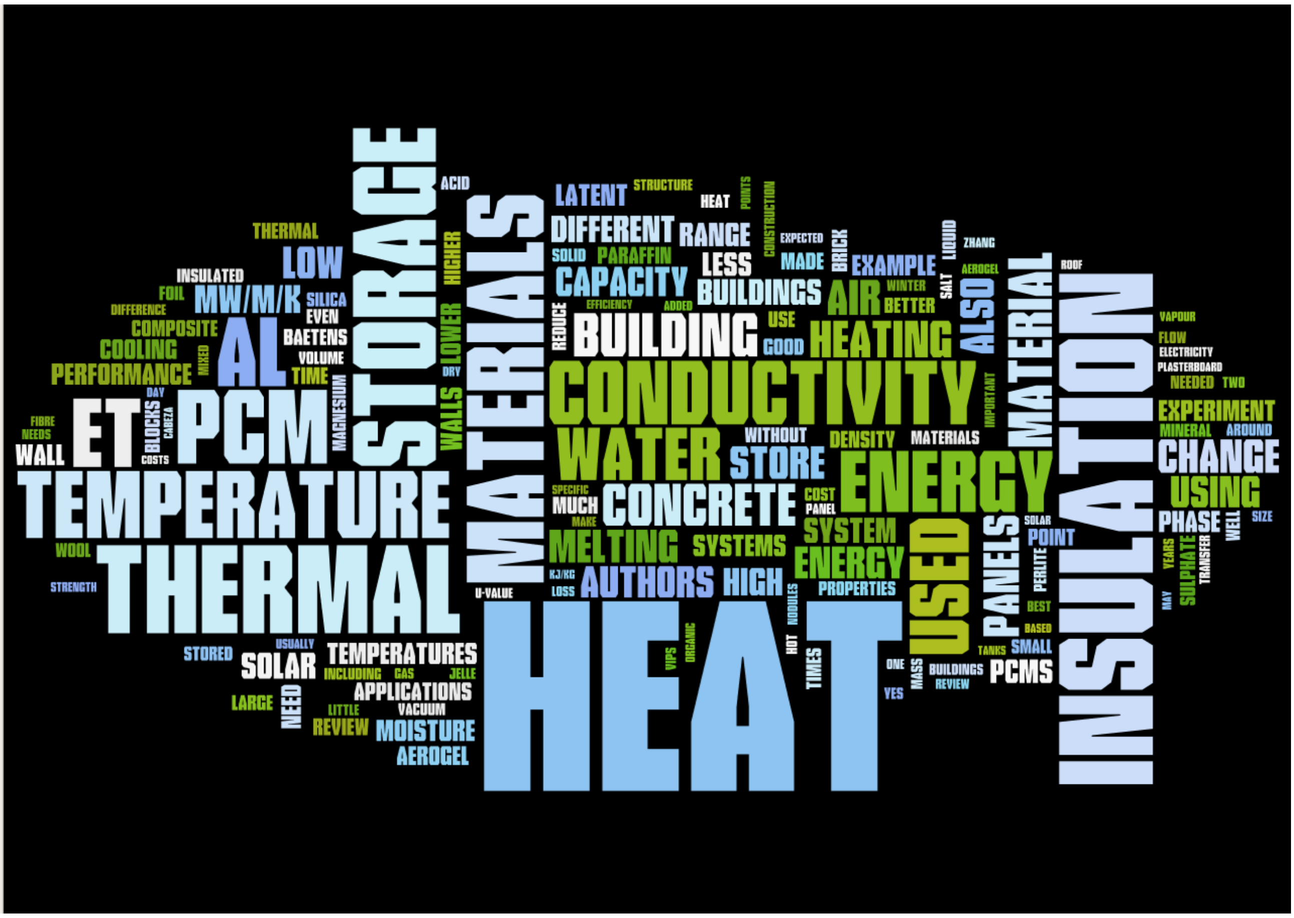
### State-of-the-Art Review:

# Insulation and Thermal Storage Materials

### Pre-Publication Draft



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# State of the Art Review: Thermal Storage and Insulation Materials
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# Executive Summary

Thousands of publications have been written about thermal storage and insulation, even in just the past few years. Our literature search found more than 2000 sources on thermal storage published in the last four years, and more than 600 sources on thermal insulation.

The literature on **thermal storage** divides into three slices:

1. Phase-change materials – which absorb heat when they melt from solid to liquid, and can add thermal capacity without affecting the heating response time
2. Long-term heat storage – including inter-seasonal storage
3. Short-term applications, including cooling

Experiments using **phase-change materials** (PCM) in plasterboard, aimed at reducing overheating, have been found to cut peak temperatures by 2-4°C. They can double the heat stored in some constructions. Up to 25 percent PCM can safely be included in plasterboard, or up to 5 percent in concrete.

Paraffin PCMs are the most commonly used in building applications – partly because they are economical, have good latent heat from 120-266 kJ/kg, and useful melting points from 20-112°C. (These figures are for commercial paraffins.) However, paraffins change volume on solidification and melting, which makes them prone to leaking. Fatty acids, 'oleochemical carbonates' (derived from animal and plant fats) could also be used in future, and salt hydrates (salts containing water of crystalisation) are already available commercially, but there are unresolved issues with all three at present.

| Material | Phase change temperature | Latent heat |
|---|---|---|
| Paraffins | -57 to 112°C | 120-266 kJ/kg |
| Fatty acids | 30-70°C | 150-220 kJ/kg |
| Oleochemical carbonates | -5.9-46.9°C | 144-227 kJ/kg |
| Polyethylene glycols | 10-55°C | 108-176 kJ/kg |
| Inorganic PCMs | -31-117°C | 126-251 kJ/kg |

Both thermal capacity (how much heat can be stored) and thermal conductivity (how fast heat is absorbed or released) are important in thermal storage. While many PCMs have low thermal conductivity, this can be raised using additives or building small nodules in a large matrix.

There is also some concern about the service life of PCMs in buildings, and these materials may need to be replaced periodically. The quality standard for PCMs includes testing for 10,000 heating and cooling cycles – equivalent to around 27 years for normal uses in buildings.

PCM nodules have been tested in concrete floors, and allow the floors to be used as night storage heaters. Calcium chloride hexahydrate (a salt hydtrate with a melting temperature of 24°C), encapsulated in 75mm nodules, has been used like this.

It is very difficult to give cost estimates for PCMs because there are so many types and applications. However, the materials alone typically cost in the range from around £3 to £13 per kg. Encapsulation (to stop them melting and running away, and to improve conductivity) can double this cost, and micro-encapsulation (storing them as tiny particles in hard shells) doubles the cost again.

Special concretes and salts can provide **long-term storage** through a reversible chemical reaction such as dehydration and rehydration. However, water and gravel are more commonly used, and these give an energy density of 210 MJ/m$^3$ (58 kWh/m$^3$).

Refrigeration and air conditioning can draw on a cold reservoir for **short-term applications**. This can reduce the peak cooling demand and the peak load on the electricity grid. Again, PCMs can be used (sometimes in water), but there are special requirements – including stability over thousands of heating and cooling cycles.

The work on **insulation** is more focused around materials, and we scrutinised work on four sorts of materials:

1. natural insulation materials – e.g. mineral wool, cork, cellulose
2. new insulation materials – e.g. expanded polystyrene, polyeurethane, or aerogel
3. vacuum-insulated panels
4. multi-foils

Natural insulation materials perform at least 10 times better than brick or stone, see table. New insulation materials perform at least 20 times better than brick or stone, while vacuum insulated panels are better still, at least 60 times better than brick or stone. However, aerogel (the best-performing new insulation material), and vacuum-insulated panels, remain very expensive. There are also concerns about the fragility and longevity of vacuum-insulated panels, with some consensus that expected service life will be 10-40 years, although aluminium envelopes can increase this.

| Material | Thermal Conductivity (W/mK) | Minimum improvement (=reduction) in conductivity over brick or stone | Indicative costs |
|---|---|---|---|
| Brick or stone | 0.6-2.5 | - | - |
| Natural insulation materials | 0.03-0.05 | 20 | £9-£18/m$^2$ |
| Mineral insulation | 0.03-0.04 | 20 | £5/m$^2$ |
| Petro-chemical insulation | 0.02-0.04 | 30 | £5-£22/m$^2$ |
| Layered foil | 0.033-0.035 | 18 | £8-£9/m$^2$ |
| Aerogel | 0.013-0.014 | 42 | £20-£30/m$^2$ |
| Vacuum-insulated panels | 0.004-0.01 | 60 | £40-£50/m$^2$ |

Multi foils have performance similar to expanded polystyrene, although manufacturers claim much better performance, which is dependent on an air gap (ideally both sides of the foil, and ideally 3cm wide). Field trials suggest that multi-foils do not achieve manufacturers' claims, and their performance degrades over time as the surfaces tarnish.

Nearly all of these materials have higher conductivity when they are wet, which is important for construction applications.

# Introduction

The Department for Communities and Local Government commissioned Cambridge Architectural Research and Eclipse Research Consultants to carry out a State of the Art Review of insulation materials and storing thermal energy. The Department saw this work as feeding into its review of the Building Regulations scheduled for 2013.

This report brings together findings from a comprehensive review of published literature on these topics. There is a sister report presenting the findings from an Expert Panel Meeting we ran on the 13th February 2012.

This report aims to characterise both physical and practical limits to the performance of insulation and thermal storage materials in the context of applications in buildings. The report is organised in five parts:

1. a short description of our **Method** for carrying out the work

2. a list of the **Data Sources** we used

3. a description of different **Applications** of these materials in buildings, which puts the work into context

4. the **Literature Review**, which works through each of the main groups of materials used for insulation and thermal storage in turn

5. **Tables** showing each reference we have used, along with a short summary of its main points

There has been a great deal of research work on insulation and thermal storage materials in recent years, as is testified by the large number of papers published on the subject. (See Data Sources, next section.)

Insulation materials available today include natural fibres, mineral fibres, modern petrochemical insulation, foil reflective barriers, and high performance aerogels and vacuum insulated panels. Thermal storage materials incude ceramics, earth, water and high performance phase change materials (PCMs). These last store heat when they melt and release the heat when they re-solidify. Also on the horizon, but as yet only in development, are thermochemical storage materials, which store heat in reversible chemical reactions. All these are discussed in the following sections.

The relative importance of different material characteristics depends on how they are applied. For example, insulation thickness can be critical in retrofit applications, but is less important in new buildings. For thermal storage applications, the temperature at which heat is stored is as important as the heat energy density and cost. The Applications part of the report discusses these aspects in order to set the rest of the report in context.

## Method for the Literature Review

We sought to divide our time approximately evenly between insulation materials and thermal storage materials, and to prioritise literature where there was a clear link to buildings and particularly possible implications for the Building Regulations. This was consistent with our brief from the Department for Communities and Local Government. As a starting point we used the Science Direct search engine to find review papers dating from 2010 to the present using these keywords:

- thermal storage buildings
- heat storage buildings
- thermal insulation buildings
- heat insulation
- phase change materials buildings

We also searched the DECC and BRE websites for relevant papers using these keywords. From the papers identified we excluded articles which were clearly off-topic or relevant only to other climate zones. This left 18 articles.

From reading these papers we picked out more specific topics of interest such as these relating to thermochemical storage:

- adsorption
- absorption
- silica gel
- zeolite
- hydrate

We subsequently used these keywords in combination with ‘thermal storage’, and allowed a wider range of dates, to find research papers on these topics. We also used the first tier of publications to identify other work – using the lists of references at the end of each publication.

We supplemented this work with Google to search more widely on some topics. Some papers referred to the IEA Solar Heating and Cooling Task 32 project which led us to that website, from which we found the names of some participants. This enabled us to search for papers by those researchers.

We also followed up some references given to us by participants at an Expert Panel Meeting run in parallel with the Literature Review, and described elsewhere.

From the papers identified by the search engines we selected those which related to:

- reviews of the topic area
- fundamental material properties, such as thermal conductivity or thermal storage density
- field tests in a European climate
- simulation/modelling in a European climate
- real use cases in a European climate

We summarised each paper or publication in a searchable table, included at the end of this report, and we drew out salient points – especially points relating to buildings and the Building Regulations – for the main part of this report.

## Data Sources

There is a great deal of research in the areas of building insulation and thermal storage, and a large number of papers published on this subject.

The table below shows results from the Science Direct search engine, looking for journal and review articles only with search words in title, abstract and keywords. A selection from these articles was used as the starting point for this research.

| **Keywords** | **2008 to present** | **2010 to present** | |
|---|---|---|---|
| thermal storage | 2123 | 1288 | |
| thermal storage buildings | 184 | 122 | Missing lots of PCM related articles |
| heat storage buildings | 165 | 108 | |
| thermal storage buildings concrete | 17 | 11 | |
| thermal storage buildings pcm | 66 | 42 | |
| phase change materials buildings | 132 | 90 | |
| thermal storage buildings wallboard | 18 | 10 | |
| thermal storage buildings water | 58 | 45 | Mostly refer to water as a carrier e.g. paraffin emulsion |
| thermal storage buildings seasonal | 20 | 13 | |
| thermal insulation | 607 | 376 | |
| thermal insulation buildings | 198 | 135 | |
| heat insulation | 379 | 240 | |
| heat insulation buildings | 113 | 82 | |
| insulation foil | 19 | 12 | |
| thermal insulation market | 13 | | Mostly case studies |
| thermal storage buildings market | 2 | | Case studies |
| **Review articles only** | | | |
| thermal insulation buildings | 16 | 13 | |
| thermal storage buildings | 13 | 10 | |
| phase change materials buildings | 13 | 11 | |

## Applications

Our review focused on on materials used for insulation and storing thermal energy. This part of the report discusses how these materials are (or could be) used in buildings, and highlights the most important characteristics of the materials when used in each different application.

The range of applications is large and is categorised here into four broad categories:

1. reducing heat loss through the building envelope
2. avoiding uncomfortably high temperatures due to solar gain, appliances or people
3. short term storage over hours or days: storing heat (or cooling energy) when it is available cheaply for use when it is more expensive
4. long term heat storage, storing heat in summer for use in winter for space heating or hot water

There is an overlap between the first and second categories because one of the mechanisms to reduce solar gain is to add insulation. Similarly, there is overlap between the second and third categories because another way to avoid high temperatures is to store the excess heat for later. These overlaps are difficult to avoid because of the complexity of the topic. In practice a single building element can have different uses.

### *Reducing heat loss*

The most important way to reduce heating energy using in buildings in the UK is to reduce heat loss through the building envelope. There are two main aspects to this:

- conduction and radiation losses through the outside walls, ground floor, roof, windows and doors
- air leakage – warm air leaking outside and cold air entering as draughts

Conduction losses through walls, roofs and floors are addressed by adding insulation. Ideally insulation materials:

- have very low thermal conductivity, especially where space is at a premium – which is usual in retrofit when adding insulation on the inside of the walls, floors or in doors. If a material has half the conductivity of another then you only need half the thickness to achieve the same level of insulation
- can be cut to fit the required shape and size
- perform well when damp (since it is very difficult to keep moisture out)
- are robust and durable

Different materials are suitable for different parts of the building envelope as shown in the table below.

*Characteristics required for insulation in different parts of a building*

| | **New build** | **Retrofit** |
|---|---|---|
| Walls | Any kind of insulation can be used as part of pre-fabricated components. Otherwise the material will have to be cut to fit, which excludes vacuum insulated panels and gas | Any kind of insulation which can be cut to fit can be added either on the inside or the outside of the wall. Internal insulation can lead to |

| | | |
|---|---|---|
| | filled panels and loose insulation. Insulation can be installed in cavities. | moisture problems in the wall, because it will then be cold and will not dry out quickly.<br>Cavity wall insulation needs to be inserted through small holes in the wall so it has to be loose, flowing or sprayable.<br>Some cavities are small and hard to fill (Iwaszkiewicz et al, 2010). |
| Floors | Rigid insulation can be laid over a concrete floor. Alternatively insulation can be cut to fit between joists, though rigid foam blocks will leave air gaps while fibre fluffs out to fit. | As new build but there will be very little room in a retrofit with solid floors without expensive reconstruction. |
| Roof | Any kind of insulation can be cut to fit between roof rafters or attached under them (foil is often used in this way) or both.<br>If the roof space does not need to be heated then insulation can be laid between and over the joists. Loose insulation can be poured between the joists.<br>If the roof is used for storage then insulation over the joists has to bear loads. Rigid foams can be used. Thickness may be limited if space is an issue. | |
| Windows | There are two parts to a window: the glass and the frame and both parts need to be insulated for a high performance window. Window frames can incorporate any kind of insulation since they are supplied as pre-fabricated components and do not have to be cut to fit.<br>Translucent material can be sandwiched between polymer sheets for use in glazing that is intended for lighting, rather than viewing (Baetens et al, 2011; Sadenini et al, 2011). | |
| Doors | Composite doors can include high performance insulation materials in a sandwich. Since the door is supplied as a unit within a protective layer even fragile vacuum insulated panels can be used (Baetens et al, 2010). | |

### Air leakage

Draughts can be a major component of heat loss, especially in old houses, and they can be hard to locate and fix. Any retrofit which fails to address draughts as well as conductive losses will have limited success. Some insulation materials are inherently more air tight than others. For example Van Den Bossche et al (2012) shows that fibrous filling or partial foam filling for cavity walls leads to poor air tightness around window frames. However, this report does not focus on air leakage.

## *Avoiding high temperatures*

Buildings have windows and walls that absorb radiant heat from the sun. This can make rooms uncomfortably warm, especially if the building is airtight and well insulated. In the UK this is usually only a problem in the summer as the winter sun is weaker and frequently obscured by cloud.

Heat gains can also come from inside the building: from occupants, lighting and electricial appliances. If the building is unused overnight then the difference between day and night time heating loads can similarly cause fluctuating temperatures, particularly if the building is well insulated (Al-Homoud, 2005).

There are a number of strategies to reduce these problem.

- Increase the thermal capacity of the building with heat-absorbing materials, possibly using PCM incorporated into the walls of the building. The heat stored during the daytime is released at night when the air temperature is cooler. This is discussed further below.
- Use natural or forced ventilation to dump the excess heat during the day. This works well when the outside air temperature is low. If it is too warm outside then 'evaporative cooling' (which uses the effect of water evaporating to remove heat from a building) can be used as long as the air outside is dry (Raj and Velraj, 2010). Ventilation is outside the scope of this report.

For solar gain, but not internal heat loads:

- Shade windows and walls with low hanging eaves, so as to reduce direct sunlight when the sun is high. This can be more effective than adding thermal capacity (Arce et al, 2012).
- Use external roof and wall insulation, or reflective materials such as foil systems, reflective paint coatings and/or or window film coatings. These all reduce the flow of heat into the building but can also increase the need for heating in the winter, since there is less solar gain, (Kolokotroni et al, 2011). This report investigates insulation and foil systems.

## Heat capacity and responsiveness

When a building has a high heat capacity it can absorb a lot of heat without getting uncomfortably warm. However, it also takes a lot of heat to warm it up to a comfortable temperature from cold. This means it takes a long time to respond when you turn the heating on.

You can add heat capacity to a building without making it unresponsive to the heating system by incorporating phase change materials (PCMs). These are materials that absorb heat when they melt from solid to liquid. At temperatures below the melting point the PCM has a fairly low heat capacity so the building can warm up quickly. However, before the building gets too hot the PCM starts to melt, absorbing more heat.

PCM can be integrated into the building itself or it can be used in a dedicated 'cool store' with a fan to drive air through it. This is a form of 'free cooling' – the cooling is free though the fan takes some energy. Most PCM materials have a low conductivity, as does air, so the time taken to store and release heat in PCM stores is significant.

The PCM melting temperature needs to be within the comfortable range for the room and the night time temperatures need to be below the solidification point, otherwise the PCM does not re-freeze and cannot absorb more heat the next day. There have been many experimental studies on the impact of using plasterboard impregnated with PCM in buildings. These typically reduce peak temperatures by 2-4°C (Kuznik et al, 2011). Most of these experiments are done in Central Europe, the Middle East or Far East – very few in the UK. Colclough et al (2009) has simulations from four locations in central and western Europe.

Raj and Velraj (2010) recommends that careful design is needed if the difference between external and internal temperatures is less than 15°C. For the UK climate, the difference between average daily maximum and minimum temperature is less than 10°C (MET Office, 2012).

## *Short term heat storage*

Short term storage (from hours to a few days) can be used in various ways, summarised in the table below.

*Uses of passive and active thermal storage*

| Type of storage | Uses |
|---|---|
| Passive storage – usually embedded in the building walls, floor or roof, works within the ambient temperature range. | Absorbs solar gain or heat from appliances during the day, reducing the demand for cooling during the day and heating in the evening (Kuznik et al, 2011; Baetens et al, 2010; Arce et al, 2012). |
| Active storage – usually in modular systems such as night storage heaters but can also be built into floors (Farid and Kong, 2007; Cabrol and Rowley, 2012). Ceramic chimneys for wood stoves are another option (Buchner and Hofbauer, 2003). Heat can be stored at higher temperatures depending on the material and means to control the rate of energy release (and fire risk). | Reduces the cost of heating by storing heat energy when it is cheap. This can be using fixed rate economy tariffs such as Economy 7 or Economy 10 (Cabrol and Rowley, 2012), or in the future more flexible tariffs may be available when there is wind and sunshine to power renewables.<br>Can support CHP systems: when electricity is needed but heat is not the heat can be stored for later (Barbieri et al, 2011; Ren et al, 2008).<br>Solar powered refrigerators use a heat source instead of electricity for power. A heat store can be used to compensate for intermittent sunshine (Chidambaram et al, 2011). |

Phase change materials are useful in both passive and active heating systems but they are more important for passive heating systems, because the temperature range is low (typically between 20°C and 30°C, giving a range of 10°C at most). Conventional materials such as concrete, brick, earth and clay cannot store much heat over such a narrow range. Adding PCM can double the heat stored in some constructions (Cabeza et al, 2011).

Passive storage is an essential element of a ‘trombe wall’, which connects the main rooms in a building with a sun-trapping air space behind glass, usually on the southern wall. The wall stores the solar energy absorbed by the glass. Ventilation between the wall and the rooms can be adjusted, which helps to control when the stored heat is released. Using PCMs, trombe walls can be made thinner. For example an 8cm PCM panel can perform better than a 40cm masonry wall (Tyagi et al, 2007).

Passive storage can also be used for cooling electrical components, for example PV panels, which need to be cooled to maintain optimum efficiency (Huang, 2011).

For active storage, PCMs can reduce the size of the building unit needed to store the requisite amount of energy, or allow more energy to be stored at a lower temperature (Farid and Kong, 2007). The optimium temperature depends on how the heat is going to be used. For example, underfloor heating systems need lower temperatures than conventional radiators. According to simulations for several locations in the UK, adding PCM to a concrete slab in an underfloor heating system driven by an air source heat pump enables cost savings without loss of comfort, by only running the heating system at off-peak times (Cabrol and Rowley, 2012).

Heat storage materials require space and ideally they are integrated into the fabric of the building. Buildings with a mainly brick or concrete construction already have a considerable heat capacity and this is used by products such as Termodeck, which links the thermal mass of concrete with an mechanical ventilation ducting system. PCM can be incorporated into plasterboard (up to about 25 percent, Zhou et al (2011) or into lightweight concrete, making ‘thermocrete’ (up to 5 percent PCM) without weakening the concrete excessively (Cabeza et al, 2007)). Alternatively it can be made into panels encased in metal or plastic foil. However, many organic PCMs, such as paraffin wax, are flammable so using them can contribute to a fire risk (Cabeza et al, 2011, Zhou et al, 2011).

For heat storage, the material’s thermal *conductivity* (how quickly it conducts heat) is important as well as the thermal *capacity* (how much heat it can store) because this affects how fast heat can be stored and used. For example organic PCMs often have low conductivity and work best when used in small nodules in a larger matrix (Cabeza et al, 2007) or with additives to improve conductivity (Wang et al, 2009; Mei et al, 2011; Sari and Karaipekli, 2011).

Another factor to consider is how the heat release is controlled. Ideally, heat should be stored until it is needed, rather than being simply released at a rate depending on the temperature of the storage medium (as in night storage heaters).

## Short term cool storage

Refrigeration and air conditioning applications with a variable load can use a cold reservoir to even out the demand. Reducing the peak cooling demand means:

- a smaller refrigeration unit can be used – using less refrigerant and reducing the capital cost
- the peak load on the electricity grid is reduced

When the cold store is used in the form of slurry, such as an ice/water slurry or PCM in water, then it can be used as heat transfer fluid as well as thermal store. In this case there are additional requirements for the material used:

- low viscosity
- uniform particle size to prevent clogging
- physical resiliance to withstand mechanical pumping
- stability over thousands of heating/cooling cycles – potentially several times a day (Zhang et al, 2009)

Absorption refrigeration units are powered by a heat source, such as a solar panel, rather than electricity. A heat store can be used to compensate for the fact that the sunshine is intermittent but it needs to operate over a narrow range of temperatures. A PCM heat store has the advantage both of high energy density and a steady temperature. Rather than store the cooling energy generated by the refrigerator there is also the option of storing heat to drive it (Chidambaram et al, 2011).

## *Long term heat storage*

If heat can be stored in summer for use in winter then heating energy demand in winter can be substantially reduced.

