PHASE CHANGE MATERIALS IN ARCHITECTURE

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ABSTRACT

Phase change materials (PCMs) have potential to reduce energy consumption in buildings but despite decades of development for building purposes they have not yet made it into mainstream interior architecture. PCMs are capable of storing and releasing large amounts of energy by melting and solidifying at a given temperature. PCMs bridge the gap between when energy is available and when it is needed, and thus have the potential to reduce the energy needed for space heating and cooling whilst improving the quality of the space, in residential and commercial applications where use of a large material mass is inappropriate. The first documented use of a PCM was in a system for the passive solar heating of a house by Dr Maria Telkes, in 1948. Since then, more resources have been invested in the development of PCMs, and composite materials have been developed as replacements for materials that already exist, as with plasterboard and glass, rather than being used in a specific system. Although they are more expensive than the conventional product they replace, other expensive products have found a place in making the low energy/zero energy building, such as photovoltaic panels and high specification glazing systems. The momentum for the widespread use of PCMs has stalled and accessible information has been limited and scattered. This paper looks briefly at the history of PCMs, explores the products that are available and considers appropriate design opportunities for integrating PCMs into the interior environment. This exploration leads to the suggestion that PCMs are not more widely used because of the types of PCM products that are being manufactured.

KEYWORDS:

Phase Change Material; PCM; passive heating; substitute products; thermal mass

INTRODUCTION

Despite decades of development of phase change materials (PCMs) for building purposes they have not yet made it into mainstream interior architecture. It is the purpose of this paper to locate the stumbling blocks to this acceptance and propose how they might be overcome.

The fundamental relationship between the science of materials development and architecture seems to be out of phase. Two distinct forms of innovation have emerged, scientific innovation where science is forging ahead with development of ‘improved’ products where an almost complete product is being sent to the market for feedback, and design innovation where an entirely new product is created to give the user something they never knew they wanted. An example of scientific innovation in the field of PCMs is “Smartboard” which has been developed as a straight replacement for gypsum plasterboard without any thought as to whether this is the best way to encourage designers to use PCMs. At this stage the new product, and its increased cost, is automatically compared to the old and its typology fixed, and a substantial opportunity for the development of something new has been missed. In contrast design innovation has, for example, led to the development of a new series of light fittings using light emitting diodes (LEDs) which, originally introduced in 1962 (http://web.mit.edu/invent/a-winners/a-holonyak.html), have undergone reinvention to create radical new products including the lighting of whole interior surfaces, as well as attempts to 'fit' LEDs into something that resembles a conventional light bulb as a direct replacement for a familiar product.

WHAT ARE PCMS?

Phase change materials are substances with a high heat of fusion. Exploiting their endothermic and exothermic reactions using the latent heat of fusion means they are capable of storing and releasing large amounts of energy by melting and solidifying at a given temperature. PCMs use the energy stored in chemical bonds. The thermal energy transfer occurs when materials changes state, or phase, from liquid to solid, or solid to liquid (Vavan Vuceljic, 2009). PCMs bridge the gap between when energy is available and when it is needed. The only other material that does this in a building is mass, so PCMs can be viewed as a thin version of "mass". For use in the interior environment PCMs with a melting temperature of between 19 and 24 degrees are used, as this temperature range is close to human comfort level (Rohles, 2007). The PCM must be able to cycle continuously though changes of state without loss of its attributes. It must be contained, either by micro encapsulation or encapsulation at a larger scale, to prevent loss in mass through evaporation. Specific paraffin waxes match the necessary temperature range well but due to their expense and origin in non-sustainable petrochemicals other PCMs are being explored, such as fatty acids, as these can come from organic sources. Current construction industry based developments largely use paraffin based PCMs encapsulated at the micro level and impregnated into other materials such as gypsum board. These products are potentially well suited for residential applications in New Zealand, due to the wide use of light weight timber framed buildings in the residential sector and the ability of PCMs to replace mass as a passive heat store.

WHY MIGHT PCMS BE A DESIRABLE PRODUCT?

