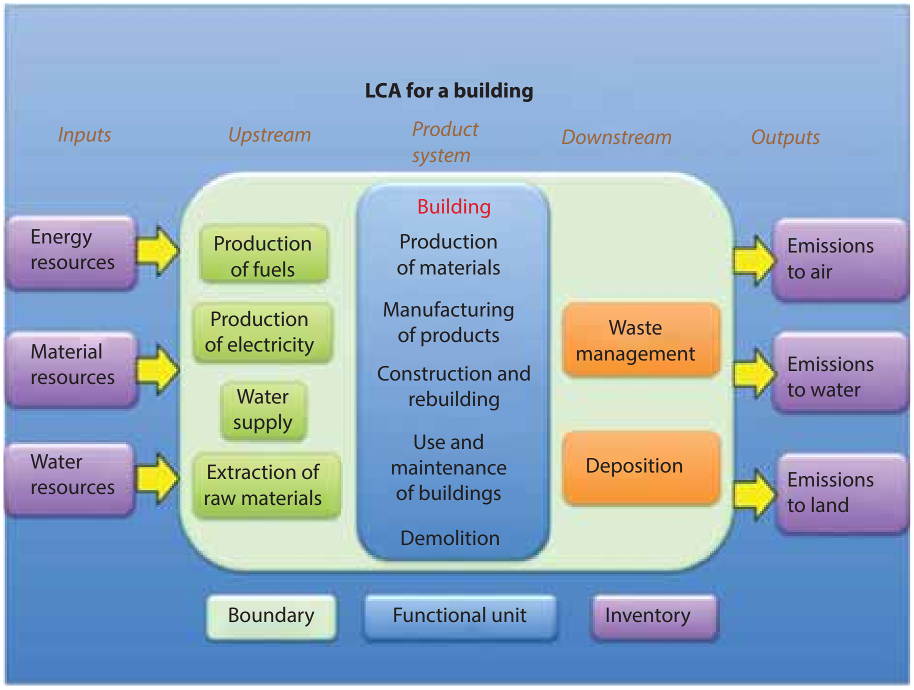

Figure 1 Schematic for the LCA of a building.

2.1 Embodied Energy

Table 1 shows the contribution to CO_2 emissions made by the UK construction sector in 2008. It is often said that buildings are responsible for about half the country's CO_2 emissions, but this only takes into account operational energy. That is the energy expended by people inhabiting or otherwise using buildings. This figure does not, however, take into account embodied energy—the energy consumed in the extraction or manufacture of the materials and products required for construction work, or in the process of transporting and assembling them. This is generally counted as the operational energy of the industrial and transportation sectors, but in reality, these emissions are caused by the demand from the construction sector, and should therefore more correctly be included in the environmental impact of that sector. It can therefore be seen that, for the purposes of a life-cycle assessment (LCA), the true impact of the construction sector is nearly 57% of the total UK carbon emissions.

Many construction materials (concrete, cement, fired bricks, blocks) use large amounts of energy in their manufacture and transport. Most of this energy comes from the burning of fossil fuels, increasing the amount of CO_2 released into the atmosphere, with the consequent global warming effect.

2.2 In-Use Energy

The operation of a building is responsible for the vast majority of the energy currently consumed by the construction industry. This includes heating, cooling, lighting and operation of equipment. As at 2008 in the UK this represented nearly 83% of the total [3]. It is this figure that has been targeted by energy reduction policies initiated by the Kyoto Protocol.

Draughty buildings have been sealed; walls, floors and roofs have been heavily insulated; windows have been triple glazed; orientation of buildings has been optimised to make best use of solar gain; thermal mass has been mobilised; ventilation is designed to use heat recovery; and high efficiency equipment is specified. In addition to reducing energy demand for heating and cooling through these strategies, building design now includes the use of renewable energy sources such as ground source heat pumps, solar heating, photovoltaics and wind power. Many of these technologies have high embodied energy, and in some cases their effective life span is considerably less than that of the building in which they have been installed.