There are working examples in many countries where heat is stored :

- in natural or artificial ponds (Novo et al, 2010)
- in gravel pits (Novo et al, 2010)
- in the ground, in aquifers or rock. Solar assisted heat storage in this way has been demonstrated in Norway (Stojanović and Akander, 2010) and in Germany (Bauer et al, 2010)

There are at least two companies installing inter-seasonal storage in the UK: ICAX Ltd and IFTech Ltd. They deploy storage in earth banks or aquifers. There are case studies on their website but we did not find any published literature.

Greater storage densities could be achieved by new materials under development including:

- phase change materials
- using special materials such as concrete (Kaufmann and Winnefeld, 2010) or various salts (N'Tsoukpoe, 2009; Ghommem et al, 2011), where the storage and release is through a reversible chemical reaction, such as dehydration and rehydration

Water or gravel is the most common medium for large scale storage. Typically the temperature range could be 50°C, which gives an energy density of 210 MJ/$m^3$ (58 kWh/$m^3$).

The average yearly demand for space heating for a home in Great Britain is 4800 GJ (13,000 kWh) (Palmer & Cooper, 2011). A heat store for 4800GJ, based on water and a temperature range of 50°C would require 230 $m^3$. This is equivalent to a small swimming pool.

For a newly built house, the energy requirement would be much less. Also a system which contributed only a proportion of the heating needs could still make a large contribution to reducing winter energy requirements and overall carbon emissions.

## Insulation Materials

To reduce the heat flow through walls and roofs, etc. you need insulation. Heat loss is described by the U-value for a structure - this is in watts per unit area per unit temperature difference $W/m^2/K$. To achieve a low U-value you need a high thermal resistance; each layer in the building envelope contributes to this resistance but some more than others. For example, for a U-value of 0.3 $W/m^2/K$ you need a total resistance of 3.3 $m^2K/W$ which could be achieved by: 3.3m of concrete or 16.5cm of cork or 4.6cm of aerogel.

The resistance of a layer is the thickness divided by the conductivity (t/c). Adding thickness or reducing the conductivity increases the resistance and reduces heat loss; highly insulated materials have low conductivity. The units of conductivity are W/mK. For most materials, this is rather small so we use milliwatts rather than watts: mW/mK.

Traditional building materials such as brick, stone and concrete typically have high thermal conductivity: 600-2500 mW/mK. Woods insulating properties are a great deal better at 100-200 mW/mK. Incorporating air cavities into bricks or blocks, especially small bubbles as in foamed breeze blocks, has the advantage of making the blocks lighter as well as less conductive, but even the best is still nowhere near as good as even organic insulation materials such as wool or wood fibre.

Mineral wool insulation is a little better than organic materials and petrochemical based insulation is better still - approaching or even exceeding the insulation potential of still air. The enhanced performance depends on having very small pores. This mechanism is taken to its limit in aerogel. Alternatively, removal of the air altogether results in vacuum insulation panels (commonly used in fridges and for industrial pipework). Both aerogel and vacuum insulation panels are however very expensive because they are made from very pure silica, which is not cheap.

Shiny surface materials such as aluminium foil reduce heat loss by radiation and this effect is used in multifoil insulation systems. However, lab tests and modelling suggest the improvement is marginal, and the shininess will reduce over time with dust and tarnish.

The conductivity of materials is also heavily affected by moisture content. In most cases conductivity is significantly increased when moisture is present. Also, moisture can accumulate in the other parts of the wall structure which are permeable such as brick or wood which causes damage and shortens the life of the structure. Moisture can come from inside, from the activities of the residents (cooking, clothes drying, breathing) or from rain outside. If the building is not airtight then air and moisture can travel through the structure (Al-Homoud, 2005).

There are two very different approaches to handling moisture in walls. One is to keep it out using vapour barriers, but these are vulnerable to damage from nails and screws and bad handling (MacMullen et al, 2011; Pavlík and Černý, 2009). Also, there is often moisture present when the structure is first built (Al-Homoud, 2005). A vapour barrier will hinder this moisture from drying out (Kuenzel, 1998). The other approach is to use breathable materials throughout and rely on the moisture drying out naturally (Stahl et al, 2012). Drying out is slower when the wall is cold because high performance insulation has been used, especially when the insulation has been added on the inside of the wall so the whole wall structure is cold (Al-Homoud, 2005). The approach used dictates whether the insulation material should either be breathable or not.

Whichever approach is taken the exterior surface of an insulated wall remains cold and therefore wetter than it would otherwise. This can increase the likelihod of microbes growing on the outside of the wall in humid conditions (> 80 percent relative humidity), which may reduce the life of the wall. (Sadenini et al, 2011). Frost damage is also greater in internally insulated walls because the outer brick work is cold and can freeze. Although freezing may not begin until a few degrees below 0°C, once frozen the ice conducts heat faster than liquid water and the ice front travels deep into the brickwork (Laycock, 2002). Humid and wet conditions are common in UK winters.

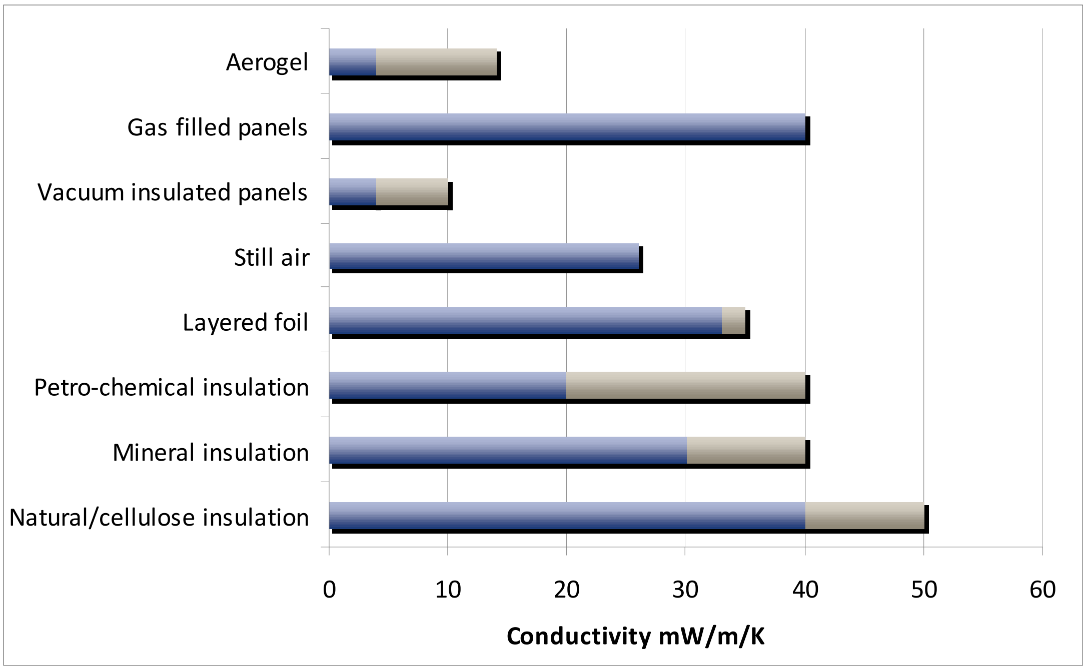
The table below summarises known characteristics of traditional and new insulation materials.

*Characteristics of different kinds of insulation*

| | **Natural/ cellulose insulation** | **Mineral insulation** | **Petro-chemical insulation** | **Layered foil** | **Vacuum insulated panels** | **Gas filled panels** | **Aerogel** |
|---|---|---|---|---|---|---|---|
| Conductivity mW/mK | 40-50 (cork )<br>40-50 (cellulose)<br>39 sheeps wool | 30-40 | 30-40 expanded polystyrene, 20-30 polyurethane | 33-35 | 4-10 | 40 typical | 13-14 commercial |
| Breathable | Yes | Yes | Variable (may have facing) | No | No | No | Yes |
| Absorbs moisture | Yes and moisture will reduce insulation | Yes but not so much as with cellulose | Variable | No | No | No | Usually hydrophobic to reduce condensation |
| Can be cut to fit | Yes | Yes | Yes | Yes | No | No | Yes |
| Installation considerations | Must be ventilated | Some fibres can cause lung damage (risk to workers) | Joints between panels must be sealed | None | Very delicate – best suited to prefabricated components | As VIPs but not so bad. | Cutting raises dust but not expected be a health risk.<br>Fragile in tension |
| In-use considerations | Must be ventilated to prevent mould and fungus. | None | Toxic fumes can be released in case of fire. | None | Easily damaged.<br>Expected age varies, even without a puncture | as VIPs but not quite so bad as not under vacuum | |
| Scalable | Yes | Yes | Yes | Yes | Manufacturing complex with manual steps. | Yes | Yes |
| Maturity | Product | Product | Product | Product | Product | Development abandoned | Early products |

The chart below illustrates the conductivity ranges for insulation materials in the table above. This also gives a guide to the thickness needed to achieve a target thermal resistance: with half the conductivity you need half the thickness.

*Minimum and maximum conductivity of some insulation materials (many sources)*



High levels of insulation have diminishing returns, as illustrated in the table below. These benefits must be balanced against costs and the calculation depends on other aspects of the building, such as its type and shape, ventilation systems and so on (Al Homoud, 2005).

*Savings from increasing thicknesses of insulation with conductivity 40 mW/mK (simplified calculation*)*

| Thickness insulation mm | Resistance $m^2K/W$ | U-value $W/m^2/K$ | Savings in heat loss |
|---|---|---|---|
| 0 | 0.0 | 2.15 | |
| 50 | 1.3 | 0.72 | 66% |
| 100 | 2.5 | 0.48 | 78% |
| 150 | 3.8 | 0.39 | 82% |

---

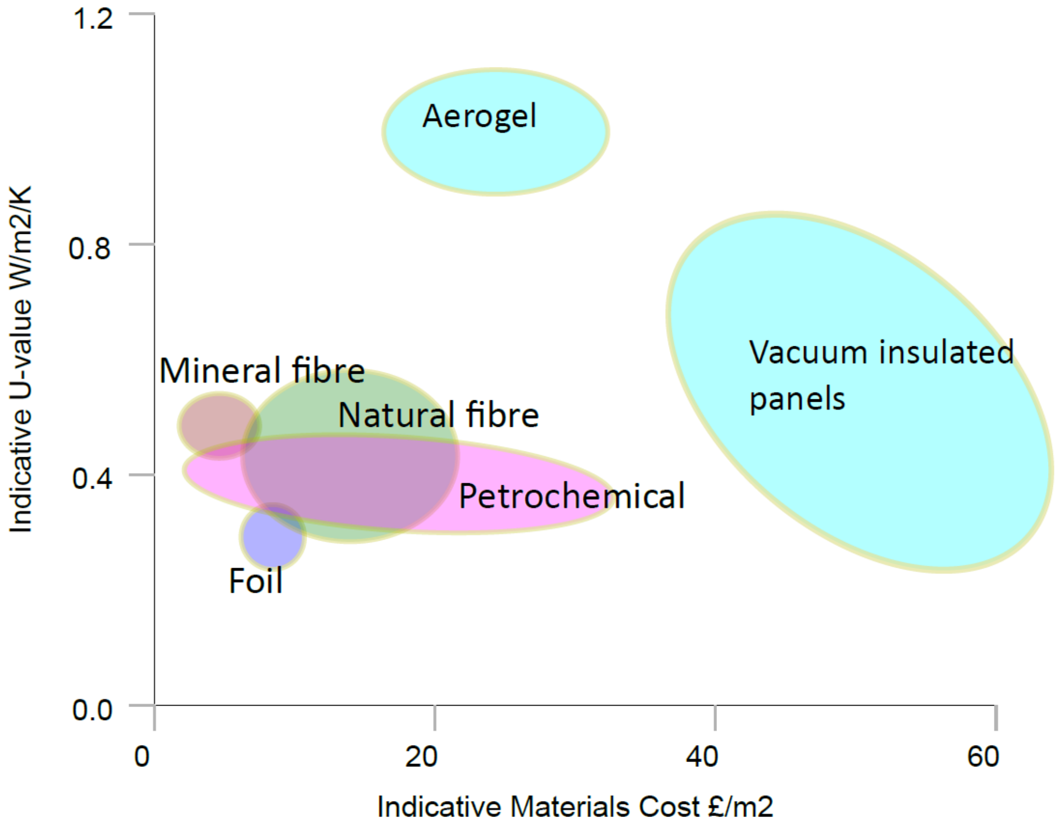
* This simplified calculation for U-value assumes a resistance of 0.5 m2 K/W for the brick, plaster and internal and external resistance, and adds a U-value of 0.15 to take account of thermal bridging, in acccordance with Standard Assessment Procedure for older properties (BRE, 2010).

The table and chart below show indicative costs for range of insulation types.

*Indicative material price (excluding installation) and U-value for insulating a solid wall (simplified calculation*)*

| | Price £/m$^2$ | U-value | Thickness (mm) |
|---|---|---|---|
| No insulation | - | 2.15 | 0 |
| Wool (N) | 14 | 0.33 | 200 |
| Wool (N) | 9 | 0.48 | 100 |
| Wood fibre (N) | 18 | 0.48 | 100 |
| Glass fibre (M) | 5 | 0.44 | 100 |
| Mineral fibre (M) | 5 | 0.47 | 85 |
| Polyisocyanurate (P) | 22 | 0.35 | 100 |
| Extruded polystyrene (P) | 28 | 0.35 | 120 |
| Expanded polystyrene (P) | 5 | 0.41 | 100 |
| Insulated plasterboard (phenolic) (P) | 22 | 0.38 | 80 |
| Multi-foil (M) | 8 | 0.27 | 30 + air gap |
| Multi-foil (M) | 9 | 0.30 | 30 + air gap |
| VIP (V) | 40 | 0.72 | 10 |
| VIP (V) | 50 | 0.48 | 20 |
| VIP (V) | 60 | 0.39 | 30 |
| Aerogel (A) | 20 | 0.97 | 10 |
| Aerogel (A) | 30 | 0.97 | 10 |

*Indicative U-values and costs for solid wall insulation*



The chart shows that natural fibres are cheap but need to be thick to achieve low U-values. Aerogel and VIPs are more expensive but can be much thinner. Even with 10mm of aerogel the heat loss through a solid wall is halved. For multi-foils the U-value is calculated for the equivalent in mineral wool as claimed by the manufacturer.

These price points come from a mix of sources including product prices from internet sites, Spon's Architects' and Builders' Price Book 2012, and private correspondence with manufacturers, as shown in the table below. Both Aspen Aerogels and Nanopore (vacuum insulation panels) indicated that the price of their products was high because of raw material costs (silica in both cases), and although there would be some savings from process improvements, these were unlikely to be more than 10-20%.

| **Material** | **£/m$^2$** | **Conductivity mW/mK** | **Source** |
|---|---|---|---|
| Sheeps wool | 13.50 | 40 | www.diy.com |
| Thermafleece | 9.00 | 39 | www.just-insulation.com |
| Pavatherm wood fibre | 18.00 | 40 | www.just-insulation.com |
| Glass fibre | 5.00 | 35 | SPON |
| Earthwool rafter roll | 5.50 | | www.diy.com (resistance given as 2.7 for a thickness of 85mm) |

| | | | |
|---|---|---|---|
| Kingspan Polyisocyanurate | 22.00 | 22 | SPON |
| Styrofoam 500 extruded polystyrene | 28.00 | 26 | SPON |
| Kay Metzeler expanded polystyrene EPS70 | 5.00 | 30 | www.just-insulation.com |
| Kingspan insulated plasterboard K17 (phenolic) | 22.00 | 21 | www.just-insulation.com |
| YBS Superquilt | 8.00 | As 270mm mineral wool | www.just-insulation.com |
| Actis Triso Super 10 | 9.00 | As 210mm mineral wool | www.just-insulation.com |
| Vacuum Insulation Panel 10mm | 40.00 | 8 | Correspondence with Nanopore |
| Vacuum Insulation Panel 10mm | 50.00 | 8 | Correspondence with Nanopore |
| Vacuum Insulation Panel 10mm | 60.00 | 8 | Correspondence with Nanopore |
| Aerogel Spaceloft 10mm minimum | £20-30 depending on process and quantity | 14 | Correspondence with Aspen Aerogels |

## *Conductivity of air*

The conductivity of still air at normal pressure is around 26 mW/mK. This is a lower limit for most forms of insulation, and to get below this level you need to:

- Fill pores with vacuum or a low-coductivity gas, as in gas filled panels or vacuum insulation panels (Baetens et al, 2011), or polystyrene or polyurethane foam (Al Homoud, 2005)
- Use very tiny pore sizes (< 500 nm). As the pore size is reduced the gas molecules change behaviour, because they are increasingly likely to bump into the pore boundaries rather than each other, so energy transfer between molecules is less effective (Baetens et al, 2011)).

## *Timber, concrete, bricks and blocks, mortar and screed*

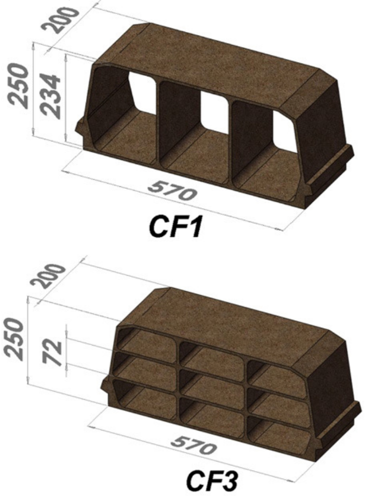
These are all materials with low insulation value used in buildings, and especially poor insulators when damp. Novel materials, treatments and manufacturing techniques can improve their performance, however even insulating renders with polymer additivies do not quite achieve the low conductivity of natural materials, see next section.

*Conductivity of different kinds of building materials*

| | Conductivity mW/mK | Notes and source |
|---|---|---|
| Timber | 100-200 | (Jelle, 2011) |
| Brick | 400-800 | (Jelle, 2011)<br>up to 1360 mW/mK when damp (MacMullen et al, 2011) |
| Concrete | 150-2500 | (Jelle, 2011) |
| Sand/cement breeze blocks: | | |
| Hollow | 1600 | (Radhi, 2011). |
| Foamed | 600 | (Radhi, 2011) |
| Alveolar brick | 270 | (de Gracia et al, 2011) |
| Fibofoam | 250 | (Monaprecast). |
| Autoclaved alveolar concrete | 120 | (Radhi, 2011) |
| Stone | 1000-2000 | (Jelle, 2011) |
| Glass | 800 | (Jelle, 2011) |
| Insulating renders (incorporating polymers such as expanded polystyrene) | 60-70 | (Stahl, 2011) |
| Sand screed | 1900-2200 | up to 2400 when wet |
| Recycled glass screed | 800-800 | Up to 1000 when wet |
| | | (Alani et al, 2012) |

Sand/cement breeze blocks are widely used to build walls, load-bearing and also partition walls. Aerated or foamed blocks are lighter and have lower conductivity. Autoclaved alveolar concrete (AAC) has only a quarter the density of foamed blocks but the autoclave process makes it strong enough for load bearing. The conductivity is around 120 mW/mK, compared to 600 mW/mK for a foamed block and 1600 mW/mK for a hollow block. However, the AAC blocks cost more than twice as much as hollow blocks and 30% more than foam blocks (Radhi, 2011). Commercially, AAC blocks are called aircrete and can be obtained from suppliers such as Hanson (Heidelberg Cement Group) which gives conductivity values from 110 to 200 mW/mK for different sorts of block (Hanson).

*Best shape floor block (CF3) and worst (CF1) from del Coz Diaz (2010)*



Expanded clay can be mixed into concrete for an intermediate product – for example Monaprecast supplies Fibotherm blocks, which have conductivity of 250 mW/mK at 3% moisture, rising slightly to 280 mW/mK at 5% moisture (Monaprecast). The strength of the concrete is reduced to 3.5 MPa. Perlite can be used in a similar way but also with a reduction in strength. 60%

perlite brings the conductivity down from 600 to 250 mW/mK but the compressive strength drops from 29 to 4.6 MPa. Also the perlite has higher moisture absorption (Sengul et al, 2010).

For blocks with hollow recesses, the shape is very important as well as the material. Del Coz Diaz et al (2010) compared the performance of six different shapes and three different materials, including lightweight concrete, for building floors. (The total floor construction also included more concrete and plaster.) The best shape standard concrete blocks performed the same as the worst shape lightweight concrete, even though the bulk conductivity of the concrete was five times worse. The best blocks had nine (3x3) or 12 (3x4) recesses and the worst had only three (as pictured).

Normal brick has a conductivity around 640 mW/mK when dry, but 1360 mW/mK when damp. Similarly, mortar is much more conductive when damp: dry conductivity 1060 mW/mK, wet 1810 mW/mK (MacMullen et al, 2011). Treating the bricks with a water repellant cream increases the conductivity when dry by a small amount, but significantly reduces the conductivity when wet. (MacMullen et al, 2011). How long these treatments last is currently uncertain.

Alveolar brick has lots of narrow holes through it (unlike hollow brick which has one big cavity). The conductivity of alveolar brick is about 270 mW/mK, less than half that of normal brick, but still eight times the conductivity of conventional materials such as mineral wool. These bricks can be used in load bearing walls (de Gracia et al, 2011).

Glass can be recycled as aggregate or into screed (Alani et al, 2012). This has a lower conductivity and a higher heat capacity than sand screed. However, the difference is not significant for the whole wall.

## *Natural insulation materials*

The table below gives the conductivity in average conditions. However all these materials are vulnerable to damp and the conductivity increases when they are damp.

*Conductivity of different kinds of natural insulation materials*

| | **Conductivity mW/mK** | **Notes/source** |
|---|---|---|
| Cork | 40-50 | (Jelle, 2011) |
| Sheeps wool | 39 | Product data sheets from www.kontrol-insulation.com and from www.sheepwoolinsulation.ie |
| Recycled cellulose | 40-50<br>40 | (Jelle, 2011), increasing with 5% moisture to 66 mW/mK<br>(Warmcel 100,300,500 data sheets) |
| Hemp/flax | 39-49<br>39 | Increasing slowly while moisture levels are below 6% which occurs at around 60% relative humidity, Korjenic (2011)<br>Breathe insulation from www.hemptechnology.co.uk |
| Straw bales | 45-60 | Depends on the orientation of the straw and also the density of the streaw (Doujet, 2009) |

## *Mineral insulation*

Mineral and glass fibre both have a texture much like wool. They can be used to fill cavities and spaces or formed into boards or mats which can be cut to fit. The thermal conductivity typically increases with moisture, but they do not absorb as much damp as the natural fibre. For example, mineral wool absorbs up to 4 times less moisture than cellulose in the same conditions (Vrana and Gudmundsson, 2010).

When using either mineral wool or natural insulations it is usual to install a water-proof membrane between the insulation and the plaster to protect the insulation from damp, but this can be punctured. Water repellant mineral wool can be used instead. It is still recommended to have a water barrier below that to protect the wall, but this is less vulnerable (Savlik et al, 2008).

*Conductivity of different kinds of mineral insulation materials*

| | **Conductivity mW/mK** | **Notes/source** |
|---|---|---|
| Mineral wool | 30-40 | Up to 55 when damp (Jelle, 2011) |
| Vermiculite (loose fill) | 23-43 | Depends on density and temperature – lower conductivity at low densities and low temperature (Perlite Institute) |

## *Petrochemical insulation*

These types of insulation are supplied as rigid blocks, often with a plasterboard or foil facing. They can be cut to fit.

*Conductivity of different kinds of petrochemical insulation*

| | **Conductivity mW/mK** | **Notes and Source** |
|---|---|---|
| Expanded polystrene | 30-40 | Increases with moisture e.g. 54 at 10% (Jelle, 2011) |
| With added graphite (Neopor) | 30-32 | BASF (www.plasticsportal.net) |
| Extruded (XPS) | 30-40 | Less affected by moisture as closed pore structure (Jelle, 2011), |
| Polyurethane | 20-30 | Gives off toxic fumes in case of fire (Jelle, 2011) |
| PIR (Celotex) | 22-23 | Kingspan |
| Phenolic | 21 | Kingspan K3 insulation for floors) |

## *Vacuum insulation panels (VIPs)*

Vacuum insulation panels are panels of vacuum-packed insulation: sheets of insulation (foam, fibre or powder) wrapped in an air-tight envelope with all the air removed. Since air conducts heat but a vacuum does not, the evacuated panel is a much better insulator than it was.

For example, the conductivity of typical expanded polystyrene (EPS) is 35 mW/mK. The same material in a VIP could be 8 mW/mK – less than a quarter of the air-filled panel. VIPs based on foams such as polyurethane foam or glass fibre can have conductivity as low as 4 mW/mK (Alam et al, 2011). This means you only need a thin panel to get a low U-value wall – at 4mW/mK you only need 2cm of insulation for a U-value of 0.2. (A good U-value even for a new 2012 building.) Typical VIPs have conductivities between 4 and 10 mW/mK (Jelle, 2011).

To achieve low conductivity the panel must have a very good vacuum but no envelope is perfect – air and moisture will seep in over time. The lifetime of the panel is defined as the time before enough gas seeps in that the conductivity rises to an unacceptable level. Starting from 4 mW/mK, different standards allow up to 8 mW/mK or 11 mW/mK (Baetens et al, 2010).

Accidental damage can also perforate the panels either during construction or in use. For example, if panels are used in walls, they can be damaged by fixings for shelves or pictures. If a panel is perforated the conductivity is likely to rise to at least 20 mW/mK (Jelle).