Home heating accounts for 35% of the average domestic power bill, or 4.3% of national energy consumption in New Zealand. Office heating/cooling is 40% of commercial energy use, making a further 3.8% of national energy consumption in New Zealand (Mithraratne, 2007). The reasons for wanting to reduce this usage are both financial and environmental. Financial reasons are clear, the less money spent as an individual or business on energy needs, the more money available for other things. Ecologically, awareness in the general population of the growing need to reduce human use of finite natural resources is increasing. Further to this, comfort and health resulting from appropriate conditions in the interior environment are a factor. This year the government has recognised the poor conditions in New Zealand homes, and the effect these have on health, by initiating a home insulation subsidy scheme for private home owners (http://www.energywise.govt.nz, 2009). This scheme is to be funded via councils, banks and power companies. Home owners will be able to get a loan from the government for installation of ceiling and underfloor insulation to homes built before 2000, only two-thirds of which will have to be repaid. Providing warmer, more efficient homes in the future is no longer thought good for just the individual but has become essential for the nation.

PCMs, although much more expensive than available lightweight insulation materials (for example fibre glass batts) in their current state of development, also have the potential to reduce the energy needed for space heating and cooling whilst improving the comfort of the space, in residential and commercial applications. This is because better use can be made of the “free” energy of the sun coming through windows. This will melt the waxes which then solidify once the temperature drops returning the heat to the space when it is most needed. In cooling situations, taking the energy out of the air from solar gain because it is absorbed by the PCMs reduces the cooling load.

PCMs in a more basic state are used as a coolant in liquid (water) based cooling systems. Contained PCM modules are immersed in a reservoir in the cooling system loop where they absorb the heat from the system during the day and hold it until the temperatures cool below the PCM melting point at night when they release the energy (heat) back into the system ready to start the cycle again when temperatures rise (Advanced Environmental Concepts Pty Ltd, 2008). Although these systems are of interest as part of a cohesive low energy building system, this study is primarily concerned with PCMs that can be applied directly to the interior environment

Current research indicates that the environmental conditions created, or enhanced, by PCM products are suitable for the commercial environment due to the usual occupation hours of commercial buildings (http://www.energain.co.uk/Energain/en_GB/index.html, 2009). Basically, offices are occupied when the sun is likely to shine which generates a cooling load. Whilst historically, cellular office environments with their solid walls on which to apply any of these wallboard products were common, the new office environment has many fewer walls (Duffy, 1997) because of the move to open planning and many of the walls that are installed are varieties of glazed partitioning, not suitable for the application of opaque wallboard. In addition to the unavailability of wall surface it is also uncommon for office buildings in New Zealand to have gypsum type ceilings as found in houses. This is because of the need for access into the ceiling plenum, and consequently office ceilings are commonly a suspended grid of fibrous tiles. Because PCMs are better suited to cooling than to heating (DuPont, 2009) due to the temperature shifts required for regeneration this would indicate that there are, perhaps, better opportunities for the development of PCMs into products that are more suitable for commercial application.

Although the merits of an open plan workspace have again recently been questioned (Oommen, 2008) the fact remains that due to work place economics, they mean a saving of up to 20% in development cost (Hedge, 1982), so it is unlikely they will soon be replaced by a cellular office arrangement. The advantages of the ‘new’ open-plan work environment are the increased spatial flexibility and the ability to choose a space fit for the current task. For many commercial businesses this means defining operating zones. These are normally allotted spaces in an open plan setting for the main tasks performed, while maintaining connection with co-workers and the workings of the office. There will also be quiet spaces for individuals performing temporary tasks requiring concentration, and meeting rooms for group discussions where they will not disturb co-workers. Break-out spaces for informal gatherings are also popular. In reality, many offices at the lower end of the cost spectrum do not provide these additional spaces and staff members have little more than a desk in an open room and access to a tea station. These environments offer the least opportunity for sheet type PCM installation. This raises the question of whether there is a better PCM based product than wallboard for office interior applications.

