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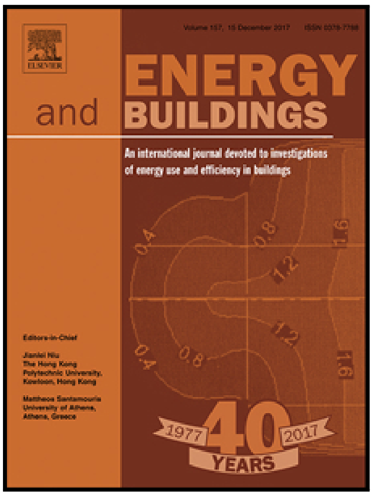

Thermal Performance of Thermal Paint and Surface Coatings in Buildings in Heating Dominated Climates

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Highlights

- Measured thermal resistance of thermal paint and general wall coverings are alike
- Thermal paint coatings & additives are thin (<1mm) and do not show low-e surfaces
- Regular EPS liners give more effective thermal insulation levels at a lower cost
- Microscopy of insulating additives suggest the structure is not nano-porous
- The payback period is longer than a human life span for thermal paint coatings

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Thermal Performance of Thermal Paint and Surface Coatings in Buildings in Heating Dominated Climates

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Abstract

A purported approach to reducing heating energy in solid wall “hard to heat” housing is the simple application of a thin layer (< 1mm) of thermal paint containing insulating additives. The objective of this study was to test the energy saving claims by a systematic study of the material characteristics and thermal performance of internal coatings using accepted international standard test methods. The coatings have been compared with conventional internal coverings such as emulsion paint, wallpapers and expanded polystyrene liner. A dynamic model of the Energy House research facility has been used to evaluate energy savings, costs, and payback times.

The thermal resistance of the thermal paint coatings was generally found to be not much better than that of conventional vinyl textured wallpapers with a lining paper. When all building heat losses are considered, modelling predictions for thermal paint coatings indicate an unfavourable payback period of several hundred years, and energy savings of between 0.4% and 2.9% depending on coating thickness and type. The evidence from the results and models, as well as scanning electron microscopy, do not support the claims that the additive powder particles are effectively nano-porous, evacuated, or that the coatings have low emissivity surfaces.

Keywords

Thermal paint coatings
Insulating paint additives
Ceramic spheres
Thermal insulation
Thermal conduction in porous materials
Emissivity
Scanning electron microscopy
Energy savings
Cost savings
Payback period

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1. Introduction

The retrofit of the existing housing stock is of particular importance to those countries where heating energy is a larger component of energy consumption. The EU has identified the issue of renovation of the domestic housing stock as an important component in addressing climate change through its EU2020 policy (Saheb et al. 2015). This has been followed through by EU countries, such as France and Germany, who have implemented policies that look to reduce emissions by far more than 20% (Sebi et al. 2018). Similar policies have been identified in the US (Sebi et al. 2018), while in China the 5-year plan identified that houses in heating dominated latitudes consumed more than 100-200% more energy than houses in countries at a similar latitude in Europe and, therefore, required retrofit (Zhao et al. 2018). The existing stock remains a challenge; in the UK for example, 65-80% of stock in the late 2000s (Kelly 2009), (Boardman 2007), (Ravetz 2008) is projected to still be standing in 2050, with much of it constructed prior to energy efficiency standards. The technical solutions for retrofit have global ramifications.

Whilst many consider that deep fabric and services retrofitting (Gupta and Gregg 2016) combined with behaviour change, are an important way of meeting these targets (Swan, Ruddock, Smith, & Fitton, 2013), there is another aspect of energy savings which is less explored in the literature; low cost interventions. Examples of these types of measures are; airtightness measures (Gillott et al., 2016), window treatments such as curtains and blinds (Baker, 2008) (Fitton et al, 2017) and the effect of heating controls (Fitton et al, 2016). Window coverings and airtightness measure are considered effective in that they need limited occupant intervention to generate savings (Sadineni et al, 2011).

Passive fabric interventions such as external and internal insulation can be expensive, complicated to design install and have a disruptive effect on the occupant during installation (Dowson et al, 2012). Solid wall “hard to treat” housing often prove to be the most expensive and complicated construction types to insulate. A purported solution to treating solid walls is thermal paint (Dowson et al, 2012).

Thermal or insulating paint additives, usually made up of microscopic hollow ceramic spheres, are marketed as making paints or coatings insulate. The resultant coatings are commonly known as “thermal paint”. These can be applied anywhere that conventional paint and coatings are used in domestic and commercial applications. Marketing literature indicates that some thermal paints contain a reflective additive, as well as possessing enhanced intrinsic insulating properties. The reflective property is mainly effective where the goal is reducing solar radiation absorption to decrease air conditioning loads. In the built environment, thermal paint is mainly applied to the surfaces of poorly insulated buildings. In the UK there are some 5 to 7 million properties considered to be hard to insulate, with external solid walls, and no provision for cavity wall insulation. The relatively simple application of a thin layer of thermal paint to a surface appears to be a convenient alternative to structural changes incorporating some 50 to 100mm of conventional insulation material.