Silica fume (fine-grain silica with a very high surface area) is the best core material because:

- The nano-size pores retain low conductivity, up to 10 mbar, extending the life of the panel. Other materials require 100 times better air tightness for the same conductivity (Fricke et al, 2008).
- It is robust in compression.
- It has a completely open cell structure, which enables a good vacuum to be achieved (Baetens et al, 2010).

Silicon carbide can also be added to the fume to reduce heat flow by radiation (Fricke et al, 2008).

However, silica fume is expensive. It might be possible to use a cheaper core material if the envelope was more air tight and durable (Fricke et al, 2008).

Mathematical models for predicting the panel lifetime take into account a range of factors including the material of the core and envelope and the conditions the panel is subjected to (temperature and moisture). Some work has been done to validate them with accelerated aging tests (Wegger et al, 2011). Lifetimes of 10-40 years have been predicted for panels with a metallized foil envelope, but aluminium foil is stronger and gives longer lifetimes – up to 160 years (Baetens et al, 2010).

In situ testing over 3 years on VIPs incorporated into a flat roof suggested an expected lifetime of only 25 years. The panel envelope was three-ply metallised film and it was laid under a protective layer, bitumen and gravel (Brunner and Simmler, 2008).

Aluminium envelopes are stronger but also conductive, and this means there is a bigger thermal bridge effect at the edges. To insulate a wall you need to put panels side by side and heat can travel between them, along the envelope ends. When the envelope is conductive this allows the heat to travel sideways and find the edges. Even 8 µm aluminium foil conducts heat 10 times faster than metallized film, which is 10 times as thick (Alam et al, 2011).

Overall there is a trade-off between lifetime and performance. The best performing VIPs (which allow for thinner panels) have the shortest life and are most delicate. In practice VIPs are fragile and are best used as parts of prefabricated components such as pre-fab walls and roofs, doors or window frames.

Because VIPs are such good insulation and because they are not permeable to air or moisture, they can lead to problems with condensation at joints in the structure where the VIP surface is at a low temperature and humid air can seep in (Baetens et al, 2010; Jelle, 2011).

Although VIPs are manufactured on a large scale there is manual labour involved and the panels are very expensive (Baetens et al, 2010). The payback time for installing panels predicted for four different scenarios shown in (Alam et al, 2011) ranges between 7 years and 15 years compared to expanded polystyrene paying back in less than one year. However, giving a value to the space saved by using thinner panels, (£40/ft$^2$ which is £444/m$^2$, average for London office space) the payback times range from around 1 to 3 years (Alam et al, 2011).

### VIP products

There are several manufacturers selling vacuum insulation panels for building insulation at the moment.

*Conductivity of some VIP products*

| | | |
|---|---|---|
| Va-q-tec<br>www.va-q-tec.com | va-Q-vip B<br>Thicknesses 10,15,20,25,30,40 mm | 8mW/mK including aging and edge effets |
| NanoPore:<br>www.nanopore.eu | NanoPore Vacuum Insulation Sheet | 4mW/mK in centre of panel |
| Porextherm:<br>www.porextherm.de | Vacupor NT-B2-s<br>Also panels available with 1-2cm polystyrene or extruded polystyrene protective layers on either side or noise reduction sheets. | 7 mW/mK |

Vacuum insulation panels are also available for insulating refrigerators or high temperature heat stores.

## *Gas filled panels*

Gas filled panels (GFPs) are similar in many respects to vacuum insulated panels but they are filled with a gas such as argon, xenon or krypton rather than vacuum. Prototypes have conductivities around 40 mW/mK although theoretically they could be much better (Jelle, 2011).

The conductivity of still air at 25°C is 26 mW/mK. For xenon it is 5.6 mW/mK (Baetens et al, 2010).

Theoretically, the conductivity of GFPs containing air, argon and krypton have been predicted as 35, 21 and 10 mW/mK but by experiment these values are not achieved: 46 and 40 for air and argon. This is not as good as traditional building materials (Baetens et al, 2010).

There are very few papers being published on this subject at the moment.

## *Layered foil systems*

Multi-foil systems consist of several layers with low-emissivity surfaces (typically aluminium or aluminized film) separated by insulation. The intention is to reduce heat loss via radiation as well as conduction. Radiation energy increases with the 4th power of temperature in Kelvin (Mavromatidis et al, 2011) so this effect is greater at larger temperature differences. However, over the range of temperatures likely to be encountered in buildings, the additional resistence is almost constant.

(Considering $T_1$= 6-22°C, $T_2$= 3°C, then $(T_1^4 – T_2^4)/(T_1-T_2)$ varies by only 10%.)

TLX Silver (30mm) and TLX Silver FB (50mm) from Web Dynamics are typical products. The British Board of Agrément has measured their thermal resistance (the reciprocal of conductivity, a measure of how good materials are at resisting heat flow) at 0.91 $m^2K/W$ and 1.43 $m^2K/W$. This translates to conductivity of 33-35 mW/mK.

Manufacturers claim that these tests under-estimate the effect of the multifoil system because they put the sample between hot plates, which tests conduction only. In order to make use of the reduction in radiation you need to have an air gap of 1-3cm on at least one side.

Several studies of layered foil systems have used models of the heat flow, taking account of convection as well as radiation and conduction. Modelling with an air gap on both sides has shown (Mavromatidis et al, 2011) that the optimum air gap is 30mm. This significantly adds to the overall depth of insulation.

A slightly different scenario, with two layers of extruded polystyrene separated by a totally enclosed air gap with foil on only one side, was investigated in Saber (2011). They found that the presence of the low emissivity surface of the foil reduced the conductivity of the sandwich construction by up to 15% when heat came from below – a little more, up to 20%, when heat was flowing from top to bottom.

The low emissivity effect of multi-foil degrades over time as the surfaces tarnish (Mavromatidis et al, 2011).

Trada technology Ltd state that their Triso Super-10 insulation (30mm thick, 19 layers) is equivalent to 210 mm of mineral wool (Trada, 2009). However, this claim is based on in-situ testing (in France) and they do not declare the equivalent U-value.

Thermal modelling conducted for the Department for Communities and Local Government by Eames (2009) showed that a 30mm thick multi-foil system with 25mm air gap on either side performes poorly in comparison to mineral wool. Even with aerogel blanket between the layers, the multifoil system was not as good as 200mm of mineral wool. However, this model was not validated by testing against a physical construction.

Field tests on an earlier version of the Triso product (Ward and Doran, 2005), where heat flow was measured, found that in fact the U-values on site were 2-4 times higher (=worse) than would be expected based on the manufacturs' claims. In fact, the measured heat flows were close to the expected values based on the conductivity determined from lab testing.

## *Aerogel*

Aerogel consists of a silica gel with nano-sized gas-filled pores. It is very light, very fragile, and an excellent insulator. With such tiny pores – below about 40nm pore size (for air) – gas molecules start bumping into the walls rather than each other (the 'Knudsen effect') and conductivity is dramatically reduced. State of the art gels can have conductivity as low as 4 mW/mK. However, below about 10,000 nm the pores are transparent to IR at some wavelengths so there could be some heat loss through the panels by radiation. This may or may not be signicant (Jelle, 2011).

Commercially available aerogels typically have a conductivity of around 13 mW/mK – not quite as good as vacuum insulated panels, but reportedly with better durability. Aerogel can be made more robust by adding ceramic fibres with little impact on its conductivity (Yang et al, 2011).

Nano insulation materials can be sandwiched within or even mixed into concrete (Jelle, 2011). Tests on aerogel mixed with a cement-free binder as high performance external wall insulation have shown promising results (Stahl et al, 2012). Areogel is also breathable.

Handling aerogel produces silica dust but the particles are not crystalline and animal experiments have not found evidence that they promote silicosis or cancer (Baetens et al, 2011). However, manufacturing aerogel is complicated and expensive. There are three basic stages: gel preparation, aging – which strengthens and stiffens the cell structure, and drying (Baetens et al, 2011).

Aerogel can be made as granules of different sizes or as monolithic aerogel, which is highly translucent. However, it is hard to make it in large enough sheets for glazing applications. Tests on small samples suggest that it would have similar thermal insulation values to the best conventional glazing available now: triple glazing with argon fill and low-e coatings, U-value 0.6 W/m$^2$/K (Stahl et al, 212).

Aerogel is currently available in sheets (with fibre reinforcement) for insulation from Aspen Aerogels and as pipe insulation and in translucent form as lightweight insulating glass from Cabot Corp. as ‘Cabot Aerogel Nanogel’.

## Heat Storage Materials

There are two fundamentally different ways to store heat in a material.

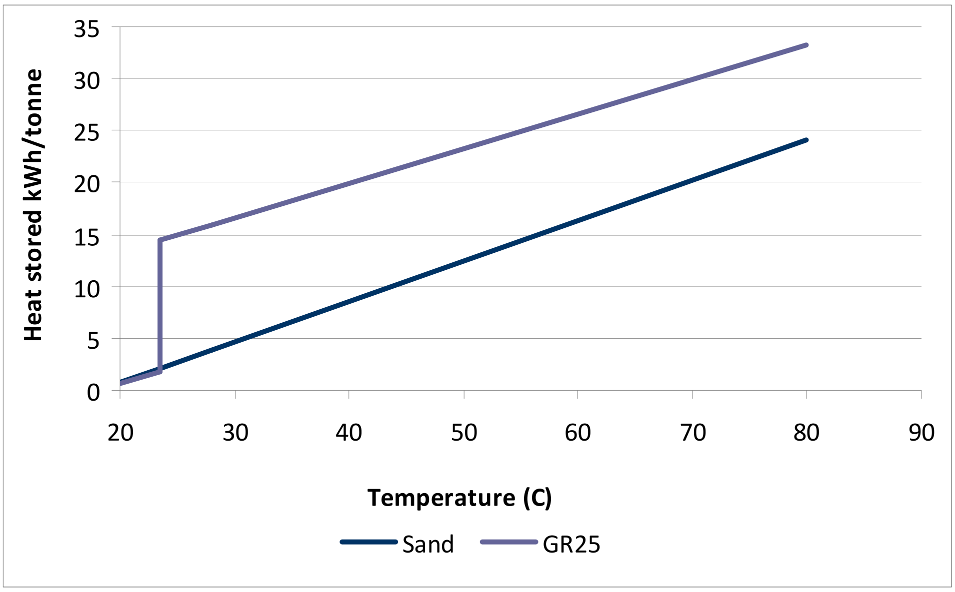
> **1. With a temperature change** – raising the temperature of the material stores heat, and cooling releases it. The amount of heat that can be stored depends on the specific heat capacity of the material and the temperature change that can be used. *Passive* heating applications, such as storing heat during the day and releasing it overnight, take place at ambient temperatures. This means you only have a useful range of at most 10°C (from 18°C to 28°C), otherwise your building gets uncomfortably warm or cold.
>
> For *active* heating the potential range is limited primarily by the temperature of the heat source. For example, solar panels of the evacuated tube type can reach 150 °C and electricity can supply much higher temperatures, limited only by safety concerns. When heat is stored in this way it tends to leak away over time and the heat store needs to be insulated to slow this process.
>
> **2. Without a temperature change** – this can be due to a phase change such as melting from solid to liquid – ice, wax, metal or many other materials – or a chemical change. For useful storage, you need to be able to get the energy back so the change needs to be reversible. Phase changes are reversible depending on the temperature only. For example, wax melts above the melting point and re-solidifies below it. The heat released when it solidifies, or absorbed when it melts, is the latent heat of fusion. However, most chemical changes are not (easily) reversed. For example, methane (natural gas) needs just a spark to burn in oxygen to produce carbon dioxide and water, but it is very diffcult to turn carbon dioxide and water back into methane and oxygen. The most common reaction useful for heat storage is hydration. For example, many salt crystals release heat when they absorb water but can be dried out again by supplying heat at a high enough temperature. Chemical reactions which involve releasing or absorbing heat are called thermochemical reactions.

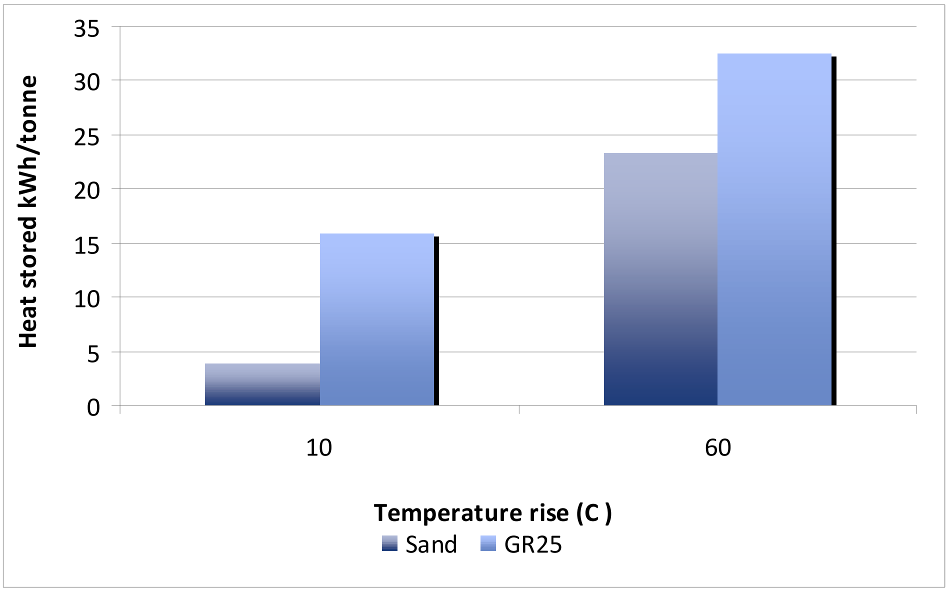
In all cases, temperature is key:

- For phase changes, you need heat above the melting point to store energy, which is released when the ambient temperature drops back below the solidification point. To store the energy for a long time you need to keep the temperature up, which means you need insulation.
- For thermochemical reactions, heat must be supplied above the turnover temperature in order to store energy, but you can retain the heat at lower temperatures afterwards. For example, you need at least 150°C in order to dry out magnesium sulphate (epsom salt paste) to a useful level, but once dry you can store it at room temperature indefinitely – so long as no moisture is allowed in (Hongois et al, 2011).

Even in phase change materials, the specific heat capacity is significant, as shown below. The line showing heat stored for sand is straight because no phase change is involved. The slope is steeper than for GR25, a commercial phase change material, because sand has a higher specific heat capacity (1.4 rather than 1.2). The vertical section of the GR25 line is the melting process – where heat is being stored but the temperature is not rising, only more of the material is becoming liquid. Over a small temperature change like 10°C , typical for passive heating applications, GR25 stores four times as much heat as the sand for the same amount of material. Over a large temperature rise there is much less difference between them.

*Heat stored by temperature change and melting*





In practice, the energy storage density is not the only important factor for heat storage: there is also the practical difficulty of getting heat into and out of the material. This is easy for liquids, or for solids with high thermal conductivity but otherwise requires some ingenuity. This will be discussed in detail for different materials.

The SI units for heat energy are Joules (J), however, at home we are more used to kilowatt hours (kWh), which appear on bills. A kWh is the total energy used in one hour at the rate of 1 kW. This is 3,600,000 J or 3.6 MJ.

The table below shows properties of some the materials which can be used for thermal storage in different ways. In practice, the energy densities achieved with PCM and thermochemical reactants are much lower than the theoretical maximum because the material has to be contained in something else. Phase change materials would otherwise flow away when melted. The resulting structure can be anything from 5% to 80% PCM.

*Characteristics of different kinds of heat storage materials*

| | **Bricks and mortar, Concrete** | **Sand (for floors)** | **Soil/rock (for under-ground)** | **Water** | **Organic PCM**<br>**Paraffin wax example from Agyenim et al (2010)** | **Inorganic PCM**<br>**$CaCl_26H_2O$: example from Agyenim et al (2010)** | **Thermochemical**<br>**Example data from Balasubramanian et al (2010) and Hongois et al (2011)** |
|---|---|---|---|---|---|---|---|
| Heat capacity by volume kJ/$m^3$/K (kWh/$m^3$/K) | 1600 (0.44) brick<br>2080(0.58) concrete<br>1700-2000 (0.47-0.55) rubberised concrete | 1024 (0.28) | 840-1400 (0.23 – 0.39) (1/5 to 1/3 of water) | 4200 (1.2) | paraffin wax:<br>solid 1594 (0.44), liquid 2710 (0.75) | $CaCl_26H_2O$:<br>solid 2400 (0.7) ; liquid 3400 (0.44) | 2520/2130 (0.70/0.59) magnesium sulphate – hydrated/dehydrated |
| Heat capacity by weight kJ/tonne/K (kWh/tonne/K) | 900 (0.25)<br>930-1000 (0.26-0.28) rubberised concrete | 800 (0.22) | 1260 (0.35) | 4200 (1.2) | 1000-2500 (0.28 – 0.69) typical.<br>paraffin wax:<br>solid 1920 (0.53) liquid 3260 (0.9) | 1500-2500 typical<br>$CaCl_26H_2O$:<br>solid 1400 (0.39) liquid 2200 (0.61) | 1500/800 (0.42/0.22) magnesium sulphate – hydrated/dehydrated |
| Latent heat capacity/reaction energy<br>MJ/$m^3$ (kWh/$m^3$) | n/a | n/a | n/a | 334 (93) | Paraffin wax 208 (58) | $CaCl_26H_2O$:<br>Solid 320 (89), liquid 286 (79) | 1710 (476) magnesium sulphate storage capacity<br>600 (170) for magnesium sulphate in zeolite. |
| Latent heat capacity/reaction energy<br>or MJ/tonne (kWh/tonne) | n/a | n/a | n/a | 334 (93) | 140-240 (39-67)<br>paraffin wax 251 (70) | 130 -230 (36-64)<br>$CaCl_26H_2O$: 187 (52) | 8500 (2400) magnesium sulphate hydration energy<br>648 (180) for magnesium sulphate in zeolite. |
| Temperature °C | n/a | n/a | n/a | 0 | typically 20-30<br>paraffin wax 32 | typically 20-30<br>$CaCl_26H_2O$: 29 | 120-180 or higher – needed for charging |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Can it be integrated into fabric | Yes. | Yes | n/a | no | Yes in building blocks or trombe walls | Yes in building blocks or trombe walls | Probably not |
| Can it be retrofitted | Not easily | Not easily | Yes – boreholes can be dug | Not easily | In plasterboard, false ceilings or floors | In plasterboard, false ceilings or floors | Maybe |
| Installation considerations | Good | | Depends on geology | Depends on container | | | |
| In-use considerations | Good | | | Depends on container | | | Needs humid air to release energy and high temperatures to store energy |
| Risks | | | | Leakage | Fire risk | Leaching, separation | |
| Scalability | Yes | Yes | | Yes | | | |

It is difficult to compare thermal storage systems without an application context to indicate thermal needs and temperature ranges. The table below lists some examples from the literature.

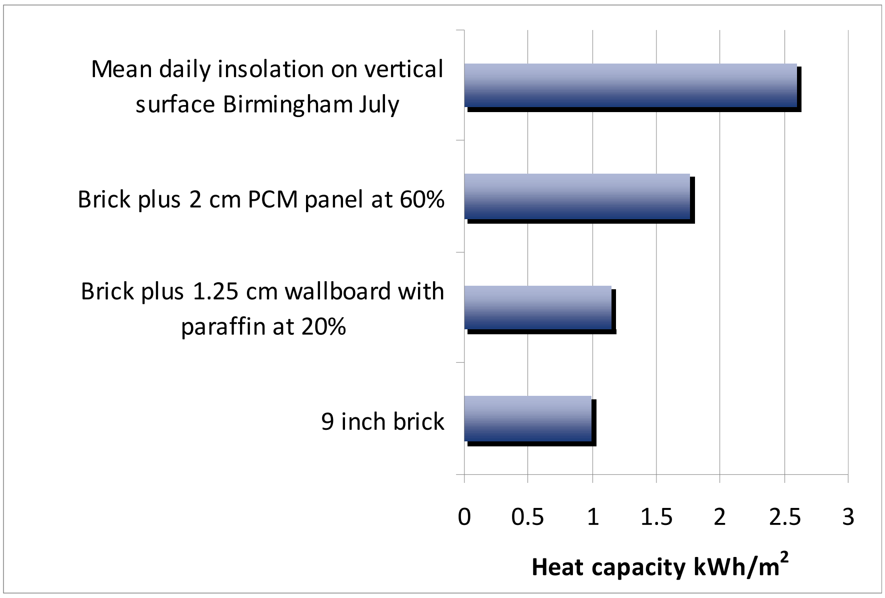
*Temperature ranges and PCM melting points used in different contexts*

| **Context** | **Temperature Range** | **PCM melting points used** |
|---|---|---|
| Air conditioning: heat storage and heat transfer fluids | Up to 15°C (must be below the target room temperature) | 0°C (Ice - in common use)<br>5-12°C recommended by Lu and Tassou (2012) and Zhou et al (2012) |
| Managing temperature gain with passive heat storage | 20-26°C target room temperature range | 26°C used by Arce et al (2012)<br>23°C and 26°C modelled by Colclough et al (2009) |
| Reducing heating needs with passive storage in wall | 20-26°C target room temperature range | 19°C found optimal by Diaconu (2011) |
| Short term storage for underfloor heating using off peak electricity | Up to 28°C floor surface temperature | 29°C Farid and Kong (2001)<br>24°C Cabrol and Rowley (2012) |
| Other active storage applications | From 10°C in large water basins, using heat pumps to upgrade the temperature (Bauer et al, 2010), theoretically up to > 100°C in high temperature insulated storage tanks (Kroll and Ziegler, 2011) | |

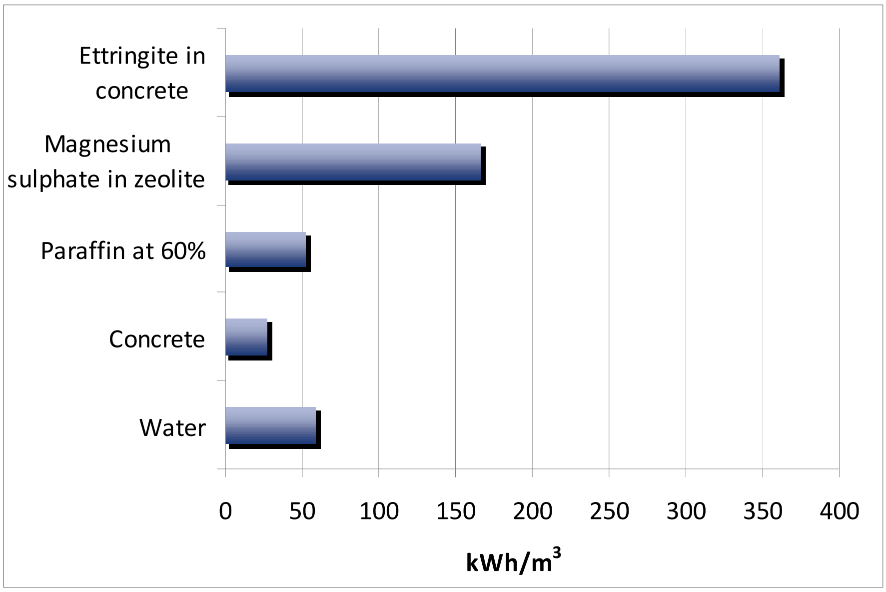
The two charts below illustrate the potentials for storage materials in two contexts. Firstly, consider a south facing brick wall which is 50% window. Insulating the wall mimimises solar gain in summer but there is solar gain through the window too. The average daily energy from sunlight per unit area is 2.6 kWh/m$^2$ in July. A plain brick wall 22.5cm (9-inch) thick would absorb less than half that. Adding 1.25cm wallboard impregnated with 20% paraffin makes very little difference to the heat capacity. (For paraffin, the specific heat capacity used is the average of the solid and liquid forms.) Adding a slightly thicker panel which is 60% paraffin helps a bit more.

The second chart shows the heat capacity for an active heating application, which could be short-term or even seasonal storage. The top bars for ettringite and for magnesium sulphate show the thermochemical storage potential; these would not have to be kept hot to retain this heat, only dry.

*Heat capacity over a 10°C temperature range for passive heating*



*Heat capacity over a 50°C temperature range for active heating*



The potential uses for thermal storage materials are very wide, and not limited to storing heat in buildings. There is ongoing research funded by the UK Energy Research Council into applications for thermal storage leading to reduced energy consumption and carbon emissions, in particular, using thermal storage in conjunction with renewable energy generation (UKERC, 2011).

## Costs of thermal storage materials

The cost of thermal storage is often more related to the containment than the material itself and this in turn relates to the application and very often the details of the site or installation. The thermal storage embodied in the building structural elements such as bricks and concrete is arguably free.

For storage using water, within a building the main cost is that of the tanks and plumbing. The weight of the tanks may be important, as well as the volume, as this needs to be taken into account in the building structure.

For large scale storage, in aquifers, tanks or ponds filled with water or gravel and water, the costs are site and scale dependent. There are advantages of scale. From a sample of 13 sites reported in Pinel et al (2011) dating from 2003, storage of less than 1,000 $m^3$ water (or equivalent) is 4-5 times as expensive (per unit of heat stored) as storage of more than 10,000 $m^3$. Aquifer storage is also likely to be half the cost of tanks. The sample costs range from £1.70 to £7.60 per kWh (with currency conversion and allowing for inflation since 2003).

For ground based storage, earthworks and drilling can be 20-40% of the system cost (Pinel et al, 2011).