HISTORICAL RESEARCH

The first documented use of a PCM as a form of passive heating was by Dr Maria Telkes, the "Sun Queen", in 1948. The Hungarian born, American scientist had been fascinated by the possibilities for solar heating since the 1920s. Unable to convince a tertiary institution of these, Telkes collaborated with sculptor Amelia Peabody, the client, who personally funded the project, and architect Eleanor Raymond (http://www.eoearth.org/article/Telkes, Maria, 2009). The House in Dover, Massachusetts contained approximately 4m^2 of Glauber salts, an original PCM material placed in drums housed in spaces between the main rooms that were ventilated with fans to move the warm air into the living space in winter. In summer the same system delivered cool air to the rooms. This system alone could keep the house warm for approximately 11 sunless days. Unfortunately the life cycle of Glauber salts meant they stopped working in the third winter and conventional heating needed to be installed. A realist, Telkes is reputed to have said "Who can expect the first of its kind to be 100 percent effective?" and indeed, 60 years later this form of heating has yet to be perfected. In 1951 Telkes wrote "Sunlight will be used as a source of energy sooner or later anyway. Why wait?" (ISES, 1976)

Since 1948, more resources have been invested in the development of PCMs which have been extensively studied over decades, notably in the 1990s by Peippo (Peippo 1991a, 1991b). Yet, despite their virtues being discovered and the difficulties of designing a PCM with appropriate melt temperatures and infinite melt cycles being resolved (http://www.epsltd.co.uk/, 2009), the momentum for application has been slow to build and even Peippo seems to have lost faith. He gave PCMs no mention in his 1998 article about optimising design options for low energy solar buildings (Peippo 1998). The assumption could be drawn that the cost for benefit was simply too high for PCMs to be a design option.

EXISTING PRODUCTS

There are many varieties of PCM available on the market today in their two most common basic forms of paraffin waxes or salts, thus providing a large range of melt temperatures. However, there are only five that appear to have been developed into market-ready building products. These products, introduced below are Energain, Smart board, Delta cool 24, Glass X, and Clima 26.

- Energain from DuPont is a board material of PCM sandwiched between two layers of aluminium for application behind dry wall board (http://energain.co.uk/Energain/en_GB/index.html, 2009).

- Smartboard from BASF, marketed by Knauf, is a dry-line gypsum based board impregnated with BASF's Micronal® PCM, of paraffin droplets micro encapsulated in a non-formaldehyde capsule (http://www.knauf.de/pdf/bilder/detbl_wmv/k764e_2008-10.pdf, 2009).

- Delta-Cool 24 by Dörken is a packaged PCM suited to retrofit situations, above ceilings, under floors etc (http://www.cosella-dorken.com/bvf-ca-en/products/pcm/produkte/cool25.php, 2009).

- Glass X by Peyerbeer is an aluminium framed window element for installation in the facade with the ability to filter solar gain to seasonal requirements based on the angle of the sun (http://www.glassx.ch/fileadmin/pdf/GLASSX_AG__products_080815_k_e.pdf, 2009).

- Clima 26 by Maxit is a trowel on internal plaster finish in a gypsum base for wall finishing with added thermal insulation (http://www.basf.com/group/corporate/en/function/conversions:/publish/content/innovations/events-presentations/energy-management/images/BASF_P-421e-MSchmidt.pdf, 2009).

DuPont launched its answer to the issue of installing PCMs in buildings in December 2006. Energain®, is a paraffin based PCM held in a polymer matrix between two layers of aluminium. Although launched in 2006, the earliest referenced installation is in 2008, at the Hammond High School in Norfolk where 600m^2 of Energain was installed into the ceilings of classrooms as an alternative to concrete soffits. This meant the proposed precast concrete became lightweight timber construction. Also in 2008, at Nouveau bâtiment HQE Voirie of Grand Lyon in Venissieux, Energain was installed behind wall linings and in the ceiling plenum. Both applications are described by DuPont as “successful” and “preliminary results are in line with the expectations of thermal comfort and energy savings” (DuPont 2009). However, no detailed information is available about what was measured or how much energy was saved.

