Article:

Flammability assessment of phase change material wall lining and insulation materials with different weight fractions

Martyn S. McLaggan [a,*], Rory M. Hadden [a], Martin Gillie [b]

[a] School of Engineering, University of Edinburgh, Thomas Bayes Road, Edinburgh EH9 3JL, UK
[b] School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Oxford Road, Manchester M13 9PL, UK

ARTICLE INFO

ABSTRACT

The built environment increasingly includes innovative material aimed at drastically reducing energy consumption. Various types of phase change material (PCM) products are available but under the current fire safety guidelines their usage may be restricted due to their flammability, as is the case for some insulation materials. This study assesses the quantified fire performance of two different PCM plasterboards, a PCM-polymer sheathed in aluminium, and a polymeric macroencapsulated PCM insulation material. Insulation materials are shown to release much greater amounts of energy and are highly ignitable, and thus often require a suitable fire barrier. The thickness and thermal properties of this can be specified for the specific application to prevent ignition of the PCM. Lining materials have similar normalised burning rates for different PCM loadings and thus the optimal energy savings can be defined. Designers can select the maximum quantity of PCM loading for an acceptable fire risk, thus allowing the greatest potential for saving energy. The use of this knowledge allows designers to select the most suitable PCM for their need, and can enable the usage of materials where they are currently restricted.

Nomenclature

m	Mass (g)
t	Time (s)
$\dot{q}''$	Heat flux (kW m^{-2})

subscripts
0	Initial
fl	Flaming
i	Incident
ig	Ignition

1. Introduction

Sustainability is a major driving factor in the design of modern buildings. Stringent goals for reducing energy consumption in a short time frame require radical solutions. Increasingly, materials with extremely low thermal inertia are used but eventually these provide only diminishing returns for the quantity of material. Furthermore, the building tends to react rapidly to temperature changes owing to the low thermal mass. One innovative solution to reduce the building energy consumption whilst maintaining an equivalent high thermal mass is the use of phase change materials (PCMs) within wall assemblies. These materials contain a core component which melts at the desired room temperature, and absorb energy in the process. During the evening the material then re-solidifies and releases the stored energy. This reduces the diurnal temperature fluctuations in a building, and can reduce the cost of cooling during the day and heating during the night [1–3].

The materials with the most suitable thermal properties often take the form of paraffin wax or fatty acids, both of which are highly flammable. The existing standard fire test methods are intended for the classification of all materials and not intended to provide detailed characterisation of individual materials. This is particularly evident for materials with sophisticated composition which have complicated behaviour, and thus require bespoke testing methodologies to understand and quantify their performance. Furthermore, these tailored methods are required to provide the means for optimisation techniques which are not otherwise possible with standardised test methods.

PCMs are included in different substrates and placed within different positions of wall assemblies, and thus require a careful analysis of the associated fire risks. For some PCM insulation mate-

* Corresponding author. Present address: Division of Fire Safety Engineering, Lund Technical University, Box 118, 221 00 Lund, Sweden.
E-mail address: martyn.scott_mclaggan@brand.lth.se (M.S. McLaggan).

rials only a very poor European classification (BS 13823 [4], as part of BS ISO 13501 [5] framework) can be achieved, for example E or F, due to the quantity of highly flammable fuel. This restricts their usage in buildings, a limitation which could be avoided if the risks were known and evaluated as part of a rigorous performance-based design. This would allow for designs optimised for energy savings with quantified fire performance.

Given the above situation, the flammability of a variety of different PCMs have been evaluated in this study. These include two gypsum based wall linings which contain microencapsulated paraffin wax, one macroencapsulated fatty acid contained within mat insulation, and one sandwich panel insulation material. These materials are evaluated in the widely used cone calorimeter (ISO 5660 [6]) using a slightly modified test setup for improved research purposes. One of the materials, the gypsum with interwoven glass fibres, has already been studied extensively and is used as a baseline [7,8]. The aim of this study is to identify the different risks associated by the different types of PCMs, as well as providing knowledge through a simplified assessment of their flammability. The results can be then used as part of a holistic design process where optimised energy savings can be defined with quantified fire performance.

2. Literature review

A huge quantity of literature is available on the potential energy saving benefits of PCMs [1,2,9–13] but there remains little on the characterisation of their fire performance, nor adequate means to achieve optimisation. The flammability of PCMs has classically either not been listed, claimed to be non-flammable or to have limited flammability [1,14–17], despite no proper fire assessment. Increasingly the flammability has become of interest and studies on the flammability and energy performance of PCMs are emerging [18,19]. This study covers some of the common commercially available products, and assesses the differences in performance. Outlined below are the different types of PCM available, as well as the existing fire studies in the literature.

2.1. Encapsulation techniques

Paraffin wax was quickly identified as one of the potential materials suitable as a PCM due to its high latent heat, appropriate melting temperature, low cost, availability, chemical and thermal stability, and lack of corrosiveness [20]. The early methods were highly direct, typically either involving immersion or addition to the mixing process. For immersion, one of the most common lining materials, gypsum board, was taken and dipped into a bath of warm liquefied paraffin wax for a period of time. The wax would then be absorbed into the matrix of the gypsum, generally filling the air voids which are prevalent through gypsum boards. Surface tension was sufficient to prevent the wax from easily escaping upon melting, although still some material could be expected to be lost over repeated cycles. Alternatively, the paraffin wax could be added into the matrix during the mixing of the gypsum and was found to still be present upon completion of the material.