Phase change materials vary widely in cost depending on the material and the containment. Containment is normally at least half the cost. Overall the price of contanment may vary from £0.50/kg to £25/kg. The material alone is likely to be £2.50/kg - £13.00/kg. This means a good value PCM could cost of the order of £50-£100 per kWh stored (from personal communication with suppliers).

## *Thermodynamic limit to specific heat capacity*

The Dulong-Petit law describes the specific heat capacity of a simple crystaline solid at high temperatures. At lower temperatures the heat capacity will be less (except at very low 'cryogenic' temperatures, which are not of interest for buildings).

The law can be simply stated as :

$$C = 3R/M$$

Where

C is the specific heat capacity of the material

R is the universal gas constant = 8.31 g/mol/K

M is the mass of 1 mole of atoms of the material (not 1 mole of molecules).

Consider quartz sand for example:

The chemical composition of quartz is $SiO_2$ – one silicon and two oxygen atoms. The total atomic weight is 60 for 3 atoms.

$$C = 3 \times 8.31/(60/3) = 1.2 \text{ J/g}$$

The actual specific heat capacity for quartz (at 0°C) is 0.83 J/g – about two thirds the Dulong-Petit limit.

In fact the specific heat capactity of a substance varies with the temperature; this is an effect of quantum mechanics. At low temperatures the heat capacity is less because not all vibrational modes are used.

It follows from the Dulong-Petit law that materials with high heat capacity tend to have small atoms, which favours organic compounds. This is why adding rubber to concrete increases the heat capacity by mass. However, when heat capacity by volume is more relevant, the mass density must also be taken into account – and organic compounds are often low in mass density.

This law does not apply to complex crystals such as salt hydrates.

## *Concrete*

Concrete has different properties depending on how it is made. It can have varying proportions of cement and aggregate, and different types of both cement and aggregate. Concrete is a traditional building material and is often used in foundations and floors.

On average, concrete has about half the heat capacity of water by volume – about 2100 kJ/$m^3$/K and about a quarter that of water by weight (about 900 kJ/tonne/K according to Hall et al (2012) or 1000 kJ/tonne according to Baetens et al (2011)). Concrete contributes substantially to the thermal mass of a building. Termodeck (mentioned above) uses it to add thermal mass into a mechanical ventilation system by setting ducts in concrete slabs. This reduces peak cooling loads and benefits from night time cooling. Concrete can also be used to store heat for under floor heating. Pipes containing a heat transfer fluid such as water are embedded in the concrete to supply heat (Farid, 2001).

Adding crumbs of rubber to concrete increases its thermal capacity by weight but not by volume (as the rubber is relatively lightweight it bulks up the concrete, Hall et al, 2012). You can also add nodules containing phase change materials (Farid and Kong, 2001; Cabeza et al, 2007; Baetens et al 2011). However, it is important to allow for thermal expansion of the PCM. Adding too much PCM to the concrete will reduce its mechanical strength.

## *Bricks, blocks and mortar*

Houses are commonly built using bricks for walls with mortar between. The thermal capacities (by mass) of bricks and concrete blocks are similar to that of concrete.

## *Water*

Water has a heat capacity of 4.2 $MJ/m^3/K$. When it is used for heat storage, it is important that the container is leak-proof and the insulation is kept dry, as most insulation performs badly when wet and also leakage carries away heat. It has the advantage that water in a tank will stratify by temperature naturally, so the hottest water is at the top. The hot water can be pumped in and out of the tank easily. (Novo et al, 2010). The lower parts of the tank, which are cooler, may not need so much insulation, but if in the real system the temperatures are higher than expected the lack of insulation will lead to high losses (Bauer et al, 2010).

Interseasonal heat can be stored in water within a building, rather than in external tanks, as demonstated by an apartment block in Berne appartment blocks, heated 100% by solar collectors. The block incoporates a central shaft containing three insulated hot water tanks, storing 205$m^3$ in total. This is sufficient to supply the apartments with all their heating needs and hot water through the winter, with 2 months of sub-zero temperaturs and 80% cloud cover (Simons and Firth, 2011).

Water may also be used in artificial pits and caverns for larger district heating systems.

A mix of gravel and water in a pit usually has lower construction costs even though it needs 1.3 – 2 times the volume of water. (Novo et al, 2010). However, for large systems water storage is usually cheaper. Large systems are also cheaper to build – costs drop from around 400 €/$m^3$ for systems with volume less than 1000 $m^3$ down to €150/$m^3$ or less for systems over 10,000 $m^3$ (Pinel et al, 2011).

Underground aquifers can be used if the flow rate is sufficiently low. The maximum temperature is likely to be limited, however, as heating the water can change the chemistry (Bauer et al, 2010).

## *Sand and aggregates*

Sand has a lower specific heat capacity than water but it has some structural strength so heat storage pits filled with sand can share space with, for example, a car park or building courtyard (Terziotti et al, 2012).

## *Earth*

Heat can be stored in the ground and accessed through boreholes. You need 3-5 times as much volume as an equivalent water store. (Novo et al, 2010; Pinel et al, 2011)

A large scale installation using borehole storage relies on the low thermal conductivity of soil to make sure that the heat does not leak away even without an insulating barrier. However, if water flows through the soil it will take the heat with it.

Borehole storage systems can be operated at lower temperatures if heat pumps are used to concentrate the heat (Bauer et al, 2010).

Experience in Norway (Stojanović and Akander, 2010) suggests that simply adding heat storage to a ground source heat pump system, by running the system in reverse in the summer, makes very little difference. However, the house in this study was a leaky 1920s structure and it may be that the heat demand was too great for the system as designed.

Theoretically it should be possible to store heat in soil at temperatures higher than 100°C, if it is dry. Kroll and Ziegler(2011) has used modelling to demonstrate the feasibility of usiing this method to heat individual houses entirely from solar energy. According to the model, a house meeting current German building regulations for heat loss could be 98% heated by solar energy using a collector area of 40 $m^2$ and a store volume of 84 $m^3$. Smaller collectors would need larger stores but even with just 20 $m^2$ of collector and 60 $m^3$ of store 96% could be achieved. This model assumed a soil heat capacity of 1.02 $kWh/m^3/K$. The store would be insulated with polyurethane, which can tolerate up to 120°C for long periods and up to 250°C briefly.

## *Phase change materials*

Phase change materials are used to store heat on melting and release it when they resolidify. For these materials the key properties are:

- latent heat per unit mass or volume – however, this also needs to take encapsulation into account as it may be that only 10% of the final construction is PCM
- melting temperature – the temperature for solidification is usually a little lower than the melting temperature but for most applications it is best if they are similar
- thermal conductivity, especially in the solid phase, as in the liquid phase heat will be transferred by convection as well
- stability, so that it can melt and solidify many times without changing character
- safety in handling – most PCMs are non-toxic but some are corrosive, in which case encapsulation is particularly important

There is no simple rule for a limit to the latent heat of fusion of a solid.

The specific heat capacity of PCMs can also be useful, though it is usually lower than that of water. Most PCMs have values between 1 and 2.5 kJ/kg/K. The heat capacity can be very different in the solid and liquid phases. For example, stearic acid has 2.3 kJ/kg/K when liquid, and 1.8 kJ/kg/K when solid (Agyenim et al, 2009).

When PCMs are used for passive cooling, the melting/solidification temperatures must be appropriate for the climate so that they melt during the day and solidify completely overnight (Colclough et al, 2009).

PCMs are normally used in small nodules encapsulated with plastic or metal shells and incorporated into sheets of wallboard or building blocks. Microcapsules can also be mixed with liquid in a slurry (Zhang et al, 2010; Zhao and Zhang, 2011). The surrounding material needs to conduct heat well, so that the heat energy can get to the PCM nodules. The nodules can be as small as a few micrometres or as large as one or two centimetres. How much PCM you can add to a material depends on how it is used. For example, the more PCM you add to a building block the more you reduce its physical strength.

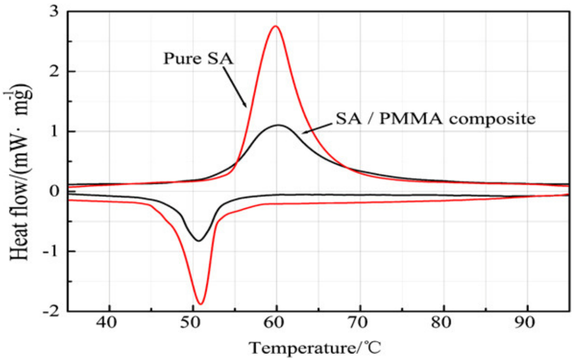
PCMs can also be used mixed with water directly (in very small droplets) to make a slurry. This is useful for cooling applications where the PCM is both heat store and heat transfer fluid (Lu and Tassou, 2012).

Some PCMs are prone to 'supercooling' (cooling a liquid below its solidification point without it solidifying), especially when encapsulated in very small nodules, only a few microns in size. When supercooling occurs, the PCM remains liquid below the solidification point. This happens because there are no nucleation points where solidification can start. Supercooling is a nuisance for most applications but can be avoided by specifically adding nucleation sites (Kuznik et al, 2011).

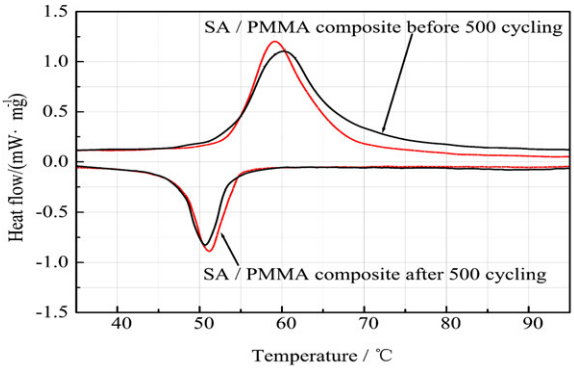
The diagrams below show heat flow from a sample with a gradually change in temperature either increasing (upper curve, melting) or decreasing (lower curve, solidifcation curve). This is obtained from a differential scanning calorimeter (DSC). The shapes are typical, with the onset of solidification at a slightly lower temperature than the onset of melting. The first diagram shows pure PCM (stearic acid) and the same shape stabilised in a polymer (PMMA).

The temperatures are very similar – showing that there is little chemical reaction between the two, but the heat flow is less for the composite because the latent heat (per unit total mass) is lower. The second diagram shows the same composite before and after repeated thermal cycling. The material has changed only slightly, showing good stability.

*DSC curves of stearic acid in bulk and shape stabilised in PMMA (Wang et al, 2011)*



*DSC curves of stearic acid in PMMA before and after 500 thermal cycles (Wang et al, 2011)*



A quality standard, RAL-GZ 896, has been defined for PCMs so that products can be certified as to their properties and longevity. The test procedure includes stability testing over up to 10,000 cycles (for cycling category A), with repeated checks for phase change temperature, heat capacity and leakage or other damage. 10,000 cycles would be 27 years at once per day, assuming typical use, and products with this certification should be reliable for many building applications.

## Paraffin PCMs

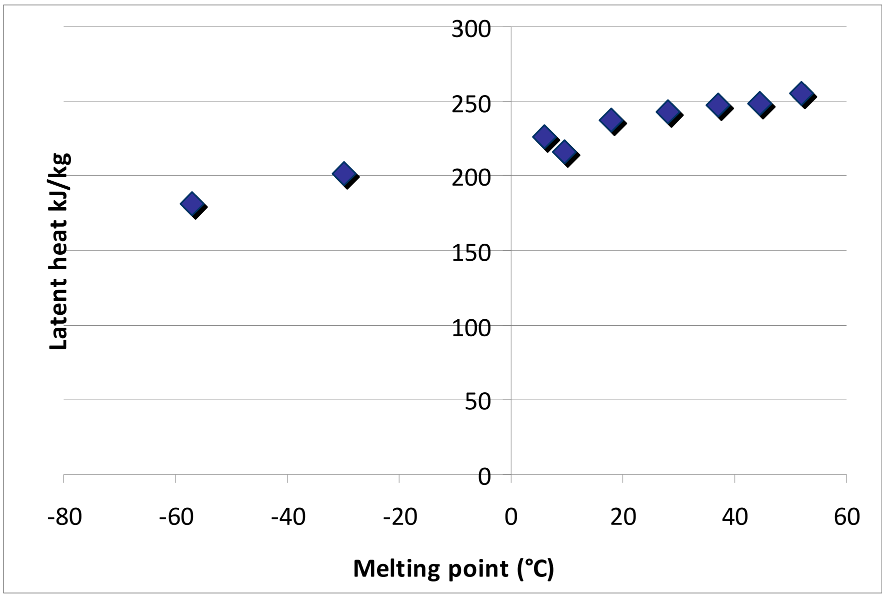
Paraffins are simple hydrocarbons with the formula $C_xH_{2x+2}$ . They have good latent heat of 120-210 kJ/kg, with useful melting points of 20-70°C (Baetens et al, 2011). However, they have low thermal conductivity (typically 0.2 W/mK). Metals and matrix structures must be added to improve this (Baetens et al, 2011; Raj and Velraj, 2010). There is also a large volume change on melting/solidifcation (Baetens, 2011). For example n-Tetradecane $C_{14}H_{30}$ has density 771 kg/$m^3$ when liquid, increasing to 825 kg/$m^3$ when solid – a 7% difference (Zhang et al, 2009).

When paraffins are directly combined with other materials such as plasterboard, the increase in volume on melting can damage the structure, leading to leakage. To get around this problem you can encapsulate the paraffin in small nodules with room inside for melting.

Paraffins can be emulsified with water by using surfactants. If the droplet size is small enough then conductivity is not a problem. Mixes with 30-50% paraffin can be used. The limit to the viable concentration is that the viscosity becomes high when the paraffin is in the solid phase. This is worse if thickeners are used to stabilise the mix for long term storage (Lu and Tassou, 2012).

Paraffins and other organic PCMs are often flammable but fire retardant treatments can be applied to the material they are embedded in (Cabeza et al, 2010). Paraffins are usually derived from mineral oil and they are cheap, although they do need to be refined to technical-grade.

*Latent heat versus melting point for a range of alkanes (Zhang* et al*, 2010)*

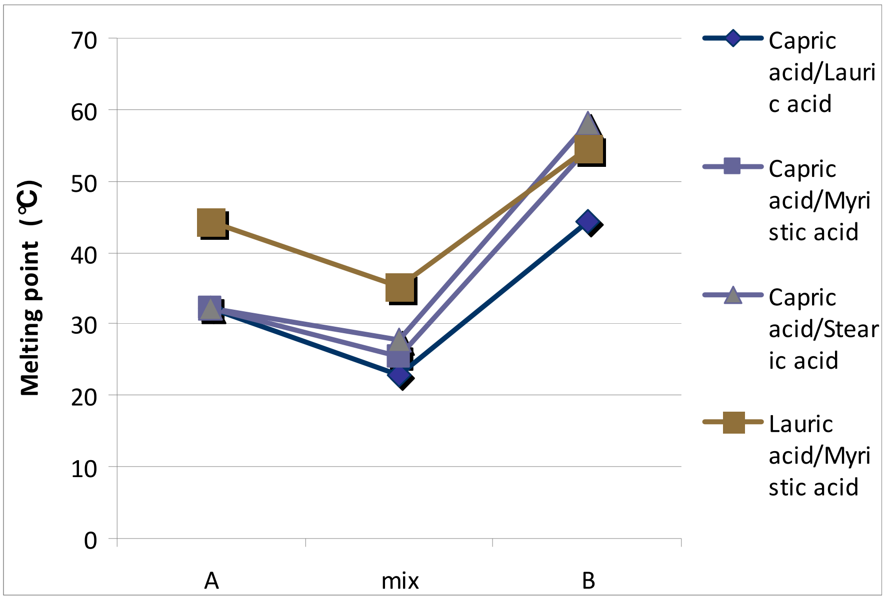


## Non-paraffin PCMs

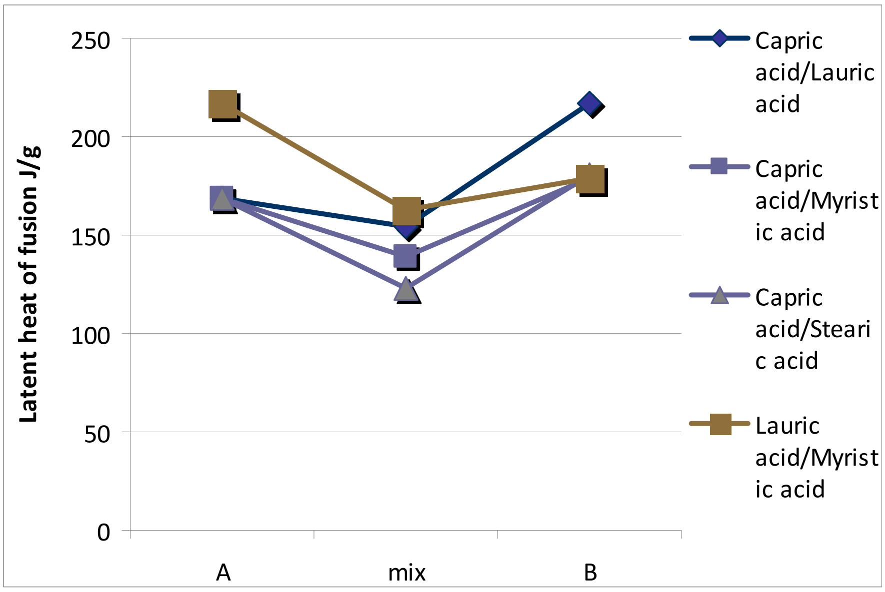
There is considerable interest in using non-paraffin PCMs from renewable resources, particularly fatty acids, which are derived from plant and animal fats. Fatty acids are commercially available but typically three times as expensive as paraffin. Industrial grade fatty acids cost around $1.5/kg. Latent heats are a little lower than for paraffins and there are none available with a melting point in the comfort range between 19°C and 26°C (Baetens et al, 2011). However, 26°C proved to be ideal for passive cooling in simulations performed by Colclough et al (2009). Fatty acids have very low volume change between the solid and liquid phase and this makes them easier to incorporate into porous materials without leakage (Li et al, 2007).

Fatty acids are often used as binary eutectic mixtures. This is a mix in such proportion that both components solidify together – otherwise the mix would tend to separate out when cooled. The melting point of the mix is lower than the melting point of either component alone, as is the latent heat. Usually fatty acid eutectics have sharply defined melting and solidifcation points (Baetens et al, 2011).

*Melting point of eutectic mixtures of fatty acids from Wang and Meng(2010)*



*Latent heats of eutectic mixtures of fatty acids from Wang and Meng, 2010*

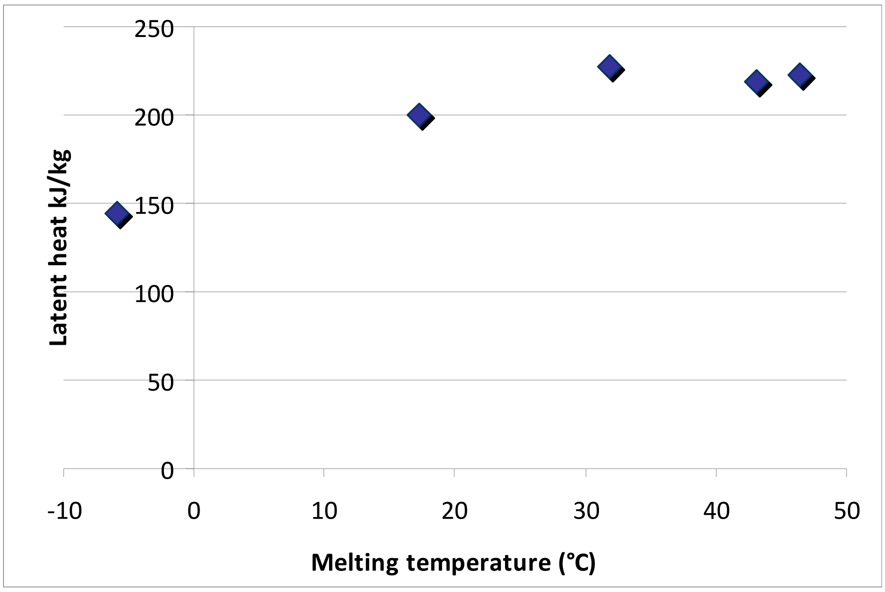


## Oleochemical carbonates PCMs

Fatty acids have the disadvantage that they are slightly corrosive. Oleochemical carbonates are another possibility for thermal storage, also derived from animal and plant fats. They are safe to handle, as are their breakdown products.

A study of five of carbonates with between 21 and 31 carbon atoms shows melting points in the range -2°C to 52°C, and useful latent heats, only a little below the paraffins (see figure below). They also have good thermal stability (Kenar, 2010).

*Latent heat and melting points for a range of oleochemical carbonates (Kenar, 2010)*



## Polyethylene Glycols PCMs

These are long chain molecules and the melting point depends on the chain length. Since they are supplied as mixtures with only the average length defined, melting takes place over a range of temperatures and not at a precise point. Products are available with average molecular weights from 'PEG 200' with melting point below -65°C to 'PEG 6000' which melts at 55-62°C. Experiments by Sarier and Onder (2008) showed latent heat of fusion from 110 kJ/kg for 'PEG 600' to 175°C for 'PEG 1500'.

## Inorganic PCMs

These are mostly salt hydrates such as calcium chloride hexahydrate. The phase change thermal capacity is typically between 200 and 400 kJ/kg but can be lower or higher (Cabeza, 2011). They are usually more dense than organic PCMs and also more conductive: typically 0.5 W/mK . They are often corrosive to metals (Cabeza et al, 2011; Baetens et al, 2011).

The specific heat capacity of salt hydrates is in a similar range to that for organic PCMs, typically 1.5-2.5 J/kg/K (Kuznik et al, 2010).

Inorganic PCM are prone to supercooling (Baetens et al, 2011; Cabeza et al, 2011; Raj and Velraj, 2010). Perhaps because of this, there are discrepancies between reports of the melting point and latent heat of fusion in these compounds. For example (Cabeza et al, 2011) lists reports of calcium chloride hexahydrate with melting point in the range 29-30°C but latent heat of fusion from 171-192 kJ/kg, except for one outlying datapoint at 296 kJ/kg. In the same source, sodium carbonate trihydrate has a melting point of 32-36°C and latent heat 246-267 kJ/kg.

Salts are also prone to separation after many cycles of heating and cooling (Baetens, 2011; Cabeza, 2011; Raj and Velraj 2010). They can also be integrated into a ceramic matrix (Baetens et al, 2011).