The net result of all these interventions is that whereas in 2008 the proportion of a building's carbon emissions embodied into the fabric of the building represents around 17%, the more energy efficient the building becomes, the more significant this embodied energy becomes as a percentage of the total contribution to carbon emissions. Thus, in meeting the 2050 emissions target, the typical building will emit only 20% of the 1990 levels (Table 1), resulting in the proportion embodied into the fabric of the building representing nearly 50% of the total. This inevitably places a greater emphasis on the need to reduce the embodied energy of the fabric of buildings, an area which receives much less attention than the reduction in energy cost of operating a building.

Table 1 Contribution to UK CO_2 emissions made by the construction sector in 2008.

Sub-sector	**co$_2$ (Mt)**	**% of total**	**% of Construction**	
			2008	***2050 (80% in use reduction)***
Construction [3,10]				
Design	1.3	0.25	0.3	*0.9*
Manufacture	45.2	8.61	15.1	*43.4*
Distribution	2.8	0.53	0.9	*2.5*
Operations on-site	2.6	0.50	0.8	*2.3*
In Use	246.4	46.93	82.6	*50*
Refurb/Demolition	1.3	0.25	0.3	*0.9*
Total Construction	**298.4**	**56.84**	**100**	***100***
Other Sectors	**226.6**	**43.16**		
Total UK [10]	**525.0**	**100**		

3 RECYCLABLE AND RENEWABLE MATERIALS

Strategies for the reduction of the energy embodied into the fabric of the building include the use and/or re-use of recycled materials and renewable materials. Recycled materials can be considered to have less embodied energy because, from an accounting point of view, the initial manufacturing energy has been accounted for in its initial use, and it is only the additional energy embodied into collection, recycling and transformation of those materials that is embodied into the new product. A recycled material is 'renewed' to the extent that the embodied material has been given an extended life, but many of these materials come from finite non-renewable resources—for example steel. Other non-renewable materials are sourced from plentiful sources such as cement sourced from limestone or sand and other aggregates. The energy required to win and manufacture these products, however, can make truly renewable materials more desirable.

Renewable materials that are viable for use in construction are essentially those materials that can be renewed sustainably within relatively short time spans. These consist essentially of bio-based materials from plants and animals that can be harvested and regenerated within years or decades rather than centuries or longer periods. The energy embodied in the creation of the raw material is almost exclusively solar energy using photosynthesis, which, in the case of animal materials is converted through digestion from photosynthesised plant material into animal-based materials such as wool and hair.

4 BIO-BASED MATERIALS USED IN BUILDING ENVELOPES

Construction materials made from crops generally use much less energy in their production, and through the judicious use of locally grown material, can also reduce the transportation energy cost. In addition to this low embodied energy in their manufacture, bio-based materials also sequester CO_2. During photosynthesis, plants absorb CO_2, using the carbon to make structural material (leaves, stem, etc.) and releasing the oxygen back into the atmosphere. Thus, using stoichiometry, it can be seen that CO_2 (44) is used to embody C (12) into the plant, releasing the balance of O_2 (32) into the atmosphere. This means that every 12 kg of plant material has removed (sequestered) 44 kg of atmospheric CO_2, which is a conversion factor of 3.67.

Bio-based insulation materials have lower embodied energy than conventional non-renewable alternatives. When these materials are used in their natural state, rather than as feed-stocks for the production of polymers, these materials are all biodegradable, so that at end of life they cause much less pollution. Unlike glass fibre, and mineral wool, these materials are nonirritant which makes them much more user friendly. Thermal conductivity of insulation materials such as Sheep's wool, flax and hemp fibre is around 0.037–0.042 $W.m^{-1}.K^{-1}$, which is comparable with rock wool values of 0.033–0.046 $W.m^{-1}.K^{-1}$ [11].

Plant-based materials have specific heat capacities of around 2.0 $kJ.kg^{-1}.K^{-1}$, compared with only 1.0 $kJ.kg^{-1}.K^{-1}$ for mineral-based materials. This means that bio-based materials can store twice as much thermal energy as mineral-based materials for comparable densities and thicknesses. The more heat a material can store, the slower it will respond to thermal changes. This thermal damping effect results in more stable internal room environments.