Modern techniques typically involve some form of encapsulation. One of the most common is microencapsulation, where a paraffin wax core is contained within polymeric capsules of diameter 1–100 µm. These can then easily be added to the matrix of a variety of materials including, gypsum, clay, and concrete. The capsules have sufficient mechanical strength to survive the mixing process and the presence of the polymeric shell prevents any chemical interactions between the substrate and the PCM core.

Alternatively, some encapsulation techniques exist on a larger scale and are termed macroencapsulation. The core PCM in these

products are easily visible to the naked eye, and tend to have diameters or widths in the range of 1–500 mm. The core is still encapsulated by a polymer, which forms an easy to use sheet, typically around 0.5–5.0 mm in thickness. These are included as a separate layer, most commonly between the lining and insulation.

Finally, rigid sheets known as shape stabilised (SSPCM) or form stable phase change materials (FSPCM) are possible solutions. For these materials, the core PCM is bound into the matrix of a polymeric material to form rigid sheets. These have very high quantities of PCM, around 60–90% commonly. This achieves very poor results in standardised testing, thus requiring the addition of a barrier of some kind or heavily restricting their usage.

The different encapsulation methods therefore produce materials which are used in different parts of a wall assembly, and may have vastly different quantities of PCM and other flammable components. Microencapsulation is often used within gypsum linings for relatively low quantities of PCM, often in the range of 5–25% by weight. Macroencapsulation and SS/FSPCMs have significantly higher PCM loadings and thus must be contained behind a barrier, but may have much greater potential for energy savings. These represent different fire hazards within the built environment that must be adequately characterised to enable designers to implement suitable risk mitigation strategies whilst still attaining greater energy performance.

2.2. Existing fire studies

PCMs have seen a surge in development over the last decade, and only in the last few years have the first fire studies started to emerge. A single early paper exists evaluating plasterboard which has the PCM incorporated via one of the previously described direct methods [21]. The applicability of this to modern PCMs is highly limited but, given the scarcity of literature, it still provides meaningful knowledge. When compared with ordinary paper faced gypsum boards, the PCM enhanced board greatly increased the total energy released by providing constant burning throughout the depth of the material and extending the length of flaming. Typically for plasterboard, a sharp peak of moderate intensity is experienced early on but its limited thickness means that it does not contribute significantly, and extinguishes within a period of a few seconds to, at most, 1–2 min. The European classification system, ISO 13501 [5], specifically restricts the thickness and weight of the paper to ensure that flashover will not occur within the ISO room corner test (BS ISO 9705 [22]).

More recently, a study was conducted by Asimakopoulou et al. [23] on paper faced gypsum with and without PCMs. This included TGA, cone calorimeter and SEM (Scanning Electron Microscope) experimental results, as well as a simple numerical model based on the results. The PCM contained within the gypsum plasterboard took the form of microencapsulated paraffin wax spread homogeneously throughout the thickness of the material. The study firstly confirmed the behaviour described above, which is that the addition of PCM is capable of producing an extended period of burning that is not typically seen in ordinary paper faced gypsum plasterboard. The SEM reveals the mechanism in which the paraffin wax is able to escape from the polymer shells. Images from before and after testing in the cone calorimeter illustrated that upon reaching its boiling point the paraffin wax is able to escape from the capsules and ignite. Broken polymer capsules were evident after combustion had ended.

Finally, some isolated studies on the performance of SSPCMs with and without flame retardants has been performed by Cai et al. [24]. The focus of the work was to investigate whether the addition of flame retardants was able to reduce the fire risk sufficiently that the materials could safely be used within a wall assembly. The study concluded that the use of flame retardants was effective due
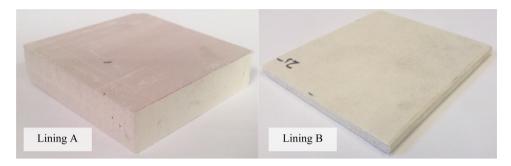
Fig. 1. Prepared PCM samples of interwoven mesh (Lining A, left) and glass fibre mat faced (Lining B, right) gypsum boards.

Table 1
Summary of PCMs in this study.

Material	ID	Thickness (mm)	Density (kg m^{-3})	Class [standard]	Est. core PCM content (%)
Glass fibre reinforced gypsumboard [8]	Lining A	25	900.25 ± 0.04	B [BS 13823]	6.51 ± 0.66
Fibre glass mat facing gypsumboard	Lining B	11.59	757.9	B [ASTM E84]	25
Sandwich panel insulation	Insulation A	5.21	947.58 ± 11.05	E [BS 13823]	60–90
Mat insulation	Insulation B	0.5–15[a]	325.67 ± 58.18	A/C/E [ASTM E84]	60–90

[a] Variable thickness.

to improvements in ignitability, although the total energy released was unaffected. Comparison to other PCMs and optimisation techniques were not discussed as part of the work.

Quantification of the fire risks associated with PCMs has also been described for one of the products contained in this paper [7,8]. These studies contain a detailed description of one of the basic lining materials, and outline methods to characterise their risks. To build upon these studies, this paper instead assesses a variety of different PCMs in order to widen the breadth of literature on the fire performance of PCMs. The results start to provide a catalogue of results for designers so that they can pick the most suitable material which can achieve adequate energy savings. This ensures that designers can achieve the greatest energy savings whilst still having adequate quantified fire performance.

