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

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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-

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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