## Summary table of PCMs (not exhaustive)

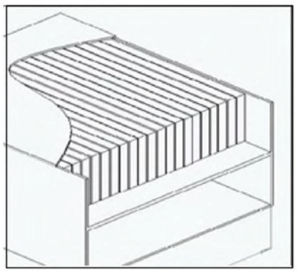
| Material | Phase change temperature °C (melt/solidify) | Latent heat kJ/kg | Latent heat MJ/m$^3$ | Thermal conductivity mW/mK (liquid/solid) |
|---|---|---|---|---|
| **Paraffins (Zang et al, 2010)** | | | | |
| Octane | -57 | 181 | 127 | 128 |
| Decane | -30 | 201 | 147 | 135 |
| Dodecane | 9.5 | 216 | 162 | 140 |
| Tetradecane | 6 | 226 | 174 | 150 |
| Hexadecane | 18 | 237 | 184 | 151 |
| Octadecane | 28 | 243 | 189 | 151 |
| Eicosane | 37 | 247 | 193 | 151 |
| Docosane | 44.5 | 249 | 194 | 151 |
| Tetradocosane | 52 | 255 | 197 | 150 |
| **Fatty acids (Wang and Meng, 2010)** | | | | |
| Capric acid | 32 | 169 | | |
| Lauric acid | 44 | 217 | | |
| Stearic acid | 58 | 181 | | |
| Myristic acid | 55 | 179 | | |
| **Oleochemical carbonates (Kenar, 2010)** | | | | |
| Decyl | -5.9/-6.3 | 144 | | |
| Dodecyl | 17.3/14.3 | 200 | | |
| Tetradecyl | 31.8/26.7 | 227 | | |
| Hexadecyl | 43.1/40.3 | 219 | | |
| Octadecyl | 46.4/46.9 | 223 | | |
| **Polyethylene glycols (Sarier and Onder, 2008)** | | | | |
| PEG 600 | 10-32 | 108 | | |
| PEG 1000 | 33-46 | 149 | | |
| PEG 1500 | 44-55 | 176 | | |
| **Inorganic PCM (Cabeza et al, 2010)** | | | | |
| $Mn(NO_3)\ 6H_2O$ | 25.8 | 126 | | |
| $CaCl_2\ 6H_2O$ | 29 | 191 | | 540/1090 |
| $Na_2SO_4\ 10H_2O$ | 32 | 251 | | |
| $Na_2CO_3\ 10H_2O$ | 32-36 | 247 | | |

## Encapsulating PCMs

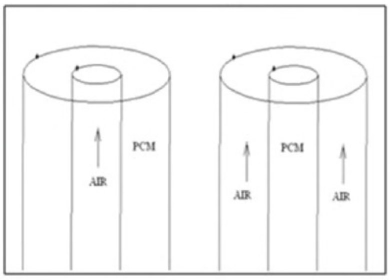
Most PCMs have to be encapsulated with something, if only because otherwise they will flow away in the melted state. The exceptions are solid-solid phase change materials such as di-n-hexylammonium bromide. This is part organic and part salt – the organic alkane chain part melts, leaving the salt part still in place (Whitman et al, 2012). Another reason for encapsulating the PCM is to isolate it chemically from its surroundings (Kuznik et al, 2011). There are several ways to encapsulate:

- Inside a pouch or panel containing the material in raw form – this is only suitable for materials with high thermal conductivity, because otherwise when it is cooling down the edge will solidify first. This forms an insulating barrier which stops the heat escaping from the rest. However, thin panels can minimise this problem, or adding graphite using 12%-20% of the volume to the PCM mix (Raj, 2010) or aluminium nanoparticles, up to 7% (Kalaiselvam, 2012).
- In tubes, with a heat transfer fluid (HTF) running through pipes within the tube, or with the HTF in the outer tube and the PCM in the inner tubes (Raj and Velraj, 2010).
- In nodules from 1mm in size and larger, with a hard shell to accommodate the change in size on melting, so they are only part full in the solid phase. This makes it easier to incorporate the PCM into concrete or plasterboard, which expands hardly at all on heating. Also, the smaller nodules reduce the thermal conductivity problem.
- In much smaller particles - microencapsulation – also with a hard shell. These have better heat transfer than the nodules and also help to improve stability, as there is simply not enough room for separation. However, some PCMs are prone to supercooling when microencapsulated (Zhang et al, 2010). The particles can be mixed with liquid to form a slurry (Zhang et al, 2010; Lu and Tassou, 2012), or mixed into a solid such as gypsum or concrete (Tyagi et al, 2011).
- As a shape stabilised composite – this means the PCM is completely encapsulated in a supporting material such as polyethylene, or a porous ceramic such as silica (Zhou and Zhang, 2009; Wang et al, 2011) or cement (Li, 2010), diatomaceous earth or perlite (Jiao, 2012; Sari, 2011). Low thermal conductivity is usually a problem, and this can be improved with additives such as B-aluminium-nitride (Wang et al, 2009) or graphite (Mei et al, 2011) but with a reduction in latent heat. The amount of PCM that can be stabilised varies with the supporting material and the type of PCM. For example (by mass):
    - silica with pores around 50nm in size absorbs up to 75% paraffin (Zhou and Zhang, 2009)
    - silica fume with particles 100-200nm absorbs up to 46% stearic acid (Wang et al, 2011)
    - perlite absorbs up to 43% of a fatty acid stearic acid/lauric acid mix (Jiao et al, 2012)
    - perlite absorbs up to 62% of fatty acids erythritol tetrastearate or erythritol tetrapalmitate (Sari and Karaipekli,2011)

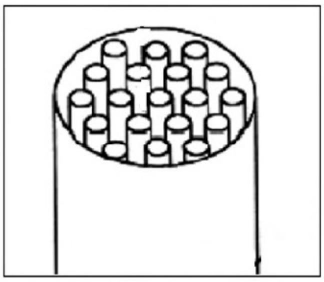
*Various ways to encapsulate PCM, from Raj and Velraj (2010)*



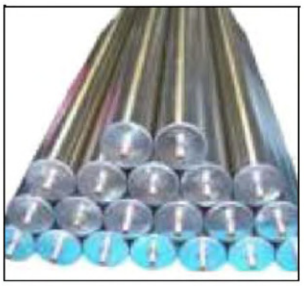
(i) Flat plate encapsulate



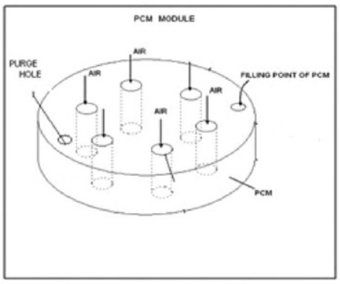
(ii) HTF in tube and PCM in tube



(iii) PCM in tube container



(iv) PCM tube encapsulation

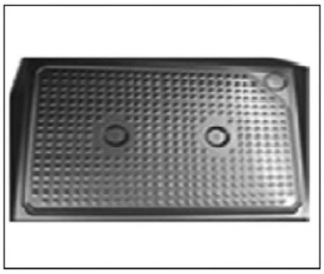


(v) PCM in Shell and HTF in tube arrangment

(vi) Fixed bed arrangement with PCM balls

(vii) Metal ball encapsulate

(viii) PCM in PVC panel



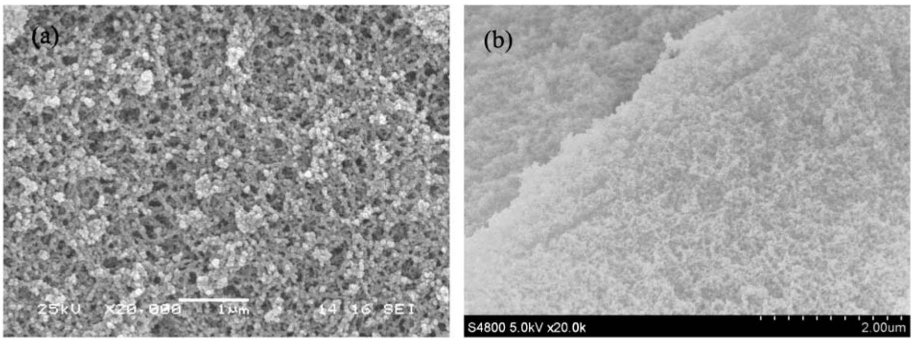
(ix) PCM in aluminium panels

(x) PCM in aluminium pouches

(xi) PCM graphite compound

(xii) PCM granules

*Porous silica and paraffin/silica composite from Zhou et al(2009)*



Encapsulating the PCM inevitably adds weight and volume. The latent heat of the composite is usually close to what you would expect from the proportion of PCM. The table below gives some examples.

*Examples of specific PCM encapsulation: mass added*

| **Material** | **%PCM by mass** | **Latent heat kJ/kg** | **Source and notes** |
|---|---|---|---|
| Cristopia nodules 75mm $CaCl_2\,6H_2O$ | 50 percent | 98 | Percentage derived from latent heat of material (Farid and Kong, 2002) and of the raw salt (Cabeza et al, 2011) |
| PCM in Gypsum plasterboard | 20-25 percent typical | | (Zhou et al, 2011) |
| Capric acid/myristic acid eutectic mix shape stabilised in PMMA polymer | 70 percent | 113 | (Wang and Meng, 2010) |
| Paraffin (melting point 56°C) in porous silica substrate | 75 percent | 165 | Pore size is 50nm, so that the paraffin is captured by capillary forces even when melted (Zhou et al, 2009) |
| Lauric acid and stearic acid eutectic mix shape stabilised in perlite | 45 percent | 131 | (Jiao et al, 2012) |
| Concrete blocks, regular or autoclaved | 4 percent regular<br>5-9% autoclaved | | (Cabeza et al, 2011) |
| Microencapsulated PCM in water slurry | 40 - 45% MEPCM in slurry, of which typically 70% is PCM | | Examples of studies using slurry for air conditioning given in (Zhao and Zhang, 2011) |

For microencapsulated PCM (MEPCM), the shells are usually made from melamine formaldehyde (MF), urea formaldehyde (UF), polyurethane (PU) or poly(methyl metacrylate) (PMMA). MF and UF shells have good impact strength, and thermal stability but free formaldehyde presents a health and environmental risk, and it is important to remove this after maufacturing the shells. Gelatin-gum arabic has superior mechanical strength. The conductivity of the resulting capsules is mainly a function of the shell material, whereas the latent heat property depends on the core (Zhao and Zhang, 2011; Su et al, 2012).

The size of MEPCM particles created depends mainly on the speed of mixing and the proportion of core/shell material used to make them. At 3:1 core:shell, the size of paraffin in MMF (methanol modied MF) ranged from 10-15 µm as the mixing speed was reduced from 3000 to 1000 rpm. Other studies have used up to 8000 rpm with different materials. The smaller particles have a lower core/shell ratio (Zhao and Zhang, 2011; Su et al, 2012).

### Incorporating PCM into building components

PCM can be incorporated into plasterboard during manufacture by mixing it into gypsum paste, or after the plasterboard is made, by impregnating the wallboard in a hot bath. Boards with 30 percent PCM by weight have been tested. Ordinary gypsum plasterboard 12.5mm thick has thermal capacity around 10 $kJ/m^2K$. Adding PCM can increase the thermal capacity to 550-800 $kJ/m^2/K$ (0.15-0.22 $kWh/m^2/K$) at the phase change temperature – which is similar to concrete 240mm thick without any PCM (Baetens et al, 2011).

Adding PCM into plasterboard directly, without encapsulation, can lead to problems with leakage or with interaction between the PCM and the plaster material (Kuznik et al, 2011).

PCM can be added to concrete to make thermocrete or mixed into clay floor tiles (Baetens et al, 2011). The mixing process is tough on the PCM capsules so they need a hard coat – for example using zeolite. Alternatively, PCM can be incorporated into porous aggregates by direct impregnation, and the dense cement surrounding the aggregate prevents leakage (Tyagi et al, 2011; Sari and Karaipekli, 2011).

PCM nodules embedded in a concrete floor can store sufficient heat to allow the floor to be used as a night storage heater. This has been demonstrated with calcium chloride hexahydrate encapsulated in 75mm nodules. The melting temperature of 24°C is suitable for underfloor heating (Farid and Kong, 2001).

PCM can be mixed with cellulose or incorporated into polyurethane foam for enhanced insulation (Baetens et al, 2011; Sarier and Onder, 2008).

### Commercial PCM products

Cabeza et al (2011) lists a range of commercially available PCM materials from half a dozen different companies. He lists 13 products with melting points between 22°C and 28°C, the range suitable for passive cooling, plus about 25 with lower melting points (mostly sub-zero for cooling applications) and 50 with higher melting points, up to 117 °C. These materials are available in various forms including contained in panels or spherical nodules, granulated or in micro-capsules with a polymer shell. Both organic and inorganic PCM materials are available.

## *Thermochemical heat storage materials*

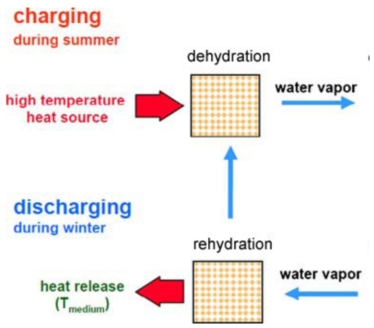
Some materials can undergo reversible chemical reactions – in one direction these need heat to drive them and in the other they release heat. For example, magnesium sulphate (epsom salt paste) has several hydrated forms, the most usual is magnesium sulphate heptahydrate.

$$MgSO_4{\cdot}7H_2O \Rightarrow MgSO_4(s)+7H_2O$$

To drive the water off the magnesium sulphate you need to heat it – 89 percent of the water can be removed at 150°C. This temperature is achievable by solar panels, using evacuated tubes. To store this heat you only have to keep the material dry. To release the energy you need to pass water vapour through it to rehydrate it. This gives a temperature lift which depends on the rate of hydration.

In experiments using magnesium sulphate encapsulated in a zeolite (15 percent PCM), a lift of over 30°C was achieved with an airflow of 8l/minute at 80 percent relative humidity, from a 200g sample. The total energy release was 648 kJ/kg: 45 percent of the theoretical maximum. This was equivalent to 600 $MJ/m^3$ (167 $kW/m^3$) (Hongois et al, 2011), which is nearly three times the energy density achievable with water using a temperature range of 50°C.

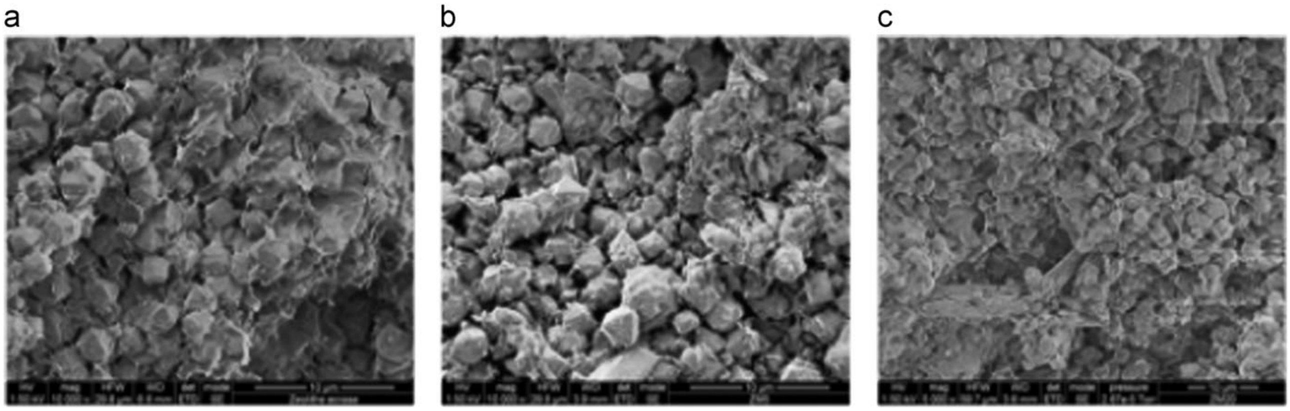
*Charging and discharging by dehydration/rehydration*



Winter weather in the UK often reaches around 80 percent relative humidity (rh), but when air from outside is warmed to room temperature the humidity drops. It can sometimes reach as low as 30 percent rh, although this is rather dry and the optimum inside buildings is 40-60 percent rh. If outside air is used then with only 30°C temperature lift, the air will not be hot enough for radiators or underfloor heating. However, if inside air is used this is likely to be too dry so more water vapour must be added, which requires energy input for evaporation.

In pure form, the magnesium sulphate turns to powder over a series of cycles, and then hydration forms a skin on the surface, which stops the water vapour getting to the rest of the system. You can avoid these problems by embedding the salt in a porous zeolite. The zeolite has a very large surface area and the salt is distributed through the pores. The optimal concentration for maximum temperature rise is 15 percent – at higher concentrations the salt tends to block the flow of vapour through the zeolite (Hongois, 2011).

*Pictures of (a) zeolite, (b) form-stable zeolite 15% weight MgSO4 composite (c) zeolite 20% weight composite (Hongois et al, 2011)*



The specific heat of magnesium sulphate is 1500 J/kg/K when hydrated and 800 J/kg/K when dehydrated (Ghommen et al, 2011).

The temperature lift from magnesium sulphate can be increased by mixing in another salt, such as magnesium chloride, which ‘deliquesces’ (becomes liquid by absorbing water from the air) at a lower relative humidity. This speeds up hydration of the sulphate, and so the rate of energy release. Magnesium chloride hydration has a higher energy density and the overall energy density is increased, which is good. However, the chloride solution produced is corrosive, so it is impractical to use magnesium chloride on its own or even a large proportion of it.

Magnesium sulphate is not the only material with a reversible reaction that can store heat. The table below lists some other candidates.

*Storage density and turnover temperature of some thermochemical materials* , from *N'Tsoukpoe et al (2009) except where indicated*

| **Material** | **Reaction** | **Storage Density GJ/m$^3$** | **Turnover Temperature T°C** |
|---|---|---|---|
| Ettringite (calcium aluminium sulphate mineral) (Kaufmann and Winnefeld, 2010) | De/re-hydration – details not given | 1.3 | 80 |
| $Na_2S$ (highly corrosive) | With water | 2.8 | 83 |
| Calcium sulphate | $CaSO4 \cdot 2H_2O \Rightarrow CaSO4 + 2H_2O$ | 1.4 | 89 |
| Magnesium sulphate | $MgSO_4 \cdot 7H_2O \Rightarrow MgSO_4(s) + 7H_2O$ | 2.8 | 122 |
| Iron hydroxide | $Fe(OH)_2 \Rightarrow FeO + H_2O$ | 2.2 | 150 |
| Iron carbonate | $FeCO_3 \Rightarrow FeO + CO_2$ | 2.6 | 180 |
| Silicon oxide | $SiO_2 \Rightarrow Si + O$ | 37.9 | 4065 |

*Thermochemical materials from the table above*

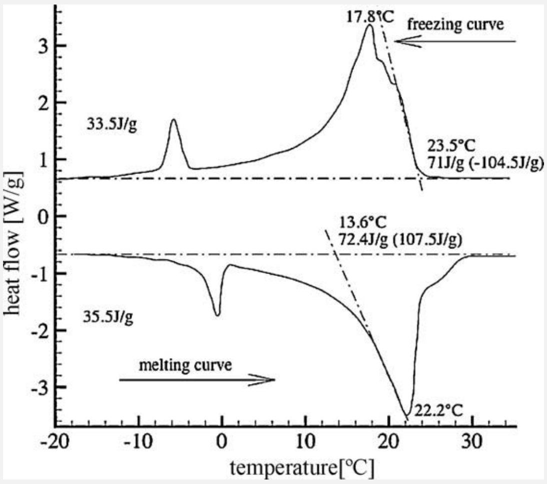
You can think of these materials as a form of heat battery, which can be charged up (heat stored) and used later. You can also think of them as artificial fuels – you could buy the charged up material from a centralised supply for use at home. This could be especially useful if charging requires high temperatures.

High temperatures also require more heat to be put into the system, which is not necessarily returned when the heat is released. For example, if the absorber is dried at 150°C this means that the water vapour separated from it has to be heated to that temperature too, and this energy is lost to the environment unless there is equipment to recapture it (as in a condensing boiler). This means that the overall storage efficiency, defined as the energy released divided by the energy put into the system, may be better at a lower regeneration temperature – at the cost of a lower storage density. This has been shown for sorption (where one substance takes up another) of water vapour by ACTIGUARD 650PCAP, which contains activated alumina and zeolite (Dicaire and Tezel, 2011), but the same principle also applies in other cases.

Sodium hydroxide has the potential for heat storage at a similar density to magnesium sulphate. It needs careful handling as it is highly corrosive and caustic. Weber and Dorer (2007) constructed a working prototype system, completely closed using stainless steel tanks and pipes, with a nickel coating on the high temperature heat exchangers. From the performance achieved, they calculated that the overall storage density for heat supplied at 40°C would be six times that of water. A house built to PassivHaus standard could in theory have heating and hot water supplied all year from solar panels using a storage volume of 7m$^3$.

Thermochemical storage system prototypes have been developed by a number of institutions and projects. The International Energy Agency Solar Heating and Cooling programme included a Task 32 (Advanced Storage Concepts for Solar Thermal Systems in Low Energy Buildings), which is now concluded. The aims of this project included thermal storage systems to allow solar panels to supply a high proportion of the heating requirement for a low energy house. Teams working under this banner have produced prototypes using plain zeolite, silica gel, sodium hydroxide, magnesium sulphate and lithium chloride. The highest storage density was obtained with sodium hydroxide (as described above, by Weber and Dorer (2007)), followed by lithium chloride, but this is very expensive. The next highest storage density was magnesium sulphate. Related work continues with Task 42: Compact Thermal Storage (N'Tsoukpoe et al, 2009).

# Glossary

| | |
|---|---|
| Aerogel | Aerogel is a silica gel with nano-sized pores, which can be filled with air or another gas. It is light, fragile and an excellent insulator. |
| Conductivity | In this report the context is heat so conductivity means thermal conductivity, not electrical conductivity. Materials with a high thermal conductivity allow heat to flow easily. This is the opposite of what is needed in building insulation, where we want to avoid the flow of heat from the inside of the building to the outside. Good insulating materials have a low conductivity. |
| Deliquesce | Some salts attract water from the atmosphere, or any other surroundings. They then dissolve into it to form a very strong solution – this process is called deliquescence. |
| Differential scanning calorimeter | This is a device for measuring the melting point and solidification temperature and the latent heat of melting/solidification of a substance. A small sample (usually a few grammes) is heated to obtain a steady increase in temperature and the heat flow from or to the material is measured (by comparison with a reference sample of another material). The rate at which the temperature is raised affects the result.<br>The resulting heat flow curves (see below) show melting over a range of temperatures because the melting is not instantaneous and the temperature rise is continuous. The melting point is taken to be the intersection with the temperature axis of a tangent at maximum heat flow change. This is normally higher than the apparent onset of melting. The melting point is easier to determine accurately using the T-history method, but this needs large samples.<br>Figure 1 DSC curve for a composite PCM from Kuznik et al (2011)<br><br> |
| Ettringite | This is a mineral component of concrete, which may be present in small or large quantities depending on the composition of the cement used to make the concrete. It is a useful thermochemical material which releases heat when it is hydrated. |

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| Eutectic mixtures | Phase change materials mixed such a proportion that both components solidify together – preventing the mix from separating out when cooled. |
| Heat capacity | The specific heat capacity of a material is how much heat energy it takes to raise its temperature by one degree. This is usually around the same for a particular type of material regardless of temperature from its solidifcation point right up to its melting point. |
| Heat pump | A heat pump concentrates heat, taking energy from a low temperature heat source and transferrring it to a higher temperature heat reservoir. For example, a refrigerator includes a heat pump which moves low temperature thermal energy from inside the fridge into the air in the room. The performance of a heat pump depends on the temperature difference it works against. The coefficient of performance(COP) might be anything from 1.5 to 5 or more, meaning that for every unit of electricity used to drive the pump 1.5 to 5 units of heat are transferred. Heat pumps are increasingly used to heat buildings, using the ground, the air, or water as a heat source. |
| Mico-encapsulation | Micro-encapsulation involves storing PCMs as tiny particles using a hard shell. These have better heat transfer than PCMs stored as nodules and also better stability, as there is simply not enough room for separation. The particles can be mixed with liquid to form a slurry, or mixed into a solid such as gypsum or concrete. However, some PCMs are prone to supercooling when micro-encapsulated. |
| PEG | Polyethylene Glycols - a family of polymers that are either colorless liquids or waxy solids and are soluble in water. They are present in many organic solvents. |
| Phase change materials (PCMs) | When a solid such as ice melts it absorbs heat. Conversely when it freezes it gives up heat. This energy is called the ‘latent heat of melting’ and the transition is called a ‘phase change’, hence the name phase change materials. Similarly, the transition from liquid to gas is also a phase change and absorbs heat called the ‘latent heat of vaporisation’, but this is less useful in the context of buildings. |
| PMMA | This is poly(methyl metacrylate). It is sometimes used to make the shells for encapsulating PCMs. |
| Salt hydrate | Many salts have the ability to bind with water to form a more complex crystal. This is called a salt hydrate. Some salts can combine with water in different ratios to form different crystal structures. For example, calcium chloride can combine with 6 or 12 water molecules and sodium sulphate can bind with either 3 or 10. Salt hydrates can be used as phase change materials, storing heat when melted; or they can be used as thermochemical materials, storing heat when dehydrated. |
| Silica gel | This material usually comes in the form of granules. It absorbs water very strongly and is used to keep things dry. For example it is used in some cat litters. Like aerogel it is made from silicon dioxide. However, silica gel does not have the large three-dimensional structure of aerogel and is much more dense, with a higher proportion of silica to air. |

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| Thermal resistance | This is the inverse of thermal conductivity: materials with low conductivity have high resistance and vice versa. |
| Thermochemical materials | Thermochemical materials are substances that undergo a reversible chemical reaction either releasing or absorbing heat - depending on temperature and some other enviromental factor such as the presence of water. |
| Turnover temperature | This is the temperature required for a thermochemical reaction to go in the direction that stores energy. |
| U-value | The U-value for a wall (or floor or ceiling etc.) tells you how much heat energy is lost per unit temperature difference per unit area. You lose more heat if there is a big temperature difference or if the wall area is large. Usually it is better to retain heat, so low U-values are good, high values are bad.<br>The U-value relates to the conductivity of the material and its thickness. For a simple construction, U = conductivity/thickness. You can get a lower U-value by using a material with a lower conductivity or increasing the thickness. |
| Vacuum insulation panels | Usually vacuum insulation panels are made from fine grained silica fume, so fine it is mostly air. The powder is enclosed in a strong envelope and all the air is removed. The resulting panel is an excellent insulator. |
| Zeolite | A zeolite is a porous material made principally of aluminosilicate. The structure has many cavities of micrometre dimensions that capture other small molecules or ions, for example water molecules or salts. They have a huge range of uses, including water purification. Zeolites can occur naturally or be synthetic. |

# Tables of References

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## *Thermal Storage Materials*

### Phase Change Materials

| **Reference** | **Summary** | **Evidence base** |
|---|---|---|
| Agyenim, F., Hewitt, N., Eames, P. and Smyth, M. (2010) A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS), *Renewable and Sustainable Energy Reviews,* 14(2) 615 - 628 | The authors discuss materials briefly, and give a table of about 30 PCM materials of different types, including density, thermal conductivity and specific heat capacity in each phase as well as latent heat and melting point. They also list 8 commercial sources of PCM. The bulk of the review is however about improving heat transfer in PCM with low conductivity. Diagrams illustrate 16 different shapes and strategies for heat transfer, including simple pipe in shell systems, with or without fins and sometimes including encapsulation or dispersed conductive particles. There are few firm guidelines for which stratgies are best (and the differences between then are often small e.g. 5-10 percent).<br>For modelling the melting process it turns out there are 4 phases, in two of which heat transfer is mainly by conduction, and then as more of the material melts convection becomes more dominant. Models which take this into account work well, but it is difficult to account for 3-dimensional systems - flat plates and thin pipes are relatively easy. | Review |
| Arce, P., Castellón, C., Castell, A. and Cabeza, L.F. (2012) Use of microencapsulated PCM in buildings and the effect of | Previous experiments using PCM for passive cooling in buildings has shown up some problems. Firstly, during winter, the PCM material did not get hot enough to melt. Secondly, in summer, the hot | Experiment |