4.1 Light Structural Walls

Light structural walls have a dual function in a building, acting both as a weather-proof envelope and as insulation. As a general rule, they have poor load bearing capacity and are therefore combined with a structural frame, which is most often made from timber.

4.1.1 *Straw Bale Construction*

Straw bale construction began in Nebraska, USA, in the early 19th century, where the European settlers found few naturally occurring building materials. Stone and timber were in short supply, so they baled up grass, using them as oversized building blocks to form walls, and plastered the faces with mud. With the advent of the Industrial Revolution, improved communications and mass production, brick, steel and timber became the building materials of choice and straw bale construction ceased to be used.

In the 1980s interest in straw bale construction was revived in the American West, and the technique has since permeated across the world. Examples can be found in Australia, China, Mongolia, Saudi Arabia, Mexico, Northern and Southern Europe and South Africa. In the Western United States, construction is at a level where local building standards have been developed to deal with the peculiarities of straw bale construction in California, Arizona and New Mexico. In France, the RFCP (Réseau Français de la Construction en Paille) has developed a code of practice which has recently been submitted for approval to the national building regulation authorities, but there are currently no UK standards or codes of practice which relate specifically to straw bale construction.

The low carbon credentials of straw bale construction have encouraged research aimed at providing sufficient data and understanding of performance to allow it to be adopted more widely than just by the 'self build' community. Such research has been going on in many countries since the 1980s. Some of the publications emanating from this research are referred to here and are listed in the references at the end of this article. They cover areas such as structural performance [12], fire resistance [13], resistance to decay [14,15], acoustic performance [16] and hygrothermal performance [17]. They also include case studies on building behaviour under different climatic conditions [18].

Constructing with straw has recently been developed into having the potential for high volume construction through the development of pre-fabricated systems. In the UK, ModCell is a locally manufactured structural timber frame infilled with straw bales and coated with a lime render on both faces. Similar systems are marketed in Belgium by Paille-Tech. The advantages of the pre-fabricated system include quality assurance, protection from rainfall during construction, and rapid on-site erection.

4.1.2 *Straw-Clay Construction*

Traditional construction technology for millennia, straw-clay construction can either be used in a monolithic form or as light earth blocks. Chopped straw is mixed with clay and water and tamped into shuttering. Once dry, the straw-clay is robust and durable, provided it is protected from water by a render, an impermeable plinth and good roof cover.

This technology offers less opportunity for high volume construction than straw bale, being more suitable for self-build or individual houses.

4.1.3 *Hemp-Lime Construction*

Hemp-lime construction began in France in the 1990s, initially as a substitute for wattle and daub repairs in historic buildings. By 1993 buildings were being constructed in the southeast of France and in Brittany using a mixture of hemp shiv and lime cast around a timber frame. As the use of hemp-lime spread more widely through France, the techniques diversified. Hemp-lime is now available as pre-cast blocks of varying dimensions, and a spray application technique has also been developed, in addition to the most widely used technique of casting.

The use of hemp-lime in France is now well established, and a professional association has been formed, CenC (http://www.construction-chanvre.asso.fr), which encompasses members from all parts of the sector: researchers, farmers, manufacturers, practitioners, distributors, builders and designers. A set of guidelines has been published [19] and formal training is offered.

An International Hemp Building Association has been formed, based in Ireland (http://www.internationalhempbuilding.org/), with the objective of promoting the use of hemp-based construction materials worldwide. There is also a European Industrial Hemp Association (http://www.eiha.org/) aimed at supporting the cultivation, processing and use of hemp within the EU. The Hemp Lime Construction Products Association (http://www.hemplime.org.uk/) was set up in the UK "To promote the responsible development and use of hemp lime and associated products in the construction industry".

In the UK, hemp has been grown and processed since 1993. The majority of this processing was done by Hemp Technology Limited which went into administration in 2013. The market is now supplied by Yorkshire Hemp who grow as well as process hemp, and by imports from producers in France.