3. Description of materials

The four products which have been tested as part of this flammability study are summarised in Table 1, and photographs of each are given in Figs. 1 and 2. The properties have been obtained from a variety of sources. The thickness and density have both been measured directly in the laboratory, and checked against information from the manufacturer. The classification is based directly on information from the manufacturers, whilst the estimated PCM core content are based on a combination of experimental findings, such as TGA data, and available knowledge from the manufacturers. Thus, it is not guaranteed to be correct but represents a best guess and may be relevant to each of their respective performances when quantifying their flammability. Nonetheless, it is expected that the values given are correct and relevant to the analysis. The products chosen reflect some of the most widely spread PCMs in use in the built environment at present, and each have a specified melting point of 23 °C. A description of each of the materials is given in more detail in the following sections.

3.1. Gypsum boards

Two different gypsum boards were obtained from different manufacturers which both contained the same type of microencapsulated PCM. This is also the same PCM which has been studied using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) previously [7,25]. Despite the umbrella term of "gypsum board" being applied to many plasterboards, there can

be large differences between products even by the same manufacturer. A wide variety of additives can be introduced to boost performance, such as glass fibres to reduce cracking or calcite to improve sound insulation. In this sense, PCMs are additives which have the potential to reduce energy consumption.

One of the gypsum boards contains a glass fibre mat facing (Lining B), as opposed to paper which is typical of many boards. The purpose of this layer is to bind the gypsum core together and form a rigid board. In ordinary applications, a paper facing represents the combustible component of the assembly and will burn for a short period when exposed to sufficient heat. A critical amount of paper is defined in the BS 13823 standard which allows a board to attain a performance of A2, or B if there are no other flammable additives. Furthermore, paper faced gypsum board was used as the basis for one of the limits of the classifications in the Single Burning Item (BS 13501) test, which is required as part of the European standard test framework (BS 13823). The use of glass fibres, either interwoven or as a mat facing, may increase the cost but result in the improvement of the fire performance. PCMs have had difficulty achieving adequate classification in the US [26] and thus the development of facings other than paper may allow them to enter the market more easily.

Lining A has a higher thickness and density, and is bound together by a layer of interwoven mesh to form a stable product. This has the advantage that it also lacks the flammable facing but may increase the cost of manufacturing. Part of the optimised design process will require a delicate balance between cost, energy savings, and fire performance. The total thickness of the Lining B was 11.59 mm, of which approximately 1.07 mm per side (or 2.14 mm for the whole cross-section) was the fibreglass mat, as measured by digital callipers.

3.2. Insulation materials

Two insulation materials have been included in this study, shown in Fig. 2. The first of these, termed Insulation A, is a PCM based sandwich panel. A combination of approximately 60% paraffin wax and 40% polyethylene forms a rigid sheet as the core, and is bound by thin sheets of aluminium on each side. Edges which are exposed, which are evident in the photo and were not tested in practice, are sealed using 70 μm thick aluminium tape. The material achieves a poor classification in standardised testing due to its highly combustible core, and in buildings is protected by a lin-
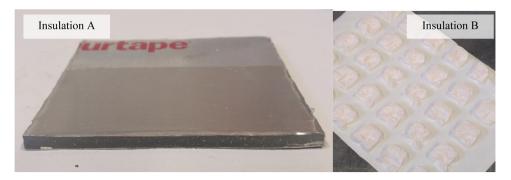
Fig. 2. PCM sandwich panel (Insulation A, left) and mat based PCM insulation (Insulation B, right). Both specimens are unprepared.

ing material such as gypsum. The high quantity of PCM contained within this material may mean that it has the potential for greater energy savings than either of the lining materials. However, the requirement for a substantial fire barrier would reduce the potential for energy savings.

The second insulation material, termed Insulation B, is a flexible mat of macroencapsulated PCM in the form of fatty acids. The PCM is contained within pockets, approximately 25 mm in width and up to 15 mm in height, along the length of the sheet. Gaps exist in between pockets of PCM which allow the material to be handled easily, whilst also reducing the total PCM content. Like the sandwich panel, this material is placed behind a lining and in front of the insulation and is easy to install. Standardised testing of the material results in a poor classification when unprotected, as would be expected. More recent developments in this product include foil as part of the mat, as opposed to simply a polymer, which results in improved classifications. However, this does not adequately assess the fire risks which are associated with this material.

3.3. Thermal analysis

Some PCMs have previously been characterised using TGA/DSC, including the microcapsules contained within both gypsum materials [7], which are the same but in varying quantities. The results for the PCM microcapsules when tested at various heating rates in air are shown in Fig. 3. A more detailed description of the experimental approach is given elsewhere [7]. Thermal analysis of the capsules identifies that evaporation and oxidation of the paraffin wax occurs within a range of 190–255 °C, and represents the most rapid mass loss. Some evaporation of the paraffin wax not properly encapsulated is evident prior to this stage, but is at insufficient temperature to combust. At higher temperature ranges, up to around 400 °C, there is decomposition of the polymer shell. This illustrates that upon exposure to heat, the initial processes are the evaporation, escape and oxidation of the paraffin wax whilst the decomposition of the polymer shell only occurs later.