Also in 2006 Knauf launched SmartBoard® which has been installed in a number of realised buildings in Germany. These include the 3 Liter-Haus in Ludwigshafen, Büroneubau der Badenova in Offenburg, DSC der LUWOGE/Fortisnova, Ludwigshafen, Hotel- und Bürokomplex in Berlin, Gotzkowskistraße, Haus der Gegenwart in München, Hölderlin Gymnasium in Lauffen am Neckar, and the Sonnenschiff Passivhaus Bürokomplex in Freiburg (BASF, 2004). These installations appear to see the use of PCMs as a component in a larger design goal of reducing energy use to near zero. Rather than seeing use of PCMs as a simple exchange of the old wallboard for the new product, the PCMs are used in conjunction with a number of other energy saving innovations, These buildings seem to be ‘show’ or expo type buildings, and as such are like marketing tools built by the manufacturers in conjunction with government initiatives.

The 3-Liter-house in The Brunck Quarter, Ludwigshafen, Germany was a 2001 modernisation of a 1951 apartment building historically consuming 25 litres of heating oil per square metre per year. The conversion was undertaken by Luwoge, the housing subsidiary of BASF. The goal was to lower the oil consumption to 7 litres, although the expectations were exceeded and a dramatic drop to 3 litres was achieved. The achievement was due to a seven innovations; new 20mm Neopore insulation foam was installed over the exterior walls and in the roof, passive solar heating from large newly glazed areas, triple glazing, active building ventilation with 85% heat recovery, efficient heat and electricity generation by a new miniature power plant in the cellar, PCM trowel-on plaster to interior wall surfaces, 3 year scientific assessment and commissioning. In addition to this the tenants selected for the building are BASF employees and are trained in how to use the innovation to maximum effect (Greifenhagen, 2004). Due to the complex designed nature of the various innovations, while the overall result is undeniably positive the portion of the success attributable to the PCM is not able to be individually assessed.

Other published researched uses of PCMs include in window frames to store solar gain (Skates, 2006), fabric coatings/ textiles, footwear, foams and bedding (http://www.microteklabs.com/micropcm.html, 2009), refrigeration and thermal protection of electronic devices. However, commercialisation of these products seems unlikely at present.

WHAT DO PCMS COST?

Peippo estimated in 1991 that the economic payback time for a PCM impregnated wall board was ten to twenty years depending on the location, due to energy costs. With the rising energy costs of recent years it could be anticipated that the payback time would be reduced. However, Peippo's research seems to have been based on the immersion bath technique for impregnating the board which has since been shown to fail due to evaporation (Farid, 2009) and the microencapsulated PCM wall board, which does not evaporate, is more expensive to manufacture. Estimated costs for supply of Smartboard in New Zealand from Knauf in Germany indicate it to be about ten times the cost of regular gypsum board. Fixed costs of other PCM building products are difficult to establish, especially in New Zealand, as there is not yet an established supply chain.

For the 3-Liter-house the annual saving in heating cost for each of the 9 flats is 880 euros per year, a reduction from 1000 euros to 120 euros. The total costs of the refurbishment of the block of 9 flats was 1.5 million euros, with 400,000 euros being attributed to the "Energetic Modernisation" and 400,000 euros being carried by partners (subsidised). The 400,000 for "Energetic Modernisation" alone equates to a 50 year financial payback based on heating cost savings. Again, the payback for the PCMs alone is impossible to discover from the data available.

UNIVERSITY OF AUCKLAND AND PCM RESEARCH

The University of Auckland Department of Chemical and Materials Engineering have been working with PCMs for more than 25 years (http://www.ecm.auckland.ac.nz/groups/energy/energy_group.htm, 2009). In 2002 funding was obtained for further research entitled 'New Materials for Phase-Change Thermal storage' of which this current project is a part.

The University of Auckland have extensive facilities for testing PCM materials both in the Research Centre for Surface and Materials Science (RCSMS) laboratory within the Engineering School and at the test facilities at the Tamaki campus. Staff and postgraduate students are working on the development of suitable phase change materials, including those based on fatty acids to give a cheaper product, and their encapsulation, and studying the effect of using these PCM materials in a built environment, mostly through simulation. They are also looking at the development of PCMs for refrigeration, glass houses, laptop pads and lithium batteries, and are working on PCM composites with graphite to improve conductivity.