Competition within the binders used for hemp-lime is greater, since binders are used very widely in construction. Experimental work with a range of different binders showed that the shiv competes strongly with the binder for available water. This means that purely hydraulic binders such as cement or hydraulic lime are unable to hydrate completely, leaving a poorly bound, powdery core to hemp-lime walls. As a result of this, special formulations have been developed for use with hemp-lime based on air lime with varying proportions of additional hydraulic and pozzolanic constituents, and possibly additives such as surfactants.

The proportion of binder used in the mix controls the density, and hence also the thermal resistance, of the hemp-lime. In addition to this, it also controls the mechanical performance of the hemp-lime. However, the mechanical performance of hemp-lime is not directly related to the strength of the binder used [20]. The way in which the material is compressed during the casting process also controls thermal and mechanical performance.

As with straw bale construction, pre-fabrication is now being applied to hemp-lime construction. HempCell®, a patented system developed in the UK, is now being marketed across the EU, conferring the benefits discussed above.

4.2 Carbon Sequestration

As discussed above, plant-based materials absorb atmospheric CO_2 through photosynthesis. This CO_2 is considered by many to be 'sequestered' within the material for its lifetime, and therefore to justifiably

Table 2 Characteristics of some building envelope materials [23].

Material	Energy (MJ/kg)	Carbon (kg C0$_2$/kg)	Carbon (kg C0$_2$/m^3)	Thermal conductivity (W/m.K) [23]	Density (kg/m^3)
Concrete block	0.67	0.073	105.85	0.48	1450
Mineral wool	16.6	1.2	28.8	0.032–0.044	24
Polyurethane foam	101.5	3.48	104.4	0.023–0.026	30
Woodwool insulation	10.8	0.98*	29.4*	0.038–0.050	30–40
Cast Hemp-lime [21]	4.60	0.468* –0.414†	128.7* –113.8†	0.06–0.09	275–330
Straw Bale	0.24	0.01*	1.1*	0.06	110–120
Cork	4.00	0.19*	38*	0.07	200-250

*excludes sequestration † includes sequestration [21]

be deducted from the carbon footprint of the material. Materials such as coal and limestone also have sequestered CO_2, but since this was removed from the atmosphere more than 200 million years ago, it is not relevant to the current environmental crisis.

Hemp and straw will remove CO_2 from the atmosphere less than 12 months before the material is embodied within the structure of a building, and timber maybe 5 to 50 years previously. In both these cases, the CO_2 absorbed from the atmosphere is within a short enough timescale to contribute to the reduction of current carbon emissions, provided always that the building has a planned lifetime of 60 to 100 years. This is of all the greater importance when these materials displace other, more carbon-intensive materials.

A study of hemp-lime construction [21] calculated that a square meter of timber framed, rendered hemp-lime wall had a carbon footprint of –35.5 kg CO_2 equivalent (CO_2e). In other words, the CO_2 sequestered within the wall is 35.5 kg CO_2e greater than the CO_2e embodied in the construction (materials, transport, energy input, etc.). This compares with a carbon footprint of the UK traditional cavity wall brick and block construction system of around 110 kg CO_2e.

This concept of sequestration is an important one, but is not always accounted for when LCA is performed. For example, the Inventory of Carbon and Energy [22] acknowledges sequestration, but does not include it in its primary figures. Table 2 gives some comparative figures for the embodied energy of conventional and bio-based building envelope materials. Figures for hemp-lime are given from the study by Boutin [21] and demonstrate the impact on the carbon emissions if sequestration is taken into account.

4.3 Vapour Active Materials

A growing area of interest is the hygrothermal performance of materials. Natural fibre insulation materials have the ability to create a breathable wall construction by readily absorbing and releasing moisture in response to changes in relative humidity and vapour pressure gradients in the surrounding environment. Heat flows are associated with these reactions. During absorption heat is released, and on desorption of moisture heat is absorbed [24]. This breathability produces a hygric damping effect, comparable to the thermal damping effect discussed earlier. When combined with the high specific heats associated with plant-based materials, and the thermal effects produced during sorption/desorption, materials such as hemp-lime demonstrate a 'virtual hygrothermal mass'. This phenomenon allows buildings to be constructed which consume less energy in use by lowering the requirement both for heating and for air conditioning.