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| adding awnings, *Energy and Buildings*, 44(1) 88 - 93 | nights prevented the PCM from refreezing. The PCM does not work properly unless it has a full melt/refreeze cycle every day. In this study, the authors added awnings to their test cubicles to see if the function of the PCM would be improved by the shade. This proved to be the case. With the window open all the time, the daily comfortable hours rose from 26% to 36%. In fact the awnings without PCM (32%) were better than PCM with no awnings (26%). | |
| Baetens, R., Jelle, B.P. and Gustavsen, A. (2010) Phase change materials for building applications: A state-of-the-art review, *Energy and Buildings,* 42(9) 1361 - 1368 | The authors discuss organic and inorganic PCMs in general terms, giving typical conductivities as well as thermal capacites. They describe some ways to prepare PCM impregnated plasterboard, and some example resulting properties. They also mention uses of PCM in concrete or clay floor tiles, and in insulation. | Review |
| Cabeza, L.F., Castell, A., Barreneche C., de Gracia, A. and Fernández, A.I. (2011) Materials used as PCM in thermal energy storage in buildings: A review, *Renewable and Sustainable Energy Reviews,* 15(3) 1675 - 1695 | Here is a long list of PCM materials with their thermal properties, including materials that melt up to 60°C (suitable for hot water applications) and higher. Also there are lists of commercial products in different ranges.<br>Inorganic PCMs can cause corrosion in metals. Organic PCMs can react with plastics. Penetration of the capsule shells by liquid or gas can affect performance. Salt hydrates can separate out over repeated cycles which reduces performance, this can be avoided by gelling or thickening. Salt hydrates are prone to supercooling.<br>The overall thermal heat storage capacity for some types of PCM-block comninations is given - in the best case the latent heat storage nearly doubles the thermal capacity, compared to sensible heat storage over a temperature range of 10°C. The authors give references for reducing fire risk and for speeding up the heat transfer rate. | Review |
| Cabeza, L.F., Castellón, C., Nogués, M., Medrano, M., Leppers, R. and Zubillaga, O. (2007) Use of microencapsulated PCM in concrete walls for energy savings, *Energy and Buildings,* | PCMs have to be encapsulated to be embedded in construction materials such as wallboard and concrete. However, large nodules do not perform well because the PCMs have low conductivity. For example, on cooling, the nodules quickly solidify around the edges and this slows the transfer of heat from the middle. Microencapsulation avoids this | Experiment |

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|---|---|---|
| 39(2) 113 - 119 | problem, but plastic or metal coatings are expensive. This authors performed some experiments using a particular type of concrete called MOPCON, which includes 5 percent by weight of a commercial PCM called Micronal based on paraffin. The mechanical strength of the concrete is good. The thermal inertia of the concrete was improved. |  |
| Cabrol, L. and Rowley, P. (2012) Towards Low Carbon Homes–A Simulation Analysis of Building-Integrated Air-Source Heat Pump Systems, *Energy and Buildings,* 48(1) 127-136 | The authors have simulated energy demand and running costs for single-storey, single zone dwellings of several construction types all with underfloor heating driven by either an air source heat pump (ASHP) or a conventional gas boiler. For the ASHP system, the simulation ran the heat pump only during off peak tariff times, unless absolutely necessary. They compared the impact of several off peak tariffs including Economy 7 (night time only) and Economy 10 (5 hours overnight, 3 in the day and 2 in the evening). They looked at 3 locations: in the Scotland, in the Midlands and in Southern England and they looked at thin or thick concrete slabs for the floor, or a thin slab with embedded PCM material to enhance the heat capacity.<br>They configured the heating system to maintain an average temperature of 20°C, and evaluated its success by requireing that the temperature remained above 19°C. The concrete slab with PCM melting at 24°C was able to maintain a comfortable temperature at all times with all building construction types. A thick slab without PCM was only able to do this in conjunction with externally insulated walls, using the heat capactity of the walls as well as the floor.<br>The ASHP system was cheaper to run than the gas system in all cases. The Economy 10 tariff allowed a greater efficiency than the Economy 7 because the ASHP is more efficient in the day, when the outside temperature is warmer. Even in Aviemore, Scotland, the ASHP Economy 10 system achieved a COP of 3.5, whereas with Economy 7 it was only 3.15. | Simulation, UK |
| Chidambaram, L.A., Ramana, A.S., Kamaraj, G., and Velraj, R. (2011) Review of solar cooling methods and thermal storage options, *Renewable and* | An absorption fridge is powered by a heat source rather than electricity. For exampe, in an absorption fridge, the heat is used to drive off gas dissolved in a liquid – typically water from a lithium bromide solution. (This needs to be at least 100°C.) The heat | Review |

| | | |
|---|---|---|
| *Sustainable Energy Reviews,* 15(6) 3220 - 3228 | can be from a solar panel. Absorption fridges are not yet efficient enough to compete with electric or gas fridges in the current market. However, when using solar power they have very low environmental impact. Solar energy is intermittent and to compensate for this you can either store heat to drive the fridge or store coolness generated by the fridge. Whether hot or cold the store needs to operate over a narrow range of temperature which makes PCM ideal. | |
| Colclough, S., Griffiths, P. and Gschwander, S. (2009) Thermal Energy Storage and the Passive House Standard: How PCM incorporated into wallboard can aid thermal comfort, *PLEA2009 - The 26th Conference on Passive and Low Energy Architecture* | The EU parliament has proposed that all new buildings across the EU should meet the German Passive House (PH) standard. Although this does not specify any particular construction materials, the requirements for heat loss and in particular air tightness are likely to bring increased use of lightweight structures. However, these structures have low thermal mass which can lead to problems of overheating, particularly in summer. PCM plasterboard is often considered as a solution. The authors have modelled a one-room structure made to PH standard, and simulated its performance in locations across Europe, with and without PCM plasterboard. They report how much the PCM improved thermal comfort, as indicated by the number of hours the temperature in the room exceeded 26°C. There was substantial improvement in Athens, Madrid and Paris but not Belfast because the temperature never exceeded 26°C in Belfast even without the PCM. In Paris, the number of uncomfortable hours in the year was 166 without PCM and only 26 with the PCM. | Simulation, across EU |
| Diaconu, B.D. (2011) Thermal energy savings in buildings with PCM-enhanced envelope: Influence of occupancy pattern and ventilation, *Energy and Buildings*, 43(1) 101 - 107 | In this paper the author uses real ambient temperature data from Romania (-15°C to 5°C) to simulate heating demand in a building with PCM wallboards under different patterns of ventilation or occupancy. With continuous ventilation, the heat load was high and the PCM made little difference. With 4 hours a day or no ventilation at all the PCM enabled savings of up to 18 percent. They also modelled different heating settings resulting from different occupancy patterns. This made much less impact than the ventilation. | Simulation |

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| Farid M. and Kong W.J. (2001) Underfloor heating with latent heat storage, *Proceedings of the Institution of Mechanical Engineers, Part A, Journal of Power and Energy*, 215(5) 601-609 | Building on previous work using paraffin wax to store heat inside night storage heaters (instead of ceramic bricks), the authors have devised a way to use it in underfloor heating. For this application only low grade heat is needed because it comes from below. They say the ideal temperature gradient in a room is 24°C at floor level and 18°C at head level. The authors incorporated nodules containing a PCM (hydrated calcium chloride, melting point 29°C) into a concrete slab, heated with hot water pipes, to simulate an under floor heating system. The slab with PCM performed better than one without. It stayed sufficiently warm all day, after being heated for only 8 hours. | Experiment |
| Huang, M.J. (2011) The effect of using two PCMs on the thermal regulation performance of BIPV systems, *Solar Energy Materials & Solar Cells* , 95(1) 957-963 | Solar PV panels lose efficiency when they get hot by up to 0.5 percent for each degree above 25°C. This is particularly a problem with building integrated PV systems, where the panels replace wall cladding and roofing. Cooling by natural ventilation is not very effective because of poor heat transfer with the air, even if metal fins are added to the rear of the panels. With an external air temperature of 23°C and running at 750 W the panels can reach up to 47°C. The author has run simulations to show that using a combination of PCM materials with different melting points it is possible to keep the panel running temperature close to 25°C. This increased the efficiency of the panels by narly a third (from 1.4 to 1.8 kWh/hr/$m^2$/day). | Simulation |
| Jiao, C., Ji, B. and Fang, D. (2012) Preparation and properties of lauric acid--stearic acid/expanded perlite composite as phase change materials for thermal energy storage, *Materials Letters,* 67(1) 352 - 354 | The authors impregnated expanded perlite with a mixture of lauric acid and stearic acid. The perlite could retain up to 43.5% PCM without leakage. The resulting material was stable. The melting point was 33°C (higher than the bulk PCM mix, which was 29.4°C) and the latent heat in the perlite was 131.3 J/g. | Experiment |
| Kalaiselvam, S., Parameshwaran, R. and Harikrishnan, S. (2012) Analytical and experimental investigations of nanoparticles embedded phase change | The authors measured the time taken for complete solidification and complete melting in spherical samples of PCM in pure form and with up to 7% nanoparticles of aluminium or alumina dispersed through. The speed of solidification was faster with aluminium - up to 20% faster, indicating that the | Experiment |

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| materials for cooling application in modern buildings, *Renewable Energy,* 39(1) 375 - 387 | aluminium helped transfer heat through the PCM sample. | |
| Karaipekli, A. and Sarı, A. (2011) Preparation and characterization of fatty acid ester/building material composites for thermal energy storage in buildings, *Energy and Buildings*, 43(8) 1952 - 1959 | Fatty acids are promising PCM for building applications because they are very stable and easy to incorporate into building materials. Also they are commercially availailable. Erythritol tetrapalmitate (ETP) and erythritol tetrastearate (ETS) have useful melting points: ETP onset melting 22°C, freezing 19°C, ETS onset melting 30°C, freezing 29°C. In this study the authors investigated composites with gypsum and with cement, including 1000 cycles of thermal testing. The cement could stabilise up to 18% PCM and the gypsum up to 22%. The melting points were unaffected by mixing and the stability of the composites was good. | Experiment |
| Kenar, J.A. (2010) Latent heat characteristics of biobased oleochemical carbonates as potential phase change materials, *Solar Energy Materials and Solar Cells,* 94(10) 1697 - 1703 | Fatty acids and their esters can be derived from plant and animal fats so they have renewable sources, which is good. However, fatty acids are mildly corrosive and the esters degrade to toxic, corrosive substances. Oleochemical carbonates are also derived from plant and animal fats and they are safer - they degrade to alcohols and carbon dioxide - so they are worthy of consideration as PCM. The authors investigated a selection of 5 carbonates with 21-31 carbons have melting points from -2°C – 52°C and latent heats 140 - 220 kJ/kg. They found mostly sharp transitions, little tendency to supercool and good thermal stability (only 30 cycles tested). | Experiment |
| Kuznik, F., Virgine, J. and Johannes, K. (2011) In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard, *Renewable Energy*, 36(1) 1458-1462 | The authors compared temperature fluctuations in two rooms, one with PCM heat storage (Energain boards containing about 60% paraffin, 5mm thick) the other without. The rooms were in a lightweight building with good insulation but low thermal mass near Lyon, France. Outside the temperature was varying between about 0 and 10°C (this was November). Without PCM the temperature in the room rose up to 30°C due to solar gain – with PCM the maximum was 2°C lower. However, in March, with more solar gain to handle, the PCM boards all melted and were unable to store more heat so they were less effective. | Experiment (France) |

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| Kuznik, F., David, S., Johannes, K. and Roux, J. (2011) A review of phase change materials integrated in building walls, *Renewable and Sustainable Energy Reviews*, 15(1) 379 - 391 | Here are lists of organic and inorganic PCM materials and their properties, and a discussion of methods of integrating them into wall boards to increase thermal mass. The authors describe in detail how thermal capacity is measured using differential scanning calorimeter or using the T-history method.<br>The authors review a number of experimental studies. Most studies use PCM impregnated in gypsum, but other materials studied include foil, PVC and even steel. 'Shape-stabilized' panels contain very high proportions of PCM. Most experimental studies record the changes in air temperature in a test cell, they do not measure the properties of the material. One study looked at the impact on electricity consumption over a summer season. More systematic studies are needed. Some numerical studies are listed with different types of modelling, but even these are very limited. For example, they do not allow for internal heat loads due to occupation. | Review |
| Li, H., Liu, X. and Fang, G. (2010) Preparation and characteristics of n-nonadecane/cement composites as thermal energy storage materials in buildings, *Energy and Buildings,* 42(10) 1661 - 1665 | The authors mixed paraffin with portland cement in different proportions to obtain a composite material. The paraffin was retained in the pores of the cement when it melted so no other encapsulation was necessary at either 4:1 cement:paraffin or 1:1. The paraffin melting point was unaffected and the latent heat of each material was close to the expected based on the proportions. At 4:1 the latent heat of fusion was 18% of pure paraffiin and at 1:1 it was 44%. | Experiment |
| Li, M., Wu, Z. and Kao, H. (2011) Study on preparation and thermal properties of binary fatty acid/diatomite shape-stabilized phase change materials, *Solar Energy Materials and Solar Cells ,* 95(8) 2412 - 2416 | Fatty acids are promising materials for buildings PCM because they are cheap, compatible with building materials, have high latent heat and low volume change. The authors calculated the expected properties of 6 combinations of 4 fatty acids: melting points ranged from 19C to 53C. They prepared 3 of the mixes and incorporated them into 4 kinds of diatomite. Between 30% and 40% could be absorbed without leakage.The best diatomite (holding most PCM) was that with the highest surface area/volume ratio. They determined the properties of a capric-lauric acid mixture in that diatomite. The melting point was raised very slightly and the latent heat was 67 J/g (57% of the bulk | Experiment |

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| | mixture). | |
| Lu, W. and Tassou, S.A. (2012) Experimental study of the thermal characteristics of phase change slurries for active cooling, *Applied Energy,* 91(1) 366 - 374 | PCM slurry can be used in cooling applications both for thermal storage and for heat transfer. Water ice can be used but you need temperatures as low as -8C to make the ice, which reduces the efficiency of the system. Phase change materials such as PCM can be used in the 5-11C range, which is more useful.<br>The thermal conductivity of paraffin alone is too low. Paraffin capsules in water can be used but the shell material also reduces the conductivity. Paraffin can be mixed directly with water, by adding surfactants to increase mixing and reduce droplet size. ‘Tween 60’, a commercial product, makes a very good surfactant for tetradecane emulsions. The concentraion of paraffin can be 30-50%.<br>If the droplet size is very small supercooling is a problem but this can be reduced using a co-surfactant such as Hexadecanol and mixing in another paraffin with a higher melting temperature.<br>When the paraffin is solid viscosity can be a problem; increasing the concentration of paraffin makes this worse. Also if the slurry is left for a long time it will tend to separate out unless thickener is added, which increases viscosity. Continuous stirring during storage would be a possible solution. | Experiment |
| Mei, D., Zhang, B., Liu, R., Zhang, Y. and Liu, J (2011) Preparation of capric acid/halloysite nanotube composite as form-stable phase change material for thermal energy storage, *Solar Energy Materials and Solar Cells ,* 95(10) 2772 - 2777 | The authors combined pure capric acid as PCM with a clay mineral comprising nanotubes of aluminosilicate. This clay is common in China and other places. The maximum proportion of acid which could be retained in the clay was 60%. The melting/freezing points of the compositie was 0.3°C lower than that of the pure acid. The thermal conductivity of the composite was only 48 mW/mK. Adding 5% expanded graphite improved the thermal conductivity of the composite by 58%. The latent heat of the composite with graphite was 76.4 J/kg. | Experiment |
| Raj, V.A.A. and Velraj, R. (2010) Review of free cooling of buildings using phase change materials, *Renewable and* | Free cooling uses a thermal energy store to store 'coolness'; overnight for use during the day. The store consists of PCM panels or pouches, which can be integrated into the floor or ceiling. Usually heat | Review |

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| *Sustainable Energy Reviews,* 14(9) 2819 - 2829 | is transferred by a flow of air along a heat exchanging surface. Since air is a poor conductor this can benefit from fins. Organic PCMs are often poor conductors too,although they have the advantage of stabilty. Conductivity can be improved by adding a metal matrix, carbon fibres or other techniques. Because of the time taken to store and release heat, the authors recommend that PCM free cooling is only used when the difference between day and night time temperatures is more than 15°C. (This investigation was done in India). | |
| Sarier, N. and Onder, E. (2008) Thermal insulation capability of PEG-containing polyurethane foams, *Thermochimica Acta,* 454(2) 90 - 98 | Rigid polyurethane foam (PU) is a widely used high performance insulating material. These experiments show how it can be improved with the addition of polyethylene glycols (PEGs) as PCM material. PEGs have a high heat of fusion, are stable, non-corrosive and low in cost. The authors chose 3 PEGs for this experiement, which they used singly and in combination. The melting points of three PEGs were around 10°C, 30°C and 40°C, and the heat of fusions were 110, 150 and 175 kJ/kg. The authors incorporated these PEGs into PU and peformed a leakage test applying mechanical pressure and shear. The main test was to check for the insulation effect. They sat a concrete container filled with water and insulated with PU inside an outer container of water which they heated up to 51°C. With PU alone the temperature increase in the centre was 7.7°C. Two of the PEG impregnated PUs did very well, with temperature increases bewlow 0.4°C. The other, which was the 30°C melting point PEG, gave only a marginal improvement. | Experiment – does not explain results |
| Sarı, A. and Karaipekli, A. (2011) Fatty acid esters-based composite phase change materials for thermal energy storage in buildings, *Applied Thermal Engineering,* 37(1) 208-216 | The authors investigated incorporating Erythritol tetrapalmitate (ETP) and erythritol tetrastearate (ETS) into expanded perlite and diatomite (diatomacesous earth). They found they could incorporate up to 57% PCM in diatomite and 62% PCM into perlite. The composite had good stability over 1000 cycles. Adding expanded graphite at 5% by weight improved the thermal conductivity by 57% for diatomite and 75% for perlite, with little change in latent heat. | Experiment |

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| Su, J., Wang, X., Wang, S., Zhao, Y. and Huang, Z. (2012) Fabrication and properties of microencapsulated-paraffin/gypsum-matrix building materials for thermal energy storage, *Energy Conversion and Management ,* 55(1) 101 - 107 | The authors made used MMF (methanol modified melamine formaldehyde) to encase paraffin as PCM in a range of core/shell ratios and particle sizes, and tested the composites they made by embedding these in gypsum in different concentration. Faster mixing of the emulsion led to smaller particles. Also particles with a low core/weight ratio were larger and had thicker shells. The encapsulated PCM had the same melting point as paraffin but lower latent heat. It was more thermally stable (up to 250°C, compared to 139-209°C for paraffin). For the gypsum composite, the thermal conductivity was reduced as the concentration of PCM increased, and as the size of the PCM was reduced. This reduction was due to heat absorption by the PCM. | Experiment |
| Tyagi V.V., Kaushik, S.C., and Tyagi, S.K. and Akiyama, T. (2011) Development of phase change materials based microencapsulated technology for buildings: A review, *Renewable and Sustainable Energy Reviews* , 45(1) 32 - 42 | There is a trend for more lightweight buildings, to reduce material, transport and building costs, but this reduces thermal mass. Introducing PCM can counteract this. Microcapsules are small particles (not always spherical) with a polymer shell and PCM inside. The authors list PCM manufacturers - 7 in all. They also describe experiments with PCM embedded in concrete (increasing heat capacity and lowering conductivity), plastic/wood composites, wallboard, PCM panels, and sandwich panels, all increasing the thermal mass of the wall. | Review |
| Wang, L. and Meng, D. (2010) Fatty acid eutectic/polymethyl methacrylate composite as form-stable phase change material for thermal energy storage, *Applied Energy*, 87(8) 2660 - 2665 | The authors prepared samples of lauric acid/myristic acid as PCM shape-stabilised in PMMA (polymethylmethacrylate)with different proportions of PCM from 20-80%. With more PCM the latent heat of the composite increased, but its strength decreased, especially above 70%. Latent heats of the 50% mixtures were only slightly less than expected (at most 3.3% down). The melting points were very slightly lower too. The 50% composite had better thermal stability than the bulk materia. From calculation of the thermal expansion coefficients for the mixtures, the authors considered that the composite would be stable up to 80°C. | Experiment |
| Wang, Y., Xia, T.D., Feng, H.X. and Zhang, H. (2011) Stearic acid/ polymethylmethacrylate composite as form-stable | In this study the authors used a UV photo-initiated method to prepare shape-stabilised stearic acid as PCM in PMMA (polymethylmethacrylate). The PMMA formed spherical microcapsules enveloping | Experiment |

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| phase change materials for latent heat thermal energy storage, *Renewable Energy ,* 36(6) 1814 - 1820 | the PCM and joined together with resin particles. Up to 52% PCM could be stabilised and the resulting composite had latent heat slightly lower than expected. There was little change in thermal or chemical properties after 500 cycles. Also the composite was considerably more stable thermally than the bulk material. | |
| Wang, Y., Xia, T.D., Zheng, H. and Feng, H.X. (2011) Stearic acid/silica fume composite as form-stable phase change material for thermal energy storage, *Energy and Buildings,* 43(9) 2365 - 2370 | Silica fume is a by-product generated by electric arc furnaces in the production of ferrosilicon alloy. It is added to cement to improve strength, durability and thermal resistance. It is fine, non-crystaline silica. It is good at absorbing and holding other substances. In this study it absorbed up to 46% by weight of stearic acid PCM. The resulting material had good stability and close to the expected melting temperature (51.8C) and latent heat (84.5 J/g). | Experiment |
| Wang, W., Yang, X., Fang, Y., Ding, J. and Yan, J. (2009) Enhanced thermal conductivity and thermal performance of form-stable composite phase change materials by using β-Aluminum nitride, *Applied Energy,* 86(7) 1196 - 1200 | Solid-liquid PCM can be mixed into other material to stabilise the shape and prevernt leakage. For example, paraffin can be mixed with polyethylene, with up to 75% paraffin without leakage. The authors have previously used polyethylene glycol (PEG) with silica. This gave a good latent heat but disappointing thermal conductivity. However, this can be improved by adding β-Aluminum nitride (β-ALN) as an additive. PEG has a big difference between its melting point and solidification temperature - it melts at around 60C and solidifies at about 44C. Adding β-ALN made little difference to these temperatures but the latent heat was reduced - down from 133 kJ/kg to 107kJ/kg at 20% β-ALN. Over the same range the thermal conductivity went up from aabout 0.35 to 0.55 W/(m.K). | Experiment |
| Whitman, C.A., Johnson, M.B. and White, M.A. (2012) Characterization of thermal performance of a solid--solid phase change material, di-n-hexylammonium bromide, for potential integration in building materials, *Thermochimica Acta,* 531(1) | di-n-hexylammonium bromide $(C_6H_{13})2NH_2Br$ is partly organic and partly salt. On heating, the organic part 'melts' but the salt part remains solid so overall the material is still solid even though it has absorbed latent heat. It does not need to be encapsulated to stop it flowing away. The latent heat proved to be 85 J/g, which is nearly as good as commercial paraffin based PCM materials after encapculation. Experiments both on the raw material and on a composite made with 30% PCM | Experiment |

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| 54-59 | in gypsum, to simulate wallboard, showed the material has good stability, with only 3% drop in latent heat after 1000 cycles. | |
| Zhang, P. and Ma, Z.W., and Wang, R.Z. (2010) An overview of phase change material slurries: MPCS and CHS, *Renewable and Sustainable Energy Reviews,* 14(2) 598 - 614 | Increasingly energy is used for refrigeration and air conditioning. Adding a secondary cooling circuit acting as a cool store can reduce the peak refrigeration load and hence reduce the amount of refrigerant required. This strategy can be used when converting an existing refrigeration system from CFCs to less efficient but safer refrigerant fluids. PCM can be very effective as a cold store.<br>Ice slurry can be used but there are practical problems in generating the ice and in avoiding supercooling. This paper discusses micro-encapsulated PCM slurry and clathrate hydrates (both in water) as alternatives. Both have the advantage of smaller particles, leading to less wear and clogging, and a higher melting temperature, which leads to greater overall efficiency - the cooling system has to work harder to reach ice freezing point than a more convenient 5-12C.<br>For this application PCMs need to be very stable as they can cycle melt/solidify many times in one day and they also need to be tough to withstand the physical impacts of pumping. Some PCMs show supercooling when encapculated at sizes less than 100 micrometres. | Review |
| Zhao, C.Y. and Zhang, G.H. (2011) Review on microencapsulated phase change materials (MEPCMs): Fabrication, characterization and applications, *Renewable and Sustainable Energy Reviews,* 15(8) 3813 - 3832 | Organic pcms are stable and have high latent heat but low thermal conductivity. Inorganic pcms have high latent heat by volume and high conductivity but are corrosive, less stable and suffer from supercooling. All these issues can be resolved by microencapsulatiion - improving stability and conductivity. Five fundamental ways to make microencapsulated pcms (MEPCM) are described. The properties of the shell material are very important: thickness, physical integrity, and temperature stability. Also the ratio of core material to shell can be varied and the average and range in size of the particles. The stirring rate is important for particle size. MEPCM can then be incorporated into building materials or textiles, or mixed with water as a slurry. This can be both a heat store and a heat transfer fluid. An important use is in seconday cooling loops. Usually MPECMs are mixed | Review |