As seen from the DSC results, the greatest contribution of energy is from the oxidation of the paraffin wax, but there is still some contribution from the shell material. Evaporation of leaked paraffin wax is evident before 190 °C, but no exothermic reaction is present since the critical temperature is not reached.

No thermal analysis has been performed on the specific insulation PCMs contained in this study, but some literature is available on SSPCMs. The key decomposition points given above are generally maintained, but without a shell the degradation process is simpler. In each case, the paraffin wax [24] or fatty acid [27] evaporates and is free to oxidise. The polymer substrate also typically pyrolyses at a similar temperature to the evaporation and oxidation temperature of the core PCM. The use of different polymers can affect the thermal stability, and can be used to modify both the melting and boiling points of the resulting product. This is due to the fact that different polymers have varying thermal properties thus affecting the rate of heat transfer.

4. Experimental approach

Experiments were conducted in the cone calorimeter (ISO 5660 [6]) with some minor modifications to the standardised setup. Specimens were wrapped in 10 mm of ceramic fibre paper to promote one dimensional heat transfer, similar to the holder proposed by De Ris & Khan [28]. Ceramic fibre insulation was also placed at the rear face to be able to assume no heat losses, and this was replaced between tests. In cases where the number of specimens were limited they were tested to an incident heat flux of 50 kW m^{-2}. Where there were additional specimens available the heat flux was decreased to obtain points to apply the classic ignition theory of solids [29]. An initial estimate of the critical heat flux required for piloted ignition was made for some of the materials where possible. Heat release rates were calculated using oxygen consumption calorimetry based on Janssens approach [30].
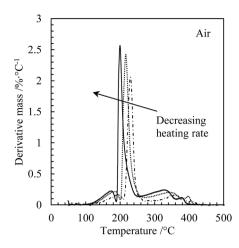
5. Results and analysis

Each of the described materials has been assessed and key properties are identified. The time to ignition, heat release rate, mass loss, and total heat released are all found to be most pertinent. These are summarised in Table 2, and then described and discussed in detail later.

5.1. Ignition

Application of the classic flaming ignition theory of solids [29] is shown for each of the materials tested in Fig. 4. Estimates of apparent thermal inertia and ignition temperature are not given since not all materials were tested across a range of incident heat fluxes. There is a clear difference between the wall lining and insulation materials which would be as expected owing to their different roles and vastly differing PCM loadings. The proximity of the wall lining to fire exposures in a compartment require significantly less ignitability for the risk to be manageable. Insulation materials on the other hand can be protected by a suitable wall lining, and thus contain substantially more flammable PCM material, in the order of 60–90%, with the remaining portion filled by a polymer such as polyethylene. When insulation is exposed to heat, the low thermal inertia causes a rapid temperature rise, and a relatively low ignition temperature is reached quickly. This is similar to other modern flammable insulation materials with extremely low thermal inertia as shown by Hidalgo-Medina [31].

There is significant deviation in the results from the aluminium PCM panel, Insulation A, due to the different ways in which the material was tested. This illustrates the importance of suitable fire testing when assessing PCMs. When the top sheet of aluminium
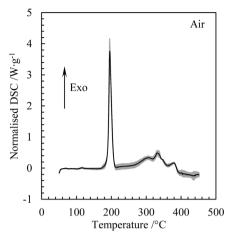
Fig. 3. DTG (left) and DSC (right) of PCM microcapsules tested at heating rates of 1, 2.5, and 5 °C min^{-1}. DSC results are only shown for a heating rate of 1 °C min^{-1} for the sake of clarity.

Table 2
Flammability properties for an incident heat flux of 50 kW m^{-2} in horizontal orientation.

Parameter	Lining A [8]	Lining B	Insulation A	Insulation B
Time to ignition (s)	31.6 ± 3.3	18	8–583[b]	6
Approximate critical heat flux (kW m^{-2})	<12	n/a[a]	n/a[a]	<9
Peak heat release rate (kW m^{-2})	42.6 ± 1.9	105	610	1040
Peak mass loss rate (g s^{-1} m^{-2})	6.15 ± 0.76	10.5	30.0	42.8
Total heat released (kJ m^{-2})	10.2	44.4	71.0	74.4
Effective heat of combustion (J g^{-1})	12.1 ± 1.2	11.4	20.8	19.3
Residual mass (%)	91.4 ± 0.2	65.0	10.4	15.2

[a] Not evaluated.
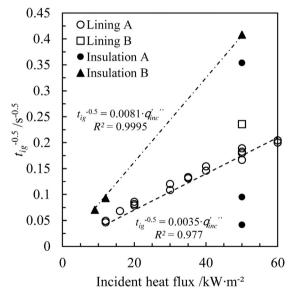[b] Dependent upon specimen preparation.

Fig. 4. Incident heat flux against $1/\sqrt{t_{ig}}$ for various PCMs in this study. Wall linings are indicated by hollow symbols, while insulation materials are indicated by solid symbols.

was removed the ignition behaviour of the substrate can be evaluated, and was found to be similar to the fatty acid mat insulation. Ignition in this case occurred in 8 s as there was no barrier to protect the PCM. Thus, it was directly exposed to the cone heater and the surface temperature rose rapidly to the critical point.