However, research by the CCHRC in Alaska (Garber-Slaght & Craven, 2009), concluded that there was no discernible difference in the performance of the two insulating paint products in comparison to regular latex paint during energy monitoring tests. The Slovak University of Technology (Ganobjakl & Kraloval, 2017) found that the paint insulation layers did not contribute noticeably to the U-value of the building structure that they were used on.

A thermal modelling study in Energy and Buildings by Azemati et al. (2013) on mineral insulator in paints makes claims of a 17% of energy savings during winter. Closer examination shows this to be an overestimation as important data used in the modelling lacks credibility. It is assumed that a 0.4mm thick ceramic mineral paint coating has a thermal resistance of 1.06 $m^2 \cdot K/W$, based on the work of Poppendiek (2003), which implies that the thermal conductivity (0.0004 $W/(m \cdot K)$) is a

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factor of 10 times less than that for the best insulation currently marketed i.e. vacuum insulation panels. Furthermore, the density of the insulator ceramic particles assumed to be 0.73 kg/m^3 does not appear to be realistic. In the experience of the authors this is considerably less than typical densities of up to 400kg/m^3 for insulating additives. It is worth noting that the density given by Azemati et al is about 40% lighter than that of air which would render the paint mixing process impractical.

Using accepted European standard test procedures under steady state conditions, an in-house method has been developed at the Thermal Measurement Laboratory to measure the increase in thermal resistance resulting from the application of thermal paints & coatings that may be used on various substrates such as plasterboard. The increase is determined by the difference between the measured thermal resistance of the substrate, before and after coating.

The objective of this study was to test the energy saving claims by carrying out a systematic study of the thermal insulation performance of a wide range of thermal paint coatings available in the UK. These have been compared with conventional internal surface coverings. To this end six different thermal paint coatings, from five different suppliers, have been examined. The relative improvement in thermal resistance and the surface emissivity has been measured for each type of coating. Measurements of the thermal conductivity have also been made on specially constructed samples of additive, and a mixture of paint and additive. Scanning electron microscopy (SEM) and X-ray analysis by Salford Analytical Services of the cell structures of additives and thermal paints has been included. The results have also been used in a dynamic model by the Applied Buildings and Energy Research Group at the University to evaluate energy savings, costs, and payback times.

2. Surface Coating Test Samples

Six different thermal paint coatings and two different insulating paint additives have been examined. These have been compared with conventional internal coverings such as emulsion paint, wallpapers and expanded polystyrene liner.

Thermal paints 1 and 2 were mixed in the laboratory by adding insulating paint additives 1 and 2 to standard emulsion paint according to manufacturer’s instructions. Thermal paints 3, 4, and 6 were “off the shelf” premixed additives in water-based coatings. Thermal paint 5 was described in detail by the supplier as a paintable, sprayable and printable paste with aerogel and glass micro spheres dispersed in an elastomeric polymer.

Table 1 below gives descriptions of the coating samples tested as applied to skimmed 12mm plasterboard samples, including information about how the products were applied, before re-conditioning to constant mass before test. The coatings were applied using a standard paint brush according to the instructions on each of the products packaging.