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| | with water, and emulsifiers can be added to reduce clogging. The resulting viscosity depends on the concentration of MPECM in the slurry. However, the cold storage capacity of slurry is 50-160% larger than that of sensible heat capacity in water. | |
| Zhou, D., Zhao, C.Y., and Tian, Y. (2012) Review on thermal energy storage with phase change materials (PCMs) in building applications, *Applied Energy*, 92(1) 593 - 605 | The authors discuss a range of organic, inorganic and eutectic PCMs, methods of incorporating them into buildings and applications. Most of the applications involve passive cooling, but they also mention PCM ceilings for active heating or cooling and under-floor electric heating. High thermal conductivity is important, as well as heat capacity. | Review |
| Zhou, X., Xiao, H., Feng, J., Zhang, C. and Jiang, Y. (2009) Preparation and thermal properties of porous silica ceramic composite, *Composites Science and Technology* , 69(7) 1246 - 1249 | The authors created a porous silica ceramic with pore size around 50nm and soaked this in melted paraffin. After 3 minutes the ceramic had soaked up close to the maximum paraffin - about 75% by mass. This resulting material had thermal properties similar to pure paraffin and did not leak when the paraffin melted. They tested  the thermal stability of the composite at 40°C for 30 minutes and it was good. | Experiment |

## Thermochemical Materials

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| Balasubramanian, G., Ghommem, M., Hajj, M.R., Wong, W.P. Tomlin, J.A. and Puri, I.K. (2010) Modeling of thermochemical energy storage by salt hydrates, *International Journal of Heat and Mass Transfer,* 53(25) 5700 - 5706 | This paper presents a model describing the reaction of dehydrating a metal salt and applies it to magnesium sulphate. The thermal properties of magnesium sulphate are given. The energy absorbed in dehydration is 8.5 kJ/kg. | Modelling |
| Dicaire, D. and Tezel, F.H. (2011) Regeneration and efficiency characterization of hybrid adsorbent for thermal energy storage of excess and solar heat, *Renewable Energy ,* 36(3) 986 - 992 | This paper discusses the storage efficiency obtained experimentally using a hybrid material consisting of activated alumina and zeolite both of which absorb water vapour. Airflow rate during dehydration made very little difference but the temperature did - the efficiency was greater at lower temperatures even though the energy storage density achieved was less. For example, at around 100°C the efficiency (amount of energy released on hydration/amount of energy used to dehydrate) was around 50% but at 200°C the efficiency was only around 35%. This was because during dehydration the system lost the energy needed to heat up the water vapour that had been driven off the absorbent. The authors also did experiments to test if continued cycling impaired the performance but even after 50 cycles there was no difference in efficiency. | Experiment |
| Ghommem, M., Balasubramanian, G., Hajj, M.R., Wong, W.P., Tomlin, J.A. and Puri, I.K. (2011) Release of stored thermochemical energy from dehydrated salts, *International Journal of Heat and Mass Transfer,* 54(23) 4856 - 4863 | This paper is companion to Balasubramanian (2010) 'Modelling of thermochemical energy storage by salt hydrates' above. It models the release of the stored energy under condition where heat is extracted at a constant rate (not actually achievable by experiment).<br>Describes magnesium sulphate hydrate: thermal conductivity, hydration temperature and other relevant parameters. | Modelling |
| Hongois, S., Kuznik, F., Stevens P. and Roux, J. (2011) Development and characterisation of a new MgSO4-zeolite composite for long-term thermal energy storage, *Solar Energy Materials and Solar Cells ,* | Magnesium sulphate is the most promising candidate for thermochemical energy storage because of its high energy density, practical temperature range, availability and low toxicity. The authors embedded this material in a microporous zeolite, for maximum surface area of reaction. They also tested silica gel, but the zeolite gave a better temperature lift on hydration. They | Experiment |

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| 95(7) 1831 - 1837 | soaked pellets of zeolite in magnesium sulphate solution and dried them in an oven. 150°C was sufficient to remove 89% of the water (200°C would be needed for 100%). 15% concentration of salt in the zeolite proved optimal for energy charging. In experiments on rehydration, the reaction rate depended mainly on the relative humidity of the airflow through the sample and less on the airflow rate. Overall, the energy density achieved was 648kJ/kg, 600 MJ/$m^3$, or 45% of the maximum theoretically achievable with that concentration of salt. |  |
| Kaufmann, K. and Winnefeld, F. (2010) Long-Term Heat Storage in Calcium Sulfoaluminate Cement (CSA) based Concrete *wwww.empa.ch* | This is a technology offer for a CSA-concrete high in ettringite that can store energy using a hydration/dehydration reaction. This is fully reversible and can store between 250 and 500 MJ/$m^3$ depending on charging temperature 40-120°C. The concrete costs little more than ordinary concrete. | Technology offer from EMPA |
| N'Tsoukpoe, K.E., Liu, H., Le Pierrès, N., and Luo, L. (2009) A review on long-term sorption solar energy storage, *Renewable and Sustainable Energy Reviews*, 13(9) 2385 - 2396 | Sorption energy storage has the potential to be nearly as energy dense as biomass energy. Sorption reactions are used in heat pumps and for long distance energy transport. Energy storage with sorption can be open or closed, depending on whether water vapour is retained or released to the air. Closed systems yield heat at a higher temperature but also need a higher temperature to charge them so overall are less efficient in enthalpy.<br>The authors recommend that different reactors are used for storage and release of heat and that storage material is processed a little at a time, so it is not necessary to heat large amounts of material to the drying temperature at once. This is because large tanks would have high heat loss.<br>In 2004 a study by the Energy Research Centre of Netherlands considered 90 different materials and concluded that magnesium sulphate and iron hydroxide were the most promising for sorption heat storage.<br>Other materials that have been considered more recently include sodium hydroxide (too corrosive), lithium chloride (too expensive) lithium bromide (simulated only). | Review |

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|  | For simple physical absorption, zeolites can attain 446 MJ/$m^3$ for heating. Synthetic zeolites are expensive but natural zeolites can only be used up to 100°C. Silica gel has not matched its theoretical promise: up to 1080 MJ/$m^3$ was expected, but only 180 MJ/$m^3$ achieved. For chemical reactions, hydrated sodium sulphide could store up to 7000 MJ/$m^3$ but is too corrosive. Magnesium sulphate heptahydrate has high energy density but low power density.<br>There were a number of projects in this area included in IEA SHC Task 32 and this work is now continuing as Task 42. Compact Thermal Energy Storage: Material Development and System Integration. This should conclude in 2012. |  |
| Posern, K. and Kaps, Ch. (2010) Calorimetric studies of thermochemical heat storage materials based on mixtures of MgSO4 and MgCl2, *Thermochimica Acta,* 502(1) 73 - 76 | The temperature lift obtained from hydrating magnesium sulphate can be increased by mixing in a salt such as magnesium chloride, which deliquesces at a lower relative humidity. This also increases the energy density, since magnesium chloride has a higher heat of hydration. However, the chloride solution is corrosive so only small amounts can be used. | Experiment |
| Weber, R. and Dorer, V. (2008) Long-term heat storage with NaOH, *Vacuum*, 82(7) 708 - 716 | Concentrated sodium hydroxide solution releases considerable heat when it is hydrated and is a candidate for thermochemical heat storage. The energy storage density is high and sodium hydroxide is cheap, stable and forms thin films on heat exchangers, allowing for rapid heat transfer. The disadvantages of sodium hydroxide are that it is caustic and corrosive. The authors constructed a totally enclosed system with tanks and heat exchangers allowing sodium hydroxide to store heat for space heating and hot water in a house. The charging temperature was 150°C, so achievable from a solar collector. The storage density for the whole system was 3 times that of water for heat at 65-70°C and 6 times water for heat at 40°C. They calculated the space needed to store heat for the whole winter season for a house in Zurich, built to PassivHaus standard. The total heat demand would be 1800 kWh at 35°C for space heating and 50 litres/day of hot water at 60°C (winter only). They calculated the space needed (including all tanks and heat exchangers) would be 7$m^3$. | Prototype |

## Other Storage Materials

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| Barbieri, E. S., Spina, P. R. and Venturini, M. (forthcoming) Analysis of innovative micro-CHP systems to meet household energy demands, *Applied Energy (*In press corrected proof)<br>www.sciencedirect.com/science/article/pii/S0306261911007872 | Domestic sized CHP systems are under development. The authors have put together a model to show the energy savings that might be expected by some typical Italian households using them, and hence what the maximum capital cost would be to make the systems profitable. They modelled a range of different CHP technologies with different electricity generating efficiencies from 10% to 26%. The model assumed that each house had a CHP system, a heat store and a backup heat generator. The economic analysis showed that none of the CHP systems currently available were viable: this would require a capital cost for the CHP of no more than €3000/$kW_{e.}$ However, there were energy savings to be made of 0.4-1.0 toe/year (4,600 – 11,600 kWh/year). The use of the heat store was critical. The optimal size was between 0.7 and 2.0$m^3$, depending on CHP type and building size. | Model only |
| Bauer, D., Marx, R., Nußbicker-Lux, J., Ochs, F., Heidemann, W. and Müller-Steinhagen, H. (2010) German central solar heating plants with seasonal heat storage, *Solar Energy*, 84(4) 612 - 623 | The authors describe 4 very different examples of district heating with solar collectors and thermal stores, which have been operating in Germany for some years.<br>Friedrichshafen uses a reinforced concrete tank containing 12,000 $m^3$ water, for around 400 residential units: flats and terraced houses. In its best year the solar fraction (% of heating from the solar system) was 33%. Losses are higher than anticipated because the return temperature from the heating system is higher than expected, which means the tank is hotter and loses more heat than was hoped.<br>At Necharsulm, heat for 300 apartments is stored in the ground using borehole heat exchangers. There are also buffer tanks as temporary stores because the rate at which the boreholes can transfer heat is limited. In the summer time, the buffer tanks take some of the heat in the day, which is stored at night. It took 5 years to heat the ground store to a usable temperature. The highest solar fraction achieved so far is 45%.<br>At Rostock the thermal energy store uses an aquifer. The storage temperature is limited to 50°C because of the water chemistry but heat pumps are used to raise the temperature for heating | Working systems |

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| | water (45°C for heating and 65°C for hot water). The heat pumps continue to operate down to an aquifer temperature of 10°C. The best solar fraction achieved is 57%.<br>The last example is at Eggenstein-Leopoldsharen and it uses a gravel-water thermal energy store of 45,000 m$^3$. Again, a heat pump is deployed when the store temperature drops below that needed. It operates down to 10°C. Also there is a 30m$^3$ buffer store. This system is still being built but it should achieve a solar fraction of 40%.<br>Overall, there is no clearly better technology - it all depends on the site. However, heat pumps are definitely recommended with geothermal storage systems. On average, 62% of solar heat collected was delivered to the buildings.<br>Because of the inertia of the systems it takes several years of operation before performance can be reliably evaluated. | |
| Buchner, K and Hofbauer, H. (2003) Optimisation of ceramic heat storage of stoves, *Energy and Buildings,* 35(11) 1121 - 1128 | Ceramic stoves are designed to store heat from a fire and release it over a long time. You can burn for an hour, and the stove will continue to warm the room for 12 hours. The stove has a complex arrangement of flue gas channels to ensure that as much heat as possible is captured by the bricks. They are typically made of chamotte, a high temperature refractory material. Standard chamotte has a density of 1850 kg/m$^3$, thermal conductivity 930 mW/mK and thermal capacity 1780 kJ/m$^3$/K. Other bricks are available with higher conductivity and/or thermal capacity, up to 3200 mW/mK and up to 2470 kJ/m$^3$/K. These improve the efficiency of the stove. | Prototype |
| Kroll, J.A. and Ziegler, F. (2011) The use of ground heat storages and evacuated tube solar collectors for meeting the annual heating demand of family-sized houses, *Solar Energy*, 85(11) 2611 - 2621 | The authors argue that single-dwelling installations of seasonal storage using soil to store heat are feasible and that the costs would be similar to large-scale district heating storage. They have performed simulations to show that a house meeting current German building regulations could be 98% heated by solar energy using a collector area of 40 m$^2$ and a store volume of 84 m$^3$. Smaller collectors would need larger stores, but even with just 20 m$^2$ of collector and 60 m$^3$ of store, 96% can be achieved. The key is to create a cube-shaped | Model only |

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| | soil heat store (for low surface/volume ratio), insulate it well and run it at very high temperatures – even more than 100°C. The soil must be dry so that no steam is created. Also there would be separate heat transfer circuits for loading and using the heat, so that all the heat from the solar collector goes directly into the store and heat can be used at the same time. The simulation was for the climate of Hamburg. | |
| Nordell, B. and Skogsberg, K (2007) THE SUNDSVALL SNOW STORAGE--SIX YEARS OF OPERATION from 'Thermal Energy Storage for Sustainable Energy Consumption', *Springer Netherlands,* NATO Science Series 234(V) 349-366 | A cooling plant for a hospital in Sundsvall, Sweden, uses stored snow (natural and artificial) in winter for cooling in summer (May to August). This paper describes the experiences from 6 years of operation. | Working system |
| Novo, A.V., Bayon, J.R., Castro-Fresno, D. and Rodriguez-Hernandez, J. (2010) Review of seasonal heat storage in large basins: Water tanks and gravel--water pits, *Applied Energy*, 87(2) 390 - 397 | The authors describe experiences from 14 different heat storage projects, mostly in Denmark, Sweden and Germany, and of sizes varying from 500 to 12,000 m$^3$. Eleven of the projects had water tanks and some were successful but others had leakage problems. Gravel-water pits were usually less costly. The authors give the relative volume requirements of water, water/gravel and soil/rock storage but they do not specify the temperature range considered. | Working systems |
| Pinel, P., Cruickshank, C.A., Beausoleil-Morrison, I. and Wills, A. (2011) A review of available methods for seasonal storage of solar thermal energy in residential applications, *Renewable and Sustainable Energy Reviews,* 15(7) 3341 - 3359 | The authors talk about past and present practical systems rather than future potential. They have a nice comparison of storage volume needed using different storage types: reactions, sorption, latent heat and water (using 70°C range in temperature). They list some candidate materials for chemical storage including Silicon/Silicon oxide - which would need to be charged industrially, but energy could be released in a residential building - as well as sorption storage using silica gel, sodium hydroxide or calcium chloride.<br>However, chemical storage needs a lot more development to find a material that is practical and economical. They dismiss latent heat storage because it is not a great improvement over water storage for most applications. They compare sensible heat storage in water tanks, solar ponds, | Review |

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| | rock beds and ground.<br>Ground based systems, where the storage volume is not contained, are prone to leak heat due to water seepage - water barriers help but are expensive. Solid storage materials such as carbon, concrete or iron pellets are expensive and only economic when high temperature heat is needed.<br>Water tanks are naturally stratified, which is a good thing, but this is disrupted if heat is always injected at the bottom. Variable position inlets can help.<br>Heat always leaks from the container of a tank. A low surface to volume ratio is desirable, and lots of insulation. Earth can be an effective insulator, once it has warmed up.<br>Examples of working seasonal storage systems across Europe show clear economies of scale - e.g. 400 €/m$^3$ for less than 1000 m$^3$ down to 150 €/m$^3$ for systems greater than 10,000 m$^3$ | |
| Ren, H., Gao, W. and Ruan, Y. (2008) Optimal sizing for residential CHP system, *Applied Thermal Engineering,* 28(5) 514 - 523 | Combined Heat and Power systems can be very efficient for generating electricity but in Japan they have hitherto been mainly used in the commerical and industrial sectors. For residential use, a small system of 0.7 – 1.0 kW is being developed, and the authors have developed a model to show what cost savings can be expected for households buying this sytem.<br>The model assumes a grid connection and backup gas boiler as well as a gas-powered CHP unit and a small storage tank holding water for heating. The storage increases the flexibility of the system – if electricity is needed when heating is not then the CHP plant can run and store the heat for later, as long as the tank is not full. This reduces the time when heat is needed but electricity is not.<br>Conversely, if heat is needed but electricity is not, it may be better to run the CHP and feed the electricity onto the grid rather than run the backup boiler alone – depending on the spot electricity price. The authors modelled a particular load demand with a zero buy-back price for electricity, and the CHP generating electricity at about 30% efficiency. In this scenario it turned out that the optimal CHP capacity was 1kW and the corresponding optimum storage tank needed was | Simulation |

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| | 6kWh. This would be 250l using a temperature range of 20°C. The cost saving for the system, allowing for capital cost of CHP system, was about 5% but the savings are higher if the electricity price varies with time of day and it is sensitive to the relative price of gas and electricity and the capital cost of the plant. | |
| Simons, A. and Firth, S.K. (2011) Life-cycle assessment of a 100% solar fraction thermal supply to a European apartment building using water-based sensible heat storage, *Energy and Buildings,* 43(6) 1231 - 1240 | In 2005 a block of 8 low energy apartments was built in Berne, central Switzerland, which relies 100% on solar energy for heating and hot water. The heat comes from solar collectors and to cover the winter months a large water store is needed so the centre of the block has a vertical shaft containing 3 insulated water tanks. This is sufficient buffer to cover the winter when for two months average temperatures are below 0°C and there is 80% cloud cover. In total there is 280 $m^2$ of solar cells and the tanks store $205m^3$ of water (18m high). This paper compares the environmental impacts of this system with other heating options: heat pumps, fossil fuel or biomass heating. The lifecycle analysis of the solar system shows the dominating component is the solar collectors. In terms of greenhouse gases the solar system was comparable with the biomass boiler, and much better than all the other systems - including air and ground source heat pumps. In terms of other impacts the results were mixed, with no clear winner. | Working system |
| Stojanović, B. and Akander, J. (2010) Build-up and long-term performance test of a full-scale solar-assisted heat pump system for residential heating in Nordic climatic conditions, *Applied Thermal Engineering,* 30(2) 188 - 195 | A house in Sandviken, built in the 1920s and with no low energy adaptions, features in this report. For 2 years it was heated using a combination of solar panels on the roof (of an unusual, unglazed form) and a ground source heat pump with pipework laid 1.5m deep over an effective area of $52m^2$. During theis period, excess heat from the solar panels in the summer was used to warm the ground, in the hope of storing this until the winter time. In the second winter the solar panels failed and for a third winter the heat pump operated alone. The temperature profiles for the heat pump in the seasons before and after the failure showed that the summer heating made very little difference. Simulation work is needed to determine if this is becaue the seasonal storage was simply too small or if it was due to soil type or moisture | Working prototype |

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| Terziotti, L.T., Sweet, M.L. and McLeskey Jr., J.T. (2012) Modeling seasonal solar thermal energy storage in a large urban residential building using TRNSYS 16, *Energy and Buildings,* 45(1) 28 - 31 | Virginia Commonwealth University is building a new block of student accommodation, 5 stories, 15,700 $m^2$ in total, comprising shops and businesses on the ground floor and student rooms above. The authors have modelled a heating system for it, uisng solar collectors on the roof, and a large heat store which will retain heat through the winter months. The store will consist of an insulated pit containing sand. This has sufficient structural strength for a car park above.<br>They modelled the building heating needs with TRNSYS Version 16, transient thermal energy modeling software developed at the University of Wisconsin-Madison. They proposed an underfloor heating system. The peak heating requirements depend on the heating efficiency – they ran the model with different values, giving peak heating load from 19 to 38 $W/m^2$. Using 1930 $m^2$ of solar collectors (two thirds of the roof) and a store volume 6200 $m^3$ (5m deep) the most efficient system could be run with 86% of the heating energy coming from the solar panels. | Simulation |
| UKERC (2011) The Future Role of Thermal Energy Storage in the UK Energy System: Assessment of Technical Feasibility and Factors Influencing Adoption<br>*UKERC research fund project*<br>*Available from:*<br>www.ukerc.ac.uk/support/tiki-index.php?page=RF3SmallThermalStorage<br>Accessed on 23 Feb 2012 | This project aims to clarify the potential for and limitations of energy storage systems in the transition to a low carbon economy. The final outcomes will include:<br>• Database of current example/ prototype applications<br>• Review of current research<br>• Characterisation of applications<br>• Estimates for the potential reduction in energy use and carbon emissions, and<br>• Review of the role of thermal storage in deployment of large scale renewable energy.<br>This project is expected to finish in 2012. The principle contact is Professor Philip Eames, Loughborough University | Ongoing<br>research project |

*Insulation Materials*

**Aerogel**

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| Aspen Aerogels (2011) Spaceloft Data Sheet *www.aerogel.com* | Spaceloft blanket insulation is made from aerogel reinforced with fibres to make it easy to handle and robust. It is breathable but repels water. It is flexible, but springs back after compression. It comes in 5mm and 10mm thicknesses, and the conductivity is 14 mW/mK. | Manufacturers data |
| Baetens R., Jelle, B.P. and Gustavsen, A. (2011) Aerogel insulation for building applications: A state-of-the-art review, *Energy and Buildings,* 43(4) 761 - 769 | The authors describe in detail the processes involved in making aerogel and its properties after it has been made. As well as low conductivity, aerogel reflects sound - multiple layers in total 7cm thick can reduce noise levels by 60dB. Working with aerogel produces silica dust but this is amorphous silica rather than crystalline so it does not have sharp points. There is no evidence that it is dangerous. Animal experiments show it is cleared completely from the lungs. Aerogel can be made translucent and used in windows. Aspen aerogel sheets have fibres mixed in so that they are less fragile. Aerogels are compared with VIPs - which have lower conductivity when new but are easily damaged and cannot be cut to fit. | Review |
| Buratti, C. and Moretti, E. (forthcoming) Experimental performance evaluation of aerogel glazing systems *Applied Energy* (In press corrected proof) http://dx.doi.org/10.1016/j.apenergy.2011.12.055 | The authors constructed glazing samples using aerogel infill between panes of glass or polycarbonate, and tested them for transmission of heat and light. They tested both monolithic aerogel and granular. They also tested a full size window with granular aerogel (1175 x 1454 mm), but not monolithic because the manufacturers could not supply a large enough pane. The granular aerogel pane had a U-value of 0.99 W/m$^2$/K, slightly lower than the value measured from the smaller samples. Of the samples, the monolithic aerogel had a U-value of 0.6 W/m$^2$/K - about the same as triple glazing with argon fill and low-e coatings. The monolithic aerogel had good light transmission, but in the granular aerogel light was reduced by half. | Experiment |
| Stahl, Th., Brunner, S., Zimmermann, M. and Wakili K.G. (2012) Thermo-hygric properties of a newly developed aerogel based | The authors have developed a new form of breathable external render that can be applied to buildings for external insulation. The render contains aerogel granules to improve its insulation properties. The authors tested this render against a | Experiment |

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| insulation rendering for both exterior and interior applications,<br>*Energy and Buildings,* 44(1) 114 - 117 | range of 12 commercial insulating render products with expanded polystyrene, perlite, cork and other additives. The aerogel outperformed all of them both for low conductivity and high breathability.<br>The aerogel mix conductivity was 25 mW/mK and that of the closest competitor was 65 mW/mK.<br>Insulating render is normally applied using a plastering machine, which applies high pressure, and this damaged the aerogel (as it did other renders), reducing the insulation effect. However, an additive was devised (patent in process) to protect the aerogel from the pressure. Further testing is needed with temperature and moisture monitoring on test walls. | |
| Wei, G., Liu, Y., Zhang, X. Yu, F. and Du, X. (2011*)* Thermal conductivities study on silica aerogel and its composite insulation materials, *International Journal of Heat and Mass Transfer*, 54(11) 2355 - 2366 | Aerogel is brittle and one way to make it stronger is by integrating it with something tough to make a composite. In this research, the authors combined aerogel with a xonotlite: a form of calcium silicate. The thermal conductivity of the composite was a little less than 30 mW/mK at room temperatures. The authors did not report anything about the mechanical strength of the resulting material. | Experiment |
| Yang, X., Sun, Y., Shi, D. and Liu, J. (2011) Experimental investigation on mechanical properties of a fiber-reinforced silica aerogel composite, *Materials Science and Engineering: A*, 528(13) 4830 - 4836 | Pure aerogels are very brittle, with compressive strength as low as 1 Mpa. However, ceramic fibre can be added with very little change to the conductivity and considerable improvement in strength. The authors prepared samples of aerogel with long, thin ceramic fibres (up to 40mm long and only 6 µm wide) of silica and alumina. They tested the compressive strength and elasticity of the samples at a range of temperatures. At low stresses the elasticity of the reinforced aerogel was the same as for the pure aerogel, but as the stress increased the fibres started to take the load. This started to happen at stresses below 1 MPa and the samples had already compressed by up to 5%. As the fibres took the load the samples compressed further but did not crumble. At higher temperatures the material deformed faster but took a greater load to break. At 25°C the strength was 13.5 MPa. | Experiment |