When Insulation A was protected by the aluminium panel then the ignition time was massively increased to 583 s. The decomposition temperature of aluminium is significantly higher than the boiling, pyrolysis and ignition temperatures of both the PCM and polymer contained within. Pyrolysis gases are slowly emitted from the specimen, but only in sufficient quantity to cause ignition after a substantial time has passed. The gases are not able to escape homogeneously from the specimen and thus the use of a spark ignitor instead of a pilot flame in this case will also result in a higher ignition time. Eventually, deformation of the aluminium begins to occur and gaps around the sides are exposed. Once these are sufficiently exposed then the lower flammability limit will be exceeded and the material will rapidly reach HRRs similar to those described later. In real fire scenarios, these mechanical effects as a result of self-weight would be evident much earlier. This has been found to be true of many materials for some time, as shown during round robin testing of the single burning item test (SBI) [32,33]. Since these problems are not unique to PCMs they are not covered in detail here. The fire behaviour and appropriate risk mitigation strategies have however recently been studied by Hidalgo et al. [34] and should be applicable to PCM insulation materials.

A third setup was also tested where a cut was made through the centre of the specimen. This cut was not sealed with aluminium tape as would be specified. This allowed a small mass flux of flammable gases to escape once the critical temperature was reached. The quantity of material which can escape is still relatively low and there is a lengthy delay before the lower flammability limit is exceeded and ignition occurs. In this case, ignition occurred after 111 s.

5.2. Heat release

The heat release rate represents a key metric in assessing the flammability of materials and the results for this study are shown in Fig. 5. For both lining materials there was an initial peak as the PCM was ignited. This was reached more rapidly for the case of Lining B, which may be because the glass fibre mat is flammable. An
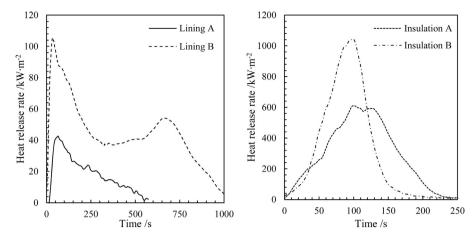
Fig. 5. Heat release rates at 50 kW m^{-2} in the horizontal orientation for the two gypsum lining materials (left) and the two insulation materials (right). Note that the axes are different.

elevated heat release rate was maintained by the evaporation and combustion of the PCM vapours as the thermal wave penetrated the depth of the material. The behaviour was the same as charring materials, as has been described for the interwoven glass fibre gypsum [8]. A peak was observed as the thermal wave reached the rear surface, as typical for materials which have insulation at the unexposed face [35]. This was not observed for Lining A due to its greater thermal penetration time. Insufficient flammable vapours were generated and thus the material extinguished before it was able to reach the rear surface. This may also drastically reduce the apparent total energy released since the flammable vapours were not at a concentration above the lower flammability limit. The reduced thickness and greater PCM loading of Lining B therefore caused much larger amounts of heat to be released, as evidenced by its higher peak heat release rate (HRR) and the total energy released (40 kW m^{-2} and 10.2 MJ m^{-2} for Lining A compared to 105 kW m^{-2} and 44.4 MJ m^{-2} for Lining B). The fuel was closer to the surface of the material, and can be liberated more easily than Lining A where the fuel is more sparsely spread across the entire thickness of the material. The sparseness of the PCM however limits the potential energy savings, despite the improvement in fire performance.

Insulation B clearly shows the mechanisms of ignition for PCMs which are not entirely apparent for microencapsulated and SSPCMs. Upon heating, the PCM within the polymer will expand rapidly but cannot escape. Once thermal decomposition of the shell occurs, which is above the boiling temperature of the PCM, the core is then able to escape and rapidly ignite. The additional heat contribution from the flame causes the shell to degrade more rapidly, and more PCM is available to burn. This causes a rapid increase in the HRR, and the material as a whole appears as a small pool fire since the entirety of the PCM is already in liquid form, and the polymer is melted as part of its decomposition process. Comparatively little material allows a very high peak HRR to be achieved, before the fuel begins to run out and the rate of pyrolysis is reduced. The material soon reaches extinction, with only some remnants of the polymer shell evident at the end of the test. For Insulation A, the time taken to reach the peak is longer. The reason for this may be due to the fact that the paraffin wax is trapped within the polymer matrix throughout the thickness of the material. As the thermal wave penetrates its depth, the polymer must be pyrolysed before the evaporated wax is able to escape and ignite. In the case of Insulation A, this only needs to occur at the start of the test and then the entirety of the wax within the material is liberated and able to ignite rapidly. A short plateau is reached for Insulation B and the burning rate drops relatively slowly down to extinction. The total energy released in each case is similar, and both peak

rates are extremely high when compared to other building materials.

5.3. Mass loss

The mass loss for both types of materials is shown in Fig. 6. For the lining materials, the mass loss has been normalised to the total mass lost. This is due to the fact that the materials have different thicknesses and thus lining B would appear to lose mass substantially faster due to its lower thickness. When normalised, the mass loss is similar for both materials but shows a slightly higher burning rate in Lining B. The same normalised MLR can be applied for different PCM loadings and will yield a suitable mass loss rate for that given material. This can allow designers to modify the amount of PCM loading to meet their energy performance and flammability requirements as necessary. The previously presented effective heat of combustions (Table 2) for both materials are similar, 12 and 11 kJ g^{-1} for Linings A and B respectively, and thus the resulting heat release rate could also be found. The effective heat of combustion was calculated by dividing the heat release rate (oxygen consumption) by the mass loss rate, and assuming a combustion efficiency of 1.0.