The transient nature of this phenomenon, responding as it does to changes in environmental conditions, means that steady-state performance measurements do not necessarily reflect actual performance in variable conditions. Shea *et al.* [17] showed that although the WUFI model for thermal transmittance predicts a steady-state temperature profile following a sudden temperature drop within 48 hours, in practice a hemp-lime wall has still not achieved a steady state after more than 240 hours. Indeed, after 24 hours, the temperature change is no longer detectable at a point 60% of the way through the thickness of the wall. This phenomenon is associated with movement of vapour through the pores of the material.

Figure 2 shows the thermal energy effects of moisture sorption/desorption within the pores of a specimen of hemp shiv (the woody core of the hemp stem).

This experiment was carried out using a SETARAM SENSYS DSC isothermally at 27ºC, exposing 17.45 mg of hemp shiv to a series of different humidity conditions (30%, 50%, 70%), both increasing and decreasing. Where the humidity increases, moisture

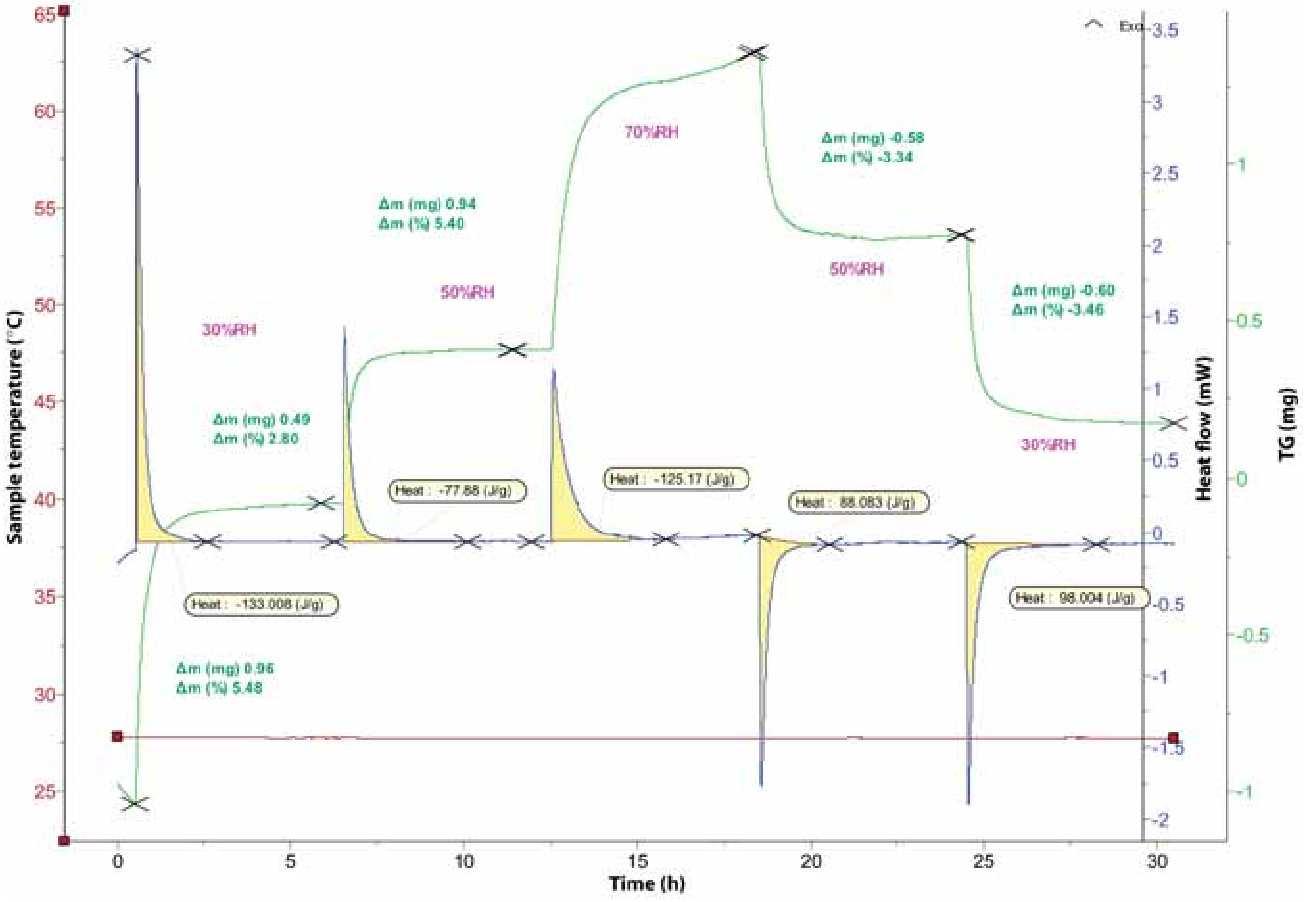

Figure 2 Isothermal heat of sorption within the pores of hemp shiv.

condenses in the pores and there is a resultant emission of thermal energy associated with the latent heat of water. Where the humidity is decreased, moisture evaporates from the pores causing a reduction in the thermal energy of the system. It can be seen that the amount of energy produced by water vapour condensation within the pores of hemp shiv can be as much as 133 J/g. These data are the initial results from a wider study, ISOBIO, funded by the European Union under the HORIZON 2020 scheme. One of the objectives of this scheme is to fully quantify these effects and build them into building physics models, in order to better predict the actual performance of vapour active materials.

5 CASE STUDIES

The following case studies relate to various particular buildings which have made use of bio-based envelopes for different purposes. They demonstrate some of the benefits of bio-based construction, which, when incorporated into more mainstream construction, will confer considerable benefits.