DESIGN WORK

Though PCM products have been developed and there is great interest in their capabilities from a range of industries, their uptake has been very limited. Stalled uptake can usually be attributed to two issues, scepticism and cost (Máté, 2009). In this instance scepticism is probably not the issue as the principles of using PCMs are well founded and proven (Vavan Vuceljic, 2009) and reducing energy is a big current issue (UNFCCC, 2007) that has reach the general population. However, there is a resistance to improved materials many times the cost of the original. Here lies the importance of design input. It is commonly acknowledged that designers (and their clients) will validate expense in achieving a point of difference, but they expect visual gratification, or 'added value', for the effort (Máté, 2009). The products currently available have been 'designed' by teams of scientists, driven by the technical abilities of the materials, and often using them to better existing products – in effect hiding the innovation in something that has already been accepted by the construction industry. Hiding innovation may work when the cost is comparable or the increase in cost small, but for a product like PCM Smartboard, which sells for approximately ten times the normal price of gib, people want to see what they are paying for. The visual characteristics of PCMs performing their melt cycle are very interesting and elegant and exposing them, for instance, would give the user an awareness of their function and of the environmental conditions that would not otherwise be easily perceptible. With the possible exception of Glass-X none of the current products exploit this opportunity.

Had a design team been consulted at the point of conception of radical new ideas for how a material, like PCMs, might be used, the development might have taken a very different course. Instead of leaving development to scientists, whose expertise is in the chemistry of materials not architecture, allowing designers to develop the innovation into a new and better, rather than existing product, might produce something more radical and hence acceptable despite the cost. The fact many open plan office interiors make use of glazed partitions, as mentioned above, would seem to offer an opportunity for a visual PCM installation where the change in the material status would become part of the office environment. This would also connect the users with what was happening in that environment giving them an awareness of why changes occur. When the sun comes out the PCMs would change state from solid to clear liquid, like ice melting, or when they solidify they become milky. Making this visible would have produced a product like no other on the market, yet one that would still make a contribution to energy savings

HOW MIGHT PCMS BE USED IN OFFICE ENVIRONMENTS?

To consider appropriate design opportunities for integrating PCMs into the office environment it is important to look at current office configurations and the possibilities they make available. PCMs have a maximum functional thickness of approximately 10mm due to their low conductivity. Greater depth also results in even lower financial viability due to the expense of the PCM, which lends them to a surface application. As the ideal room temperature is approximately 19-24 degrees Celsius, some 13-18 degrees lower than body temperature at 37 degrees, to suit this, the functioning PCM temperature also needs to be approximately 19-24 degrees. It is also necessary to consider the proximity to the human body, for instance will the surface feel uncomfortable if the PCM is too close?

In an open plan environment the most readily available surfaces are workstation components, such as desk, chair and partition/pin up board. This leads to another design consideration, ownership. There is the question of whether PCMs and their potential energy savings should be part of the structure in order for the heating, ventilation and air conditioning systems to be designed as part of the best potential building operation modes, or whether they can be part of the tenancy equipment, where if the owner moves on so does the energy saving PCM product.

In a product developed with energy conservation and eco-friendliness in mind, consideration must also be paid to the second of the ever important three Rs – Reuse. To make PCM products easily reusable in order to reduce future production - not necessarily the most profitable goal but the most socially responsible one - it is then sensible to design a package with assembly and disassembly in mind rather than focusing on the first use of the product. This brings the issue back to ownership, and questioning the relationship of possibly "temporary" PCM products with the permanent HVAC systems.

PRECEDENT PRODUCTS: PHOTOVOLTAIC PANELS

It may be useful to compare the development of PCMs to another product with similar benefits and costs. Unlike PCMs which simply store energy in the form of heat, photovoltaics are used for generating electric power using the sun's radiation, and are thus a substitute for other more environmentally costly techniques of electrical power generation. Not unlike PCMs, PVs are often positioned out of sight to get the best location for solar gain and also because they are not generally considered aesthetically pleasing. Also like PCMs the cost of PVs is generally far greater than their less environmentally beneficial counter parts, and though the cost of electricity is now higher than it was, the payback period for the cost of installing the technology to make use of the free solar energy is perceived as too long for many potential users (http://www.solarbuzz.com, 2010). Despite this, and unlike PCMs, PV production has been doubling every two years since 2002, making it the world's fastest-growing energy technology (Kropp, 2009), but these figures include PV power stations and use of panels in developing countries where alternative 'on the grid' options are not available. Importantly, many countries have introduced financial incentives for the installation of PVs which could account for much of the explosive growth. These countries include, Australia, China, Germany, Israel, Japan and several states of the US (http://www.solarbuzz.com).