For the insulation materials, both have little residual mass due to their non-charring nature. The heat of combustion throughout the test for both cases is similar, at 20.8 MJ m^{-2} for Insulation A compared to 19.3 MJ m^{-2} for Insulation B. Due to the fact that one of the aluminium facings was stripped away, this may result in a residual mass which is artificially low when compared to reality. Thus, the actual residual mass for Insulation A would be doubled to approximately 20.8% and would be higher when compared to the mat material. For Insulation B, the residual mass is a small amount of pyrolysed polymer which has no integrity.

6. General remarks

As the PCM market develops the opportunity for optimisation becomes a possibility. Products with increasingly complexity are currently being developed to achieve optimal energy savings. A suitable flammability assessment enables the usage of these materials without having to excessively compromise their energy performance in ambient conditions. The varying characteristics of different PCMs are shown in Fig. 7. The difference between Lining A and Lining B, which are both bound using glass fibres, results in a straightforward increase in the total amount of energy which is released and which will act as fuel load in the event of a compartment fire. Existing fire safety strategies for flammable wall linings are based upon avoiding the lining material causing flashover.
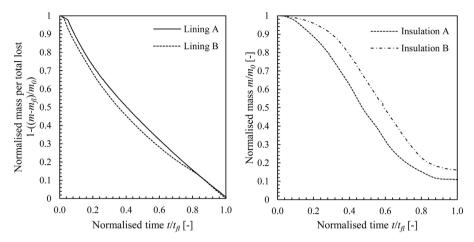
Fig. 6. Mass loss for both lining materials (left) and insulation materials (right).
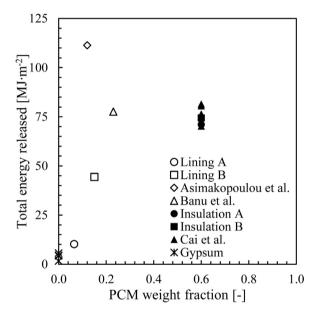

Fig. 7. Amount of energy released at 50 kW m^{-2} for estimated PCM weight fractions. Filled symbols represent insulation materials, while hollow are lining materials.

Thus, introducing increasing quantities of PCMs may at some point exceed this limit for a given room and may cause flashover. If the fire risks are quantified then this point can be found and incorporated as part of a building design. This would allow designers to find the maximum possible quantity of PCM which could be included without causing flashover. This could be determined by calculating the potential for flashover (for example, using Mowrer's model [36]) for the desired quantity of PCM based on energy saving calculations. This could be repeated until a quantity is found which does not cause flashover, but is still able to adequately achieve sufficient energy reduction in an economically viable manner.

The use of a paper facing, as in the material studied by Asimakopoulou et al. [23], is shown to drastically increase the total energy released despite only a modest PCM loading. This may therefore serve as a cheaper alternative to glass fibres but results in greatly reduced fire performance. This may be a viable solution for scenarios where the outbreak of a fire could be easily contained, and thus the energy savings could be effectively utilised at relatively low cost. However, for most situations, this finding points to a need for alternative linings to be considered for PCM products, such as glass fibres or an additional layer of ordinary gypsum plasterboard. Despite a different incorporation method, the material

studied by Banu et al. [21] falls within similar bounds to the PCM plasterboards.

The two insulation materials have drastically higher PCM loadings and behave as non-charring materials. Both materials have higher heats of combustion due to the lack of endothermic dehydration reactions present in the gypsum-based linings. The presence of dehydration reactions in the linings cause additional mass loss for no extra heat release, and increase the rate of extinction as the gas mixture can be reduced below the lower flammability limit more rapidly. Despite being presented in different forms, the two insulation materials assessed as part of this study show similar behaviour. It can also be seen that less energy is released by these materials than those in the literature [21,23], even though they contain substantially higher content of PCM. This underlines the importance of the encapsulation methods and that in different forms PCMs can behave very differently.

The materials studied by Cai et al. [24], with and without fire retardants, display similar total amounts of energy released despite differing polymers as the binding substrate. This emphasises that the optimisation techniques relating to insulation PCMs primarily lies in the design of a suitable fire barrier and are independent of the polymer.

6.1. Associated risks

The fire risks associated with the materials studied in this research are shown to be different. For linings, the performance can be quantified through a suitable framework [7] and the performance in this paper has been shown to vary depending upon the PCM loading. The addition of a paper facing clearly increases the total energy released and may be sufficient to cause flashover for certain compartments. Alternate products containing lower quantities of PCM may be an option to attain the required energy savings, or other risk mitigation strategies may need to be adopted.

For PCM insulation, the materials are shown to be highly ignitable and release similar amounts of energy regardless of the substrate which is used. The thickness and thermal properties of a suitable fire barrier can be defined to ensure that the risk associated with these materials is adequate. Existing literature [24] has analysed the addition of flame retardants, which may be capable of inhibiting ignition sufficiently for a given design.