The BaleHaus is an experimental straw bale building which demonstrates the feasibility of pre-fabricated construction techniques to deliver low embodied carbon, highly thermally efficient domestic scale housing, using bio-based materials.

The Science Museum Archive store demonstrates the significant benefits that vapour active bio-based materials can bring to the passive conditioning of internal air quality.

The Marks and Spenser superstore demonstrates, through post-occupancy monitoring, the fact that vapour active bio-based insulation performs thermally much better than steady-state modelling would suggest. These data, and other ongoing post occupancy monitoring, will be used to validate a proposal to incorporate transient thermal performance characteristics into building physics models, rather than the steady-state characteristics currently being used.

5.1 The BaleHaus

Research into straw-bale construction has developed in recent years in association with the commercial interest in large-scale mainstream straw-bale construction. Amongst other studies, the BaleHaus, (Figure 3), constructed on campus at the University of Bath, is perhaps one of the most informative.

The BaleHaus was constructed as part of a Technology Strategy Board (TSB) funded project and was subsequently disassembled and re-sited elsewhere on campus, where it is now part of a long-term study, and being used as a dwelling house.

Wall *et al.* [16] have used this building to identify the strengths and weaknesses of a pre-fabricated modular straw-bale constructive system. Studies included a life-cycle assessment (LCA) [25], moisture content over 12 months, acoustic performance, air permeability and a thermographic survey. The LCA was used to ascertain the environmental impacts of the prototype house compared with a hypothetical brick and block house with the same layout as the BaleHaus, which was used as a benchmark. Cradle-to-dismantling and cradle-to-grave analyses were used and revealed that the prototype house performs better than the conventional masonry house, especially in relation to its low global warming potential [16]. The straw-bale panels have a net embodied carbon of 3.5 kg CO_2/m^2, which for a typical house of 150–200 m2 of wall, give a potential savings of over 19 tonnes of embodied CO_2 compared with conventional masonry wall construction [26].