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Plasterboard Sample Reference	**Coating**	**Product Description**	**Details**
A	Lining Paper	800 Double Lining Paper	Applied to plasterboard sample A with standard wallpaper adhesive
B	Vinyl Wallpaper	Textured Vinyl Wallpaper	Applied to plasterboard sample B with standard wallpaper adhesive
C	EPS Liner	EPS Insulation Liner + 800 Double Lining Paper. 3.4mm average thickness	EPS liner applied to plasterboard sample C with standard wallpaper adhesive, then lining paper applied over EPS using same adhesive
D	Emulsion Paint	Standard Emulsion Acrylic Durable Matt cream colour	One coat applied to plasterboard sample D was allowed to dry for at least 2 hours before applying a second coat. Two coats total
E	Thermal Paint 1	Powdered Insulating Paint Additive 1 applied to Standard Emulsion	One pack of additive was applied to 5L of standard emulsion as per the instructions provided on the packaging. One coat of the resulting mixture was then applied to the plasterboard sample E and was allowed to dry for more than 8 hours overnight before applying a second coat. A total of two coats was applied. Note: 1 pack of additive 1 claims to contain 550g.
H	Thermal Paint 2	Powdered Insulating Paint Additive 2 applied to Standard Emulsion	One bottle of additive was applied to 5L of standard emulsion as per the instructions provided on the packaging. One coat of the resulting mixture was then applied to the plasterboard sample H and was allowed to dry for more than 8 hours overnight before applying a second coat. A total of two coats was applied. Note: 1 bottle of additive 2 contained approx. 1040mL weighing at 454.5g.
J	Thermal Paint 3	Water based coating system incorporating the use of glass microsphere technology.	As per the manufacturer’s instructions on the label, one coat applied to plasterboard sample J was allowed to dry for at least 2 hours before applying a second coat. Two coats total
I	Thermal Paint 4	Described as Insulating Paint	As per the manufacturer’s instructions on the label, one coat applied to plasterboard sample I was allowed to dry for at least 2 hours before applying a second coat. Two coats total
L	Thermal Paint 5	Described as a paintable, sprayable and printable paste with aerogel and glass micro spheres dispersed in an elastomeric polymer.	As per the manufacturer’s instructions on the label, one coat applied to plasterboard sample L was allowed to dry for at least 2 hours before applying a second coat. Two coats total
M	Thermal Paint 6	Described as a water based eco-acrylic coating	As per the manufacturer’s instructions on the label, one coat applied to plasterboard sample M was allowed to dry for at least 2 hours before applying a second coat. Two coats total

Table 1. Coating and Sample Descriptions

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The structure of the microscopic hollow ceramic spheres in thermal paint additives, and the means by which they contribute to enhanced energy saving claims, requires clarifying. Insulating paint additives are often described as using nano and insulating technologies, developed in association with aerospace industries. It has been suggested that since they have been developed from nano technology that the hollow ceramic spheres have a nano-porous structure, or that the pores may be evacuated.

A summary of the heat transfer processes in porous materials and applicable theoretical models follows. The effect on the insulation performance of porous materials which contain nano-pore structures or evacuated pores to establish a theoretical basis for the performance of the thermal paint products, has been considered.

It should be noted that the characterisation of porous solids conforms to the new pore size classification proposed by Mays (2007). The classification is based on a logarithmic scale (to base 10), and pores of interest are considered to be no smaller than 0.1 nm and no larger than 0.1 m. The new pore size classification is summarised for the three main pore size ranges as:

nanopore	pore size between 0.1 and 100 nm
micropore	pore size between 0.1 and 100 μm
millipore	pore size between 0.1 and 100 mm

Each range covers three decades of pore size, with the lower boundary of the middle decade being the reference pore size for the range (1 nm, 1 μm and 1 mm for nanopores, micropores and millipores respectively). Former International Union of Pure and Applied Chemistry (IUPAC) classifications are - Micropores have widths smaller than 2 nm. -- Mesopores have widths between 2 and 50 nm. -- Macropores have widths larger than 50 nm. Unlike the IUPAC scheme, the new scheme conforms to the spirit of the SI international units system.

3. Heat transfer processes in porous materials and applicable theoretical models

Mass-type thermal insulation materials are usually highly porous and consist of a solid matrix full of small voids that comprise the bulk of the total volume. These voids normally contain air or some other low conductivity gas. The thermal conductivity of the material is the result of various basic heat transfer mechanisms: solid and gas conduction, gas convection and long-wave radiation within the voids (Simpson & Stuckes, 1986 & 1990). The apparent conductivity depends on the kind of solid, bulk density, temperature, water content, thickness and age. Factors such as cell shape and diameter and arrangement of fibres or particles, transparency to thermal radiation or type and pressure of the gas come into play. The radiative component may become significant at very low densities or at high temperatures, but it is generally small compared with conduction at normal density and ambient temperatures in buildings.

For pores smaller than a few millimetres, air convection cannot occur and heat transfer through the gas depends on collisions between the molecules within the pores, and the conductivity is that of still air. Super-insulation material such as vacuum insulation panels rely on evacuated cells and negligible gas conduction. Other materials such as polyurethane and phenolic foam depend on low conductivity gases being trapped in the cells.

For air filled super insulation materials with a predominance of pores of < 0.1μm in size the conductivity may be effectively reduced below that of still air by restricting collisions between gas molecules. It has been shown by Kistler (6) that for a given pressure the mean length of the free path L_p for molecules confined within the pores of an insulation is given by:

$$L_p = t\, L_0/(t + L_0) \qquad (1)$$

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Where t is the mean free path of the gas in a free state and L_o is average pore dimension. According to kinetic theory the thermal conductivity of a gas is proportional to the mean free path of the molecules. Consequently, the effective conductivity of the gas contained within the pore is given by

$$\lambda_p = \lambda_g/(t + L_0) \quad (2)$$

where λ_g is the conductivity of the free gas.