Unlike photovoltaic panels, PCMs have a much cheaper, low-tech alternative—mass. While the heat absorption capacity of 20mm PCM plaster is considered to be the equivalent of 200mm of concrete (Greifenhagen, 2004), current PCM products are based on paraffin and only have an advantage in situations where lightweight building is the only option, or for upgrading the existing lightweight building stock. Once non petrochemical based PCMs are developed, with the anticipation these will have a lower cost both financially and for the environment, they maybe more likely to attract subsidies in the way PVs do.

CONCLUSION

It seems unlikely that PCM products in their current forms will achieve a significant part of the potential that the raw materials are perceived to have.

The current low cost of standard gypsum type wall linings makes them a relatively insignificant part of the total build cost. At ten times the cost of the material it is intended to replace, PCM wall board raises the cost of the wall linings component of total built cost by an order of magnitude.

The values that decision-makers bring to the decision-making process vary across populations. A large proportion of the population now reluctantly accepts that during the course of the last two hundred years people have caused significant and lasting damage to the environment. Many would now like to help undo some of the damage, or at least mitigate the damage still being done. Sadly, not many seem willing to give up much to do so. In the present case, the inevitable formal or informal cost/benefit analyses will produce different results depending on the values of the participants, but it seems reasonable to predict that for almost all this is likely to render a previously insignificant cost significant, and for most it will result in a rejection of the new, untried, vastly more expensive alternative.

Furthermore, before agreeing to bear the opportunity cost of being "environmentally friendly," most people expect, at the very least, to have some idea of what will result as a return (Máté, 2009). There is currently very little information to support decision-making. A life-cycle analysis of overall impact and cost needs to be based on reliable data for PCM materials and this is hard to come by. An estimate by the Fraunhofer-Institut for recovery of the embodied energy for a PCM plasterboard product has been calculated to be 200 cycles, which for day to day storage means the payback time would be about one year (Schossig, 2009). However, the companies producing and marketing the various products do not appear to be providing this necessary information. Moreover, more definitive data based on the modelling of field measurements from buildings using PCMs is needed.

Until these questions have been answered to the consumers' satisfaction, there seems little chance of PCM products penetrating the market, gaining first traction and then momentum, and ultimately achieving significant economies of scale.

To achieve its potential some combination of cost reduction and/or improvement in perceived benefit must result in a better "return on investment" for the consumer. The most obvious solution to this problem is to develop other, less expensive, materials capable of phase chase at the desired temperature, with infinite cycles. The fatty acids currently being worked on by the University of Auckland are an example of this approach. In addition to this, the development of designed products that express the function of the PCM and create increased perceived value is another route for bringing the product to market.

Finally, there are a couple of questions that should be asked. Whilst PCMs could be a viable aid in reducing the energy consumption in buildings, are they the best solution? Is the development of PCM products the best investment of available time and other resources? This relates back to the earlier comment on life-cycle analysis.

Passive heating and cooling are not new concepts. They have been used in many parts of the world with different techniques and different materials for centuries. However, in the years since the industrial revolution the expectations of the developed world have progressed in favour of good environmental design (and passive design) at the push of a button. At the same time as wanting buildings automatically controlled the expectation of low cost developments, and low owner occupier rates in commercial buildings drive the initial cost down along with the quality of the design. This leaves little room for introducing new, expensive products, even if they can be shown to have environmental benefits. In fact there should be no need for PCM products in new passive buildings where the design should make optimum use of the total building envelope and structure. Ideally PCMs should only be needed as part of retrofitting the existing building stock for improved environmental performance. However, this may mean effort being put into in design that could become obsolete in the next 20 years.

All this suggests that the best way forward for current PCM materials is to use them in added value products, such as part of office interior fit-outs, rather than in the commercial building envelope. However, further research needs to be done to see how effective this approach might be on the overall internal environment.

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