Moisture content of the straw in the walls was measured using wood moisture equivalent sensors, calibrated using data from Lawrence *et al.* [27]. Over the 12 month period, the average daily moisture content never exceeded 22%. Prolonged moisture contents above 25% are considered to produce a significant risk of decomposition within straw [14]. Air permeability tests showed air leakages around windows, junctions between panels and inlet pipes. Once these leakages had been resolved, further testing showed an exceptionally low air permeability at 50 Pa of $0.86\ m^3.h^{-1}.m^{-2}$. Thermal imaging revealed a very good thermal performance with no sign of thermal bridging through timber frames, floor or roof.

As with all forms of construction, good detailing and high quality construction practice on site will ensure a high performance from a straw-bale building. With good detailing straw can be considered to be a robust and durable material, and the intrinsic low thermal conductivity of straw offers the opportunity for high performance buildings with low environmental impact.

5.2 Science Museum Archive Store

The Science Museum is a museum of science and technology that holds a collection of more than 300,000 items. When not being exhibited, these items are stored at a site in Wroughton in Wiltshire. This site, formerly a World War II airfield, primarily consists of extremely large concrete aircraft hangars. In order to store these

Figure 3 The BaleHaus experimental building at Bath.

Figure 4 Archival store at the Science Museum, Wroughton.

artefacts in appropriate conditions, enclosures are constructed inside these hangars. Large amounts of energy are expended to maintain these enclosures at the desired temperature (~ 15ºC) and humidity (~ 50% RH). This approach is seen by the trustees as being unsustainable, and they are actively seeking out alternative solutions.

Hemp-lime has the reputation for excellent hygrothermal buffering, and in 2012 the trustees of the Science Museum constructed an archival store made from hemp-lime. (Figure 4).

This building was commissioned in late 2012, and is now the repository for a large number of historic artefacts. An environmental control system has been installed, designed to support the passive environmental control provided by the hemp-lime. Environmental conditions are closely monitored externally and internally and energy consumption is also monitored.

Data from the archival store are currently being analysed, but it is noteworthy that between May 2013 and July 2013 the environmental control systems were switched off. During this period external conditions have varied from 0ºC to 30ºC and from 25% RH to 98% RH. The archive store is kept closed, with infrequent entry by staff to maintain the collection, and during this period the internal conditions have varied by less than 1ºC and 5% RH. For archival storage, the most critical factor is to avoid rapid changes in temperature and/or humidity since this sets up stresses within the material and causes accelerated decay. This performance is seen by the Science Museum as being extremely encouraging.

The system used to construct the archival store was a factory pre-fabricated one, which ensures zero defects and the highest quality of manufacture. When such a system is used, high performance buildings are much more readily constructed, and when combined with vapour active materials, there are increased opportunities for the creation of ultra-low energy, low environmental impact buildings.

5.3 Marks & Spenser, Cheshire Oaks

The superstore at Cheshire Oaks, near Chester in the UK (Figure 5) is the second largest Marks and Spenser (M&S) store, carrying the full range of their products. The store is the third M&S 'sustainable learning store' incorporating sustainability features designed to provide a bank of knowledge and experience in sustainable practices relating to the design, construction, commissioning and operation of buildings. The features include:

- Heat reclaim technology from refrigeration plant used for building heating. The refrigeration plant uses CO_2 as the working refrigerant;
- Pre-fabricated hemp-lime panels in the external walls with a U-value of 0.12 W/m^{2}K and low embodied energy;
- 100% FSC Glulam timber frame roof, with the roof itself made from white painted recycled aluminium panels, and recycled post consumer waste insulation;
- Rainwater harvesting used for toilets and irrigation;

- Wood pellet fired biomass boiler designed, alongside the heat reclaim system, to provide approximately 70% of the building's heat demand;
- 300m^2 living wall, irrigated by the rainwater harvesting system;
- 100% of the construction waste diverted from landfill, was used instead for projects such as capping a contaminated quarry and developing a local MotoCross park;
- LED lighting externally, and a daylight sensing control system internally, to maximise the use of natural light;
- Brise-soleil to reduce solar gains in summer;
- Sales floor heated, cooled and ventilated via displacement air ventilation columns utilising below ground earth ducts to assist in air cooling;
- Biodiversity measures such as bird boxes, wildlife garden, nature pond and additional planting;
- Extensive submetering to monitor local energy consumption in real time to provide feedback and track improvements to systems.