**Vacuum insulation panels (VIPs) and gas filled panels**

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| Baetens, R., Jelle, B.P., Gustavsen, A. and Grynning, S. (2010) Gas-filled panels for building applications: A state-of-the-art review, *Energy and Buildings*, 42(11) 1969 - 1975 | Conventional insulation has a porous air-filled structure. The insulation performance is good but limited because the air itself will conduct heat. Noble gases such as krypton and xenon have lower conductivity than air, both because they are heavier than air, and as single-atom molecules they have few vibrational modes so they carry less energy. Theoretically, gas-filled panels with conductivity as low as 10 mW/mK should be possible but protoypes are nowhere near as good. For argon, the theoretical minimum should be 21 mW/mK but prototypes show 40 mW/mK, which is no better than much cheaper kinds of insulation. | Review |
| Baetens, R., Jelle, B.P., Thue, J.V., Tenpierik, M.J., Grynning, S. Uvsløkk, S. and Gustavsen, A. (2010) Vacuum insulation panels for building applications: A review and beyond, *Energy and Buildings*, 42(2) 147 - 172 | Vacuum insulation panels with different types of envelopes are considered. The core is almost always fumed silica because it is strong in compression, has an open cell structure that allows the vacuum to be pulled out, and very small pores mean low conductivity even without the vacuum.<br>VIP insulation can be 5-10 times thinner than conventional insulation.<br>However performance degrades over time due to gas and vapour permeating into the panels. Aluminium foil coatings are longer lasting (at least 60 years) but are not so effective due to conduction at the edges. Metalised foil coatings have service life predictions ranging from less than 10 years to 40 years. However, all VIPS are very fragile, and rough handling can completely destroy the vacuum, for example if trodden on, or pierced by a nail. The recommendation is that VIPs only be used in prefabricated components.<br>VIP panels are so light they are less effective than other systems as a sound barrier and heavier facings may be needed, for example, to exclude traffic noise.<br>VIPs are suitable for building applications such as sandwich elements in doors and window frames (up to 50% improvement in heat loss) and for insulation of hot water tanks, pipes and underfloor heating systems as well as insulating walls and roofs. | Review |
| Brunner, S. and Simmler, H. | The authors constructed a flat roof with vacuum | Experiment |

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| (2008) In situ performance assessment of vacuum insulation panels in a flat roof construction, *Vacuum, 82(7) 700 - 707* | insulated panels integrated into the insulation and monitored it for 3 years. The panels had a three-ply metalized polymer envelope and were covered with a protective layer, a bitumen barrier and gravel. The conductivity did increase over time - in line with the prediction of models based on the actual temperature and humidity over the test period. Based on the model, the service life of these panels would be 25 years. | |
| Fricke, J., Heinemann, U., and Ebert, H.P. (2008) Vacuum insulation panels---From research to market, *Vacuum,* 82(7) 680 - 690 | Vacuum insulation panel development dates back to at least 1955, when a panel structure with glass fibre in steel foil was patented. Since then the best kernel material has been found to be silica fume, because of its nano-pore open cell structure, high compressive strength and durability. Larger pore materials need a deeper vacuum to achieve low conductivity. Thermal transport in VIPs is now well understood, incorporating conduction and radiation. SiC is added to the fume to absorb and scatter radiation. Laminated foils make the best envelope materials, resisting air and water vapour incursion for longer. VIPs are too expensive for general use in buildings - we need better laminates, which would allow us to use cheaper core materials. | Review |
| Wegger, E., Jelle B.P., Sveipe, E., Grynning, S., Gustavsen, A., Baetens, R. and Thue, J.V. (2011) Aging effects on thermal properties and service life of vacuum insulation panels, *Building Physics,* 35(2) 128-167 | VIPs are expected to degrade over time as moisture and gases seep through the envelope into the core. The rate of seepage depends strongly on the conditions of temperature, moisture (relative humidity) and pressure. Testing VIP designs for 25 years or more is impractical. The authors have attempted to show that briefer testing periods can be used with more extreme conditions to simulate longer periods of normal conditions. The key considerations are that firstly the more extreme conditions do lead to more rapid aging and secondly that the mechanisms and effects are the same as normal aging, so no new factors are introduced. Their experiments did show some physical effects such as blistering of the outer protective layer at high temperatures, thickening and warping of the whole panel under high temperature and moisture conditions. However, these did not affect the overall thermal resistance, and the results after aging were within the | Experiment |

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| | expected bounds. There were some panel failures and considerable variability between samples, which shows that experiments should always use a reasonable number of samples, to get a representative result. | |

**Multi-foil insulation**

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| Actis (2010) ACTIS THIN MULTIFOIL INSULATION TRISO-SUPER 10 Acrtis Thin Multifoil Insulation Triso-Super-10 data sheet *www.actis-isolation.com* | This datasheet for Triso Super 10 multifoil insulation states that it is equivalent to 210mm of mineral wool when used in a pitched roof application according to the installation instructions. This claim is based on testing done by TRADA Technology Ltd in 2009. The data sheet does not give any value for conductivity or resistance. The insulation material is 30mm thick in 19 layers, including 8 foil layers. | Manufacturers data |
| BBA (2011) MULTIFOIL INSULATION TLX SILVER AND TLX SILVER FB FOR PITCHED ROOFS Watford: British Board of Agrément | This certificate indicates the measured thermal resistance of 2 multi-foil insulation products (TLX Silver and TLX Silver FB) and describes how they can be used in pitched roofs to achieve U-values of 0.19 W/m$^2$K. The resistance of the two products translates to conductivities of 33 and 35 mW/mK. | Manufacturers data |
| Eames P. C. (2009) Multi-foil Insulation BD2768, London: Department for Communities and Local Government | The author consulted about 22 scientific opinions as to whether or not the currently accepted methods for testing heat transfer through insulation materials were appropriate for multi-foils. Opinion was divided - a little less than half thought that an in-situ testing method should be developed. The author also reports the results of a simulation of heat transfer through a wall comparing multi foils to mineral wall. The wall model included the multifoil between air spaces, with a vapour-permeable membrane on one side and plaster board on the other. The multifoil performed worse than even 100mm of mineral wool. | Simulation and consultation only |
| Mavromatidis L.E., Bykalyuk A., Mankibi, M.E. and Michel, P. and Santamouris M. (2012) Numerical estimation of air gaps' influence on the insulating performance of multilayer thermal insulation, *Building and Environment,* | Multi-foil insulation works by reducing radiation losses rather than only conduction losses. Each layer has a low emissivity surface (though this degrades with age as water vapour penetrates and the foil tarnishes). For best results multi-foil insulation needs an air gap on either side. The authors have developed a numerical model of heat loss in this scenario and validated it against | Model validated by experiment |

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| 49(0) 227 - 237 | test results. Then they used it to simulate heat loss over a range of gap sizes. The optimum proved to be a 3cm gap on both sides. This gave an overall U-value of 0.43 $W/m^2K$. A 1cm gap gave a U-value of 0.62. | |
| Saber, H.H. (2012) Investigation of thermal performance of reflective insulations for different applications, *Building and Environment,* 52(1) 32 - 44 | Reflective insulation is usually used with an air space on at least one side, which also contributes to the insulation effect and complicates modelling and testing the situation. Standard test method ASTM C-1363 "Standard Test Method for the Thermal Performance of Building Assemblies by Means of a Hot Box Apparatus" consistently produces results which suggest a lower resistance than models predict. This is because the test measures heat flow in the centre of a sample and assumes that heat flow is uniform along it. In practice this is not the case and the heat flow is less at the edges.<br>Having verified their models, the authors looked at how much contribution the low emissivity surface in the foil makes to the assembly. This is important if only because the foil tarnishes or gets dusty over time. The contribution depends on the direction of heat flow. It is more when heat flows down than up. In upward heat flow cases the foil increases resistance by up to 15%. The conductivity of the multi-foil system was 36 mW/mK. | Model validated by experiment |
| Ward, T.I. and Doran, S.M. (2005) The thermal performance of multi-foil insulation, Glasgow: BRE | This report describes some in-situ testing done with Triso Super 9 multifoil installation on two different buildings in Scotland. Heat flow measurements taken were close to what was expected based on lab tests done by NPL in 2004. They were 2-4 times what would be expected from the manufacturers' claim of equivalence to 200mm mineral wool (i.e. it did not match manufacturers' claims). | BRE report |

**Other insulation**

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| Al-Homoud M.S. (2005) Performance characteristics and practical applications of common building thermal insulation materials, *Building and Environment,* 40(1) 353-366 | Here is a comprehensive review of the principles behind insulation – why to do it, what to use, how to fix it and so on.<br>Insulation can save energy use in buildings both from heating and cooling. The best place to put insulation depends on where heat is coming from: on the outside in hot countries, on the inside when heating is required from within. There are many different kinds of insulation, fibre/loose/panels, organic or not. They are usually rated by their conductivity, but this is in fact an apparent conductivity as measured under laboratory conditions which may include convection and radiation components as well as conductance. Performance degrades when there is moisture. Moisture can have many sources inside and outside, and through infiltration between the two. Ventilation is important to prevent moisture build-up. Vapour barriers can help but are not recommended in a mixed climate like the UK, where moisture can come from either side. Also reflective insulation is not recommended in cool climates where the dominant need is heating not cooling.<br>Adding more insulation has diminishing returns but linear costs, so there is an optimal thickness of insulation depending on energy cost, maintenance and capital costs. | Review |
| Alani, A., MacMullen, J., Telik, O. and Zhang, Z.Y. (2012) Investigation into the thermal performance of recycled glass screed for construction purposes, *Construction and Building Materials,* 29(1) 527 - 532 | The authors compared two samples of screed made from recycled glass with three more conventional screeds made with sand. The glass screed had half the conductivity of the sand screeds. (Dry/saturated, mW/mK glass: 700/1000; sand: 1900-2400.) | Experiment |
| de Gracia, A., Castell, A., Medrano, M. and Cabeza, L.F. (2011) Dynamic thermal performance of alveolar brick construction system*, Energy Conversion and Management ,* 52(7) 2495 - 2500 | The authors compared the heat loss from 4 model cubicles over several days in winter and in summer. Three had perforated brick with some kind of insulation; the fourth was constructed with alveolar brick. Alveolar brick has lower conductivity but higher density and hence thermal mass than hollow brick. The U-value for alveolar brick was 45% higher than for the insulated cases | Experiment |

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| | but there was very little difference in heating energy consumption in field tests, because of the higher thermal inertia. These experiments took place in Spain. | |
| del Coz Díaz, J.J.,García Nieto, P.J., Domínguez HernándezJ., and Álvarez Rabanal, F.P. (2010) A FEM comparative analysis of the thermal efficiency among floors made up of clay, concrete and lightweight concrete hollow blocks, *Applied Thermal Engineering*, 30(17) 2822 - 2826 | The authors used finite element analysis to predict the behaviour of floors made from 6 shapes of block with 3-12 recesses in 3 materials: plant produced concrete, lightweight concrete and clay. The floor construction type was *in situ cast floor with one-way spanning slabs.* The construction included pre-stressed concrete joists, mesh reinforcement, more concrete and plaster. They also built examples of the floors and measured their performance to validate their model. The floor with the lowest effective conductivity was the one with lightweight concrete blocks with 9 recesses (3x3). This concrete had a density of 1000 kg/m3, less than half the plant produced concrete and 30% less than the clay. Its conductivity was 347 mW/mK.<br>However, the shape of the blocks was at least as important as the material. The blocks which were not divided horizontally (3 or 4 cells extending top to bottom) were the worst, and these bricks made of lightweight concrete were worse than the best bricks made of plant produced concrete. | Model validated by experiment |
| Hall, M.R., Najim, K.B. and Hopfe C.J. (2012) Transient thermal behaviour of crumb rubber-modified concrete and implications for thermal response and energy efficiency in buildings, *Applied Thermal Engineering,* 33-34(1) 77 - 85 | Plain rubberised concrete is concrete containing fragments of rubber, for example from used car tyres. You can add up to 20% rubber in concrete for structural use, up to 30% for other uses. Adding rubber increases the heat capacity of the concrete by perhaps 5%, but also increases thermal resistance by up to 30%. The concrete can absorb more heat but it takes longer to do so. | Experiment |
| Hanson (2012) Aircrete blocks technical manual *www.hanson.com* | This 56-page manual gives the properties of 11 types of aircrete block and explains their uses for foundations, walls and floors. Thermal conductivity ranges from 110 to 190 mW/mK while compressive strength varies between 3 and 9 MPa. | Manufacturers data |

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| Iwaszkiewicz, C., Christofides, J., Wright, W. and Thompson, R.,(Inbuilt); Connaughton, J., Hayes-Lewin, B. and Newey, R. (Davis Langdon) (2010) Study on hard to fill cavity walls in domestic dwellings in Great Britain London: DECC ref: CESA EE0211 | There are 4-6 million homes in Great Britain with hard to fill cavity walls. Filling them all completely would lead to savings of up to 1 Gt $CO_2$/year. In practice this would not be possible or not economic - costs can be up to £8000 per house (2010 prices). Householders often fail to perceive the benefit from getting their cavities filled at such expense without guaranteed savings. One common reason for not filling cavity walls is narrow cavities in high exposure zones. About 2 million houses have narrow cavities (50mm or less). Also about 2 million houses were built 1990 - 1995 with partially filled cavities. There are savings to be made from filling these too but not so much as from filling empty cavities. | Report from DECC |
| Jelle B.P. (2011) Traditional, state-of-the-art and future thermal building insulation materials and solutions -- Properties, requirements and possibilities, *Energy and Buildings*, 43(10) 2549 - 2563 | This review starts with an overview of conventional insulation and building materials. It gives the conductivity of each when dry and with up to 10% moisture. The properties and capabilities of VIPs, GFPs and nano insulation materials are explained in detail, nano insulation materials meaning materials with nanometre sized pores. VIPs are regarded as too fragile to be much use. Incorporating nano into insulation in concrete is proposed to reduce conductivity (and also reduce embodied carbon emissions). This can be done in sandwich layers or mixed in. | Review |
| Kolokotroni, M., Gowreesunker B.L. and Giridharan, R. (forthcoming)<br>Cool roof technology in London: An experimental and modelling study<br>*Energy and Building* (In press corrected proof) http://dx.doi.org/10.1016/j.enbuild.2011.07.011 | Experiment shows that cool roof technology - in the form of reflective paint on a flat roof over a London office building - does improve comfort in summer by reducing solar gain. Modelling, calibrated against the measurements taken in the experiment, shows that for an air-conditioned office, the reflective paint achieves overall savings of up to 8.5% for the Summer Design Year for London weather. However, without air conditioning the increased heating needs in winter result in up to 10% greater fuel use. | Experiment and Modelling |
| Korjenic, A., Petránek, V., Zach, J. and Hroudová, J. (2011) Development and performance | The authors tested the thermal conductivity and moisture content of 6 samples of insulation made from hemp, flax and jute fibre at increasing levels | Experiment |

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| evaluation of natural thermal-insulation materials composed of renewable resources, *Energy and buildings*, 43(9) 2518 - 2523 | of humidity. For five of the six the thermal conductivity stayed fairly constant up to 6% moisture, which was reached at about 60% relative humidity. After that the conductivity increased faster than the standard as specified by EN ISO 10456. Some samples reached 10% moisture at 70% relative humidity. | |
| Kuenzel H.M. (1998) More Moisture Load Tolerance of Construction Assemblies throough the Application of a Smart Vapor Retarder, *ASHRAE Conference Proceedings Thermal Envelopes VII* | When a wall is insulated a vapour barrier is often installed on the inside to prevent interstitial condensation. Otherwise, vapour passing outwards through the wall in winter will get cold and can condense, usually on surfaces within the structure. The vapour barrier stops this happening but it also prevents the wall from drying out. Water can come from various sources and wooden structures can have a considerable amount of water still present when they are built but this will dry quickly enough if it can evaporate away from the warm side. A smart retarder can be used in conditions where winter is cold and dry and summers are warm and humid. The barrier will allow vapour to pass through in the summer but not in the winters. This behaviour was demonstrated in a cathedral roof near the Germany-Austria border. | Review |
| Le Doujet, K. (2009) Opportunities for the large scale implementation of straw based external insulation as a retrofit solution of existing UK building, *Masters thesis: Engineering Centre for Sustainable Development,* Cambridge: University of Cambridge | Straw bales are often used for new build properties but their potential for retrofit is less well recognized. The author found only 20 completed retrofit projects in Europe and the Americas, including 2 in the UK. Straw is not a waste product and there are competing uses for it, but there is a considerable supply. The main technical barrier for its use in retrofit is the thickness needed: 25-40cm. This reduces light coming through windows, even when there is physical space. The main advantage of straw bales for insulation is low embodied energy. Typical concerns concerns about risk from fire, vermin and short lifetime are not warranted.<br>The conductivity of straw bales depends on density (with an optimum value somewhere between 110 and 340 kG/m$^3$) and the orientation of the straw. Typically is it 45 W/mK for bales on edge and 60 for flat bales. | Review |

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| MacMullen, J., Zhang, Z., Rirsch, E., Dhakal, H.N. and Bennett, N. (2011) Brick and mortar treatment by cream emulsion for improved water repellence and thermal insulation, *Energy and Buildings,* 43(7) 1560 - 1565 | When brick and mortar get wet they conduct heat more quickly. The authors used a proprietary moisture repellent cream to treat bricks and measured the conductivity in dry and wet conditions with and without treatments. Also they built a model brick house and treated this, and measured the energy needed to keep it warm in dry and wet conditions. In 85% humidity the treated house needed only half the energy to heat it as the untreated house. This experiment was conducted in Portsmouth. | Experiment |
| Maref, W., Armstrong, M., Rousseau, M.Z., Nicholls, M. and Lei, W. (2010) Effect of wall energy retrofit on drying capability, *National Research Council Canada, www.nrc-cnrc.gc.ca/irc* | Even when insulation is added externally, there can still be interstitial condensation if the conditions are tough enough. The authors compared the performance of 3 test walls through autumn 2007 to Spring 2008. All were timber frame with glass fibre insulation batts. One had no additional insulation. Another had 50mm rigid foam (extruded polystyrene) insulation between the wall and the external sheathing. The third had mineral fibre insulation boards added instead. The two insulated walls had air leakage paths added intentionally, to simulate poor construction. None of the walls proved to be entirely free of condensation through the winter, although the insulated walls did better than the other one. The mineral fibre insulation dried out more quickly than the foam but there was no staining or damage to the studding in either case. | Experiment (Ottawa climate colder than here) |
| Pavlík Z. and Černý, R. (2009) Hygrothermal performance study of an innovative interior thermal insulation system, *Applied Thermal Engineering,* 29(10) 1941 - 1946 | Mineral wool insulation is degraded by moisture, which can be a problem when it is used for dry-lining walls - as is common in retrofit. Conventionally it is protected by a vapour barrier between it and the plaster - but this can be damaged, leading to moisture penetration. Using moisture repellent wool (in this case DachRock) and a water vapour retarder layer on the other side (between the wool and the wall) is an alternative. This structure (using lime plaster) was tested over a winter in Prague. The relative humidity in the wool remained low (though in the brick it was still high from initial construction) and no liquid moisture condensed in the wool. | Experiment (no control). |
| Perlite institute (no date) PERLITE LOOSE FILL | Perlite is made from a naturally occurring volcanic rock that contains some water. This is crushed and | Commercial data |

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| INSULATION www.perlite.org | heated to about 870°C so that the water vaporizes and forces the perlite to expand to 4-20 times its original volume. The thermal conductivity of perlite increases with temperature and also higher densities of perlite have higher conductivity as shown in graphs in the document. At typical building temperatures the conductivity is 23-43 mW/mK. |  |
| Radhi, H. (2011) Viability of autoclaved aerated concrete walls for the residential sector in the United Arab Emirates, *Energy and Buildings,* 43(9) 2086 - 2092 | The UAE has building regulations for insulation to save energy - albeit for cooling rather than heating. Autoclaved aerated concrete blocks can be used instead of foamed or hollow sand/cement blocks. The AAC block has one quarter the density but a similar specific heat value and one-sixth the conductivity or less. The authors conducted field performance tests and calculated payback times, but these are for UAE and not applicable here. | Field tests |
| Sengul, O., Azizi, S., Karaosmanoglu, F. and Tasdemir, M.A. (2011) Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete, *Energy and Buildings,* 43(2) 671 - 676 | Perlite is a volcanic glass that expands when heated about 870°C forming porous, absorbent granules widely used in the construction industry. Granules can be added to concrete to make lightweight blocks that can be used to make lightweight buildings with less steel. The authors prepared samples from 6 different mixes of cement, sand and perlite from 0 to 76%. They also added super-plasticiser to the perlite mixes to make them more workable.<br>Tests showed that concrete with up to 20% perlite has a compressive strength - suitable for structural purposes: 17.3 MPa. However, the perlite concrete also had a greater tendency to deform under load that would need to be taken into account. With more perlite the thermal conductivity was reduced: by 12% with 40% perlite. However, the perlite made the concrete more absorbent, especially at higher ratios of perlite, which would shorten the life of the blocks in use unless they were protected from water. | Experiment |
| Van Den Bossche, N., Huyghe, W., Moens. J., Janssens, A., Depaepe, M. (2012) Airtightness of the window--wall interface in cavity brick | The authors compared 13 methods of filling cavity walls for resulting airtightness at the interface with metal-framed windows. They built the walls according to current building standards. Fill options included mineral fibre, sprayed | Experiment |

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| walls, *Energy and Buildings,* 45(0) 32 - 42 | polyurethane foam, extruded polystyrene, foil and combinations. The walls filled with mineral fibre were the least airtight. Sprayed foam with caulking was the best. | |
| Vrána, T. and Gudmundsson, K. (2010) Comparison of insulations -- Cellulose and stone wool in terms of moisture properties resulting from condensation and ice formation, *Construction and Building Materials*, 24(7) 1151 - 1157 | The authors compared the moisture absorption of mineral wool and cellulose fibre (loose fill) in an experiment where both were subjected to high humidity at a range of internal and external temperatures. Tests lasted 100 hours. At 0°C external temperature the mineral wool absorbed only about a quarter as much as the cellulose (1.4 % against 5.4%) but at lower temperatures both materials absorbed more and the difference was less. | Experiment |

## *Miscellaneous*

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| BRE (2010) The Government's Standard Assessment Procedure for Energy Rating of Dwellings *www.bre.co.uk* | This document explains how to assess a dwelling in terms of energy performance and cost. The calculation process includes heat loss by conduction (including thermal bridging) and ventilation, and heat gains by solar gains and internal gains. Renewable energy generation is included. Lighting costs and hot water are included, but not other appliances or cooking. Thermal mass is mentioned in Appendix P - concerning thermal comfort in summer - and makes only a minor difference to the energy rating. | BRE procedure |
| Holdaway, E., Samuel, B., Greenleaf, J., Briden, A. and Gardiner, A. (2009) The hidden costs and benefits of domestic energy efficiency and carbon saving measure*s,* London: DECC | There are many hidden costs, such as householder time, for different insulation measures and other energy projects. Even without DIY there can be a lot of time put in for research, managing contractors, choosing new decorations, even temporary accommodation. Hidden benefits such as noise reduction and better use of space should also be considered. | Household survey |
| Laycock E.A. (2002) Ten years of frost testing at Sheffield Hallam University, *Construction and Building Materials*, 16(4) 195 - 205 | Sheffield Hallam University has a climatic simulator which allows building constructions to be tested under controlled temperature and humidity conditions and with simulated rain (bot not wind). The author has used this to test cavity wall constructions with and without insulation and using weather data from real weather events, for example from the Pennines, which have caused frost damage in the past. In the last set of experiments they repeated weather cycles of up to 24 hours, up to 100 times.<br>Water in brick pores may not start to freeze at 0°C and can be liquid at least down to -4°C. However, once freezing has begun the freezing front travels rapidly through the brick because ice is a better thermal conductor than liquid water. The insulated walls consistently had a lower temperature at the back of the outer brick than the uninsulated | Experiment |

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|  | walls, and sometimes had the whole brick frozen, whereas uninsulated walls rarely froze all the way. Also, insulated walls sometimes did not thaw out between cycles. The performance of the wall varied considerably depending on the type of brick and the type of mortar, and whether or not they were thermally compatible. Damage was much greater in humid climates. |  |
| McLeod, R. (2010) Thermal mass: is more always better? *Ecotech: Sustainable Architecture Today, November 2010 - Special Report: PassivHaus,* 24(1) 20-23 | The general advice in Passivhaus design is to dampen the amplitude of the 24 hours internal temperature swing to 1°C. The solar loading on an example building of 90m$^2$, single storey with large south facing windows, comes to 21kWh/day. With a lightweight construction the thermal capacity would be 110 Wh/m$^2$/K. This would give a temperature swing of 2°C per day. A heavy weight construction with twice the heat capacity would give a temperature swing in the design range. No additional thermal capacity is needed. However, if you are reliant on thermal mass it is very important to ensure the building cools overnight to dump the heat absorbed during the day, so ventilation is vital. | Not a peer reviewed journal |
| MET Office Regional Climates 2012 fromwww.metoffice.gov.uk/ climate/uk/regional/ | The MET Office gives average climate data over the period 1971 to 2000 for each of 11 regions. The temperature data shows that the summer time average daily maximum temperature is not more than 10°C greater than the minimum in any region. | Real data |
| Sadineni, S.B., Madala, S. and Boehm, R.F. (2011) Passive building energy savings: A review of building envelope components, *Renewable and Sustainable Energy Reviews,* 15(8) 3617 - 3631 | This comprehensive review contains interesting nuggets such as: PCM used for thermal mass in trombe walls (thinner and better); light weight concrete including autoclaved aerated concrete as an alternative to clay bricks (highly insulating); PCM incorporated into gypsum (up to 30%) or concrete for latent heat storage; novel window technology including aerogel glazing and reflective glazing where the tint can be switched on and off; roof insulation both to avoid overheating and to reduce cooling (up | Review |

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| | to 88% reduction in heat flux using an aluminium reflective barrier in combination with insulation on a concrete roof); fibrous insulating materials perform poorly when moist; health problems from PVC-based insulation and fibreglass; adding fire retardants to cellulose insulation reduces its effectiveness; numerical models for the energy performance adding thermal mass; BioPCM being a new kind of organic PCM which is less flammable | |