7. Concluding remarks

For PCM gypsum linings bound by glass fibre, the total energy released is shown qualitatively to loosely be a function of the PCM weight fraction. Increasing the amount of PCM has the potential

to deliver greater energy savings at ambient temperatures, but in the event of a fire will also contribute a greater amount of fuel to a compartment. Nonetheless, through a proper fire risk assessment this can be quantified and these risks can be mitigated by designers. When compared with literature, it can be seen that the use of glass fibres – either interwoven or as a mat facing – provides greatly improved fire performance over traditional paper facings albeit at higher initial cost.

Insulation PCMs are shown to present a different fire risk. The very high PCM loadings result in extremely high heat release rates, even if the burning duration is low. The behaviour of these materials is typical of non-charring polymer-based materials. In combination with the ease of ignitability, it becomes key that the fire barrier for these materials is properly designed. Thus, the optimisation of these materials lies in preventing the materials from igniting by defining an appropriate barrier. Through this, it will be possible to quantify their fire performance and safely enable their usage in buildings where they are currently restricted.

This study has shown the relative performance of these materials to provide additional knowledge of the flammability of different PCMs which are available. The mechanisms behind the different behaviours have been explained and the key parameters relating to each material are highlighted. The existing standard fire test methods are not able to deliver this information and cannot be used to optimise the energy savings. This study provides the necessary knowledge to designers to understand the fire risks posed by different PCMs so that the materials can be quantified and designers can apply adequate mitigation strategies.

An integrated approach towards evaluating energy efficiency and the fire safety risks of PCMs is crucial to allow designers to optimise material selection for the safe design of buildings. The work described herein allows systematic, repeatable comparison of the fire performance of materials and as such provides a method to benchmark products. The research tool outlined will enable this integrated approach allowing the fire safety and energy performance to be assessed jointly which will be of practical benefit to designers during material selection.

Acknowledgements

References

[1] F. Kuznik, D. David, K. Johannes, J.-J. Roux, A review on phase change materials integrated in building walls, Renew. Sustain. Energy Rev. 15 (2011) 379–391, http://dx.doi.org/10.1016/j.rser.2010.08.019.

[2] M.M. Farid, A.M. Khudhair, S.A.K. Razack, S. Al-Hallaj, A review on phase change energy storage: materials and applications, Energy Convers. Manag. 45 (2004) 1597–1615, http://dx.doi.org/10.1016/j.enconman.2003.09.015.

[3] I.O. Salyer, A.K. Sircar, Phase change materials for heating and cooling of residential buildings and other applications, in: P.A. Nelson, W.W. Schertz, R.H. Till (Eds.), 25th Intersoc. Energy Convers. Eng. Conf., American Institute of Chemical Engineers, Reno, Nevada, 1990, pp. 236–243.

[4] British Standards Institution, BS EN ISO 13823. Reaction to fire tests for building products—building products excluding floorings exposed to the thermal attack by a single burning item, 2010.

[5] British Standards Institution, BS EN 13501-1:2007+A1:2009 Fire classification of construction products and building elements—Part 1: classification using data from reaction to fire tests, Brussels, 2009.

[6] British Standards Institution, BS ISO 5660-1:2015. Reaction-to-fire tests—heat release, smoke production and mass loss rate. Part 1: heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement), Brussels, 2015.

[7] M.S. McLaggan, Novel Fire Testing Frameworks for Phase Change Materials and Hemp-lime Insulation, The University of Edinburgh, 2016 http://hdl.handle.net/1842/15896.

[8] M.S. McLaggan, R.M. Hadden, M. Gillie, Fire performance of phase change material enhanced plasterboard, Fire Technol. (2017), http://dx.doi.org/10.1007/s10694-017-0675-x (in press).

[9] F. Agyenim, N. Hewitt, P. Eames, M. Smyth, A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS), Renew. Sustain. Energy Rev. 14 (2010) 615–628, http://dx.doi.org/10.1016/j.rser.2009.10.015.

[10] L.F. Cabeza, A. Castell, C. Barreneche, A. de Gracia, A.I. Fernández, Materials used as PCM in thermal energy storage in buildings: a review, Renew. Sustain. Energy Rev. 15 (2011) 1675–1695, http://dx.doi.org/10.1016/j.rser.2010.11.018.

[11] B. Zalba, J. Marín, L.F. Cabeza, H. Mehling, Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, Appl. Therm. Eng. 23 (2003) 251–283, http://dx.doi.org/10.1016/S1359-4311(02)00192-8.

[12] L. Cabeza, C. Castellon, M. Nogues, M. Medrano, R. Leppers, O. Zubillaga, Use of microencapsulated PCM in concrete walls for energy savings, Energy Build. 39 (2007) 113–119, http://dx.doi.org/10.1016/j.enbuild.2006.03.030.

[13] F. Kuznik, J. Virgone, Experimental investigation of wallboard containing phase change material: data for validation of numerical modeling, Energy Build. 41 (2009) 561–570, http://dx.doi.org/10.1016/j.enbuild.2008.11.022.

[14] A. Sharma, V. Tyagi, C. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. 13 (2009) 318–345, http://dx.doi.org/10.1016/j.rser.2007.10.005.

[15] V.V. Tyagi, D. Buddhi, PCM thermal storage in buildings: a state of art, Renew. Sustain. Energy Rev. 11 (2007) 1146–1166, http://dx.doi.org/10.1016/j.rser.2005.10.002.