The building was specified in terms of maximum thermal permitted transmittance and benchmarks were set against a comparable store, and against the design estimate based on the building specifications (Table 3).

The energy consumption associated with the HVAC is more than 50% below the design estimate of consumption, and, as can be seen from Figure 6, the reduction is entirely associated with space heating. Faithful & Gould [28] speculate that this improvement is associated with the hemp-lime panels.

> *"These panels were a new product and therefore the in-use performance could not be fully modelled at design stage. In use proved to have better than predicted insulation properties and thermal mass. This in turn reduced the gas consumption in the winter and air conditioning load in summer".*

This supports the theory that the transient thermal performance discussed in Section 4.3 above exceeds steady-state performance by a substantial margin, since the data used for modelling were taken from steady-state measurements in accordance with the standard accepted approach.

6 CONCLUSION

It is evident that the more energy efficient buildings become, the greater becomes the importance of the embodied energy of the materials making up the fabric of the building. The contribution that can be made by bio-based materials is therefore of growing

Figure 5 Marks & Spenser Cheshire Oaks store. Front of store with planted embankment [28].

Table 3 Cheshire Oaks energy consumption against benchmarks – Nov 12 to Oct 13 [22].

Sub-meter category	Cheshire Oaks consumption (kWh/m2)	Westfield White City consumption (kWh/m2)	% reduction of actual over White City	Design estimate consumption (kWh/m2)	% reduction of actual of benchmark (kWh/m2)
Trade lighting Other lighting	103	119	13%	134	23%
Refrigeration	58	74	21%	57	–2%
HVAC	35	61	43%	74	53%
Mechanical handling	5	30	82%	23	77%
Catering	39	27	-42%	42	7%
IT/ Communications	2	7	78%	9	81%
Total Electricity consumption	**276**	**428**	**36%**	**346**	**20%**

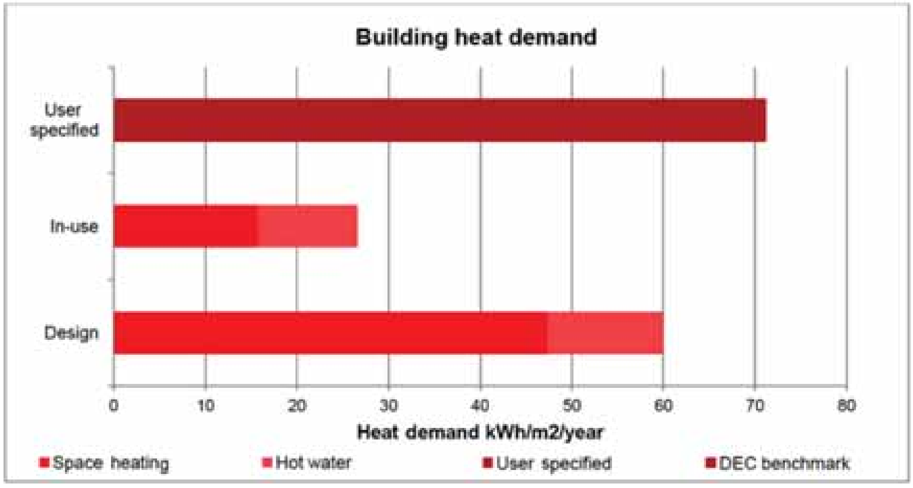

Figure 6 Cheshire Oaks building heat demand [28].

importance. In order to ensure long-term durability of bio-based materials when used for construction it is important to ensure good detailing, to avoid ingress of excess moisture within the system. Research using the HIVE at the University of Bath's Building Research Park is producing insights into transient performance of bio-based construction materials, and further work is being done to improve their resistance to decay and to fire through the EU funded ISOBIO project. With increased confidence in the robustness of such systems will come an awareness of the innate advantages that vapour active systems possess. The future of construction will become increasingly reliant on renewable materials, making research and development in this area a priority.

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