[16] R. Baetens, B.P. Jelle, A. Gustavsen, Phase change materials for building applications: a state-of-the-art review, Energy Build. 42 (2010) 1361–1368, http://dx.doi.org/10.1016/j.enbuild.2010.03.026.

[17] A. Pasupathy, R. Velraj, R.V. Seeniraj, Phase change material-based building architecture for thermal management in residential and commercial establishments, Renew. Sustain. Energy Rev. 12 (2008) 39–64, http://dx.doi.org/10.1016/j.rser.2006.05.010.

[18] L. Haurie, J. Mazo, M. Delgado, B. Zalba, Fire behaviour of a mortar with different mass fractions of phase change material for use in radiant floor systems, Energy Build. 84 (2014) 86–93, http://dx.doi.org/10.1016/j.enbuild.2014.07.026.

[19] S. Serrano, C. Barreneche, A. Navarro, L. Haurie, A.I. Fernandez, L.F. Cabeza, Use of multi-layered PCM gypsums to improve fire response. Physical, thermal and mechanical characterization, Energy Build. 127 (2016) 1–9, http://dx.doi.org/10.1016/j.enbuild.2016.05.056.

[20] I.O. Salyer, A.K. Sircar, S. Dantiki, Advanced phase change materials and systems for solar passive heating and cooling of residential buildings. Final Technical Report on DOE Grant DE-FG03-86SF16308, Dayton, USA, 1988. http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=5246122.

[21] D. Banu, D. Feldman, F. Haghighat, J. Paris, D. Hawes, Energy-storing wallboard: flammability tests, J. Mater. Civ. Eng. 10 (1998) 98–105.

[22] British Standards Institution, BS 476-33/ISO 9705 Fire tests on building materials and structures—Part 33: full-scale room test for surface products, British Standards Institution, 1993.

[23] E.K. Asimakopoulou, D.I. Kolaitis, M.A. Founti, Fire safety aspects of PCM-enhanced gypsum plasterboards: an experimental and numerical investigation, Fire Saf. J. 72 (2015) 50–58, http://dx.doi.org/10.1016/j.firesaf.2015.02.004.

[24] Y. Cai, Y. Hu, L. Song, Q. Kong, R. Yang, Y. Zhang, et al., Preparation and flammability of high density polyethylene/paraffin/organophilic montmorillonite hybrids as a form stable phase change material, Energy Convers. Manag. 48 (2007) 462–469, http://dx.doi.org/10.1016/j.enconman.2006.06.021.

[25] M.S. McLaggan, R.M. Hadden, M. Gillie, Smouldering combustion of phase change materials within a porous hemp matrix, in: Ninth Mediterr. Combust. Symp., Rhodes, Greece, 2015.

[26] J. Kośny, D.W. Yarbrough, T. Riazzi, D. Leuthold, J.B. Smith, M. Bianchi, Development and testing of ignition resistant microencapsulated phase change material, in: Proc. Effstock 2009—11th Int. Conf. Therm. Energy Storage, Stockholm, Sweden, 2009.

[27] C. Alkan, A. Sari, Fatty acid/poly(methyl methacrylate) (PMMA) blends as form-stable phase change materials for latent heat thermal energy storage, Sol. Energy 82 (2008) 118–124, http://dx.doi.org/10.1016/j.solener.2007.07.001.

[28] J.L. de Ris, M.M. Khan, Sample holder for determining material properties, Fire Mater. 24 (2000) 219–226, http://dx.doi.org/10.1002/1099-1018(200009/10)24:5<219:AID-FAM741>3.0.CO;2-7.

[29] J.L. Torero, Flaming ignition of solid fuels, in: SFPE Handb. Fire Prot. Eng, Springer, New York, NY, 2016, pp. 633–661, http://dx.doi.org/10.1007/978-1-4939-2565-0_21.

[30] M.L. Janssens, Measuring rate of heat release by oxygen consumption, Fire Technol. 27 (1991) 234–249, http://dx.doi.org/10.1007/BF01038449.

[31] J.P. Hidalgo, J.L. Torero, S. Welch, Experimental characterisation of the fire behaviour of thermal insulation materials for a performance-based design methodology, Fire Technol. 53 (2017) 1201–1232, http://dx.doi.org/10.1007/s10694-016-0625-z.

[32] P. Johansson, P. Van Hees, SP Rapport 2000:26 Development of a Test Procedure for Sandwich Panels using ISO 9705 Philosophy—Nordtest project nr 1432-99, Borås, Sweden, 2000.

[33] B. Messerschmidt, The capabilities and limitations of the single burning item (SBI) test, in: Fire Build. Saf. Single Eur. Mark., 2008, pp. 70–81.

[34] J.P. Hidalgo, S. Welch, J.L. Torero, Performance criteria for the fire safe use of thermal insulation in buildings, Constr. Build. Mater. 100 (2015) 285–297, http://dx.doi.org/10.1016/j.conbuildmat.2015.10.014.

[35] R. Carvel, T. Steinhaus, G. Rein, J.L. Torero, Determination of the flammability properties of polymeric materials: a novel method, Polym. Degrad. Stab. 96 (2011) 314–319, http://dx.doi.org/10.1016/j.polymdegradstab.2010.08.010.

[36] F.W. Mowrer, Flammability of oil-based painted gypsum wallboard subjected to fire heat fluxes, Fire Mater. 28 (2004) 355–385, http://dx.doi.org/10.1002/fam.832.