The quantity λ_p is plotted against pore size for the conductivity of free air λ_g = 0.0254W/(m·K) at 16°C and at atmospheric pressure, given a mean free path of 68nm, in Figure 1. In nano-porous materials where the size is less than 1µm the effective conductivity of air is significantly less than that of free or still air.

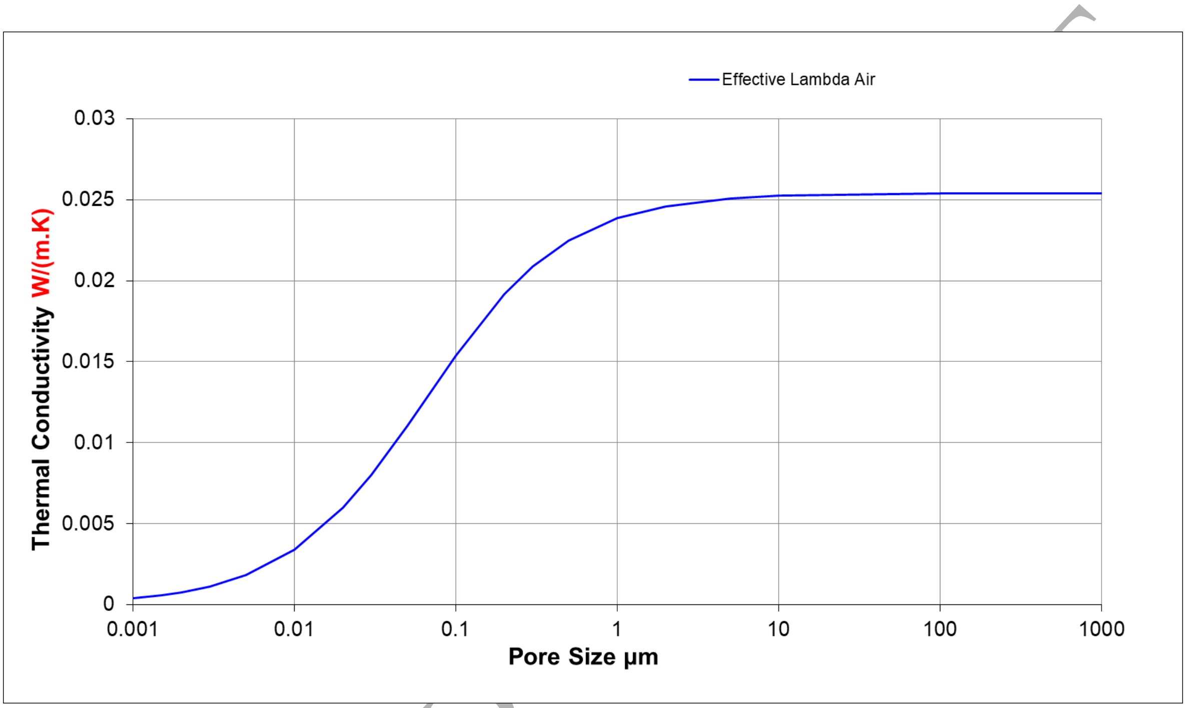

Figure 1 Effective thermal conductivity of air vs pore size for λ_g = 0.0254W/(m·K) **at 16°C**

Most porous materials may be considered as mixtures of gas (usually air) and solid. In general, the thermal behaviour of a material lies between that of its components and depends on the volume fraction of each and its distribution and shape. Due to the complexity of the structure of real materials, there are few cases where rigorous calculations are possible.

(Simpson& and Stuckes, 1986) considered a general equation for multiphase materials based on the equation for the dielectric constant of mixtures (Reynolds & Hough, 1957). The models consider a spheroidal shape of the dispersed phase in a continuous matrix material. The phases are assumed isotropic and homogeneous throughout. The general formula for the thermal conductivity λ of two phase media is

$$\lambda = (\lambda_0 V_0 f_0 + \lambda_1 V_1 \lambda f_1)/(V_0 f_0 + V_1 f_1) \quad (3)$$

Subscript 0 refers to the continuous matrix phase, and subscript 1 refers to the dispersed phase, where V_i, λ_i and f_i are the volume fraction, thermal conductivity and spheroidal field factor respectively for each phase.

Spheres provide a good approximation to the shape of the microscopic hollow ceramic cells in thermal paint additives. For spherical shapes the equation can then be simplified to two limiting cases.

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Maxwell (1904) and Eucken (1940) model for spheres of phase 1 dispersed in continuous phase 0.

$$\lambda = (\lambda_0 V_0 + 3\lambda_0 \lambda_1 V_1/(2\lambda_0 + \lambda_1))/(V_0 + 3\lambda_0 V_1/(2\lambda_0 + \lambda_1)) \tag{4}$$

(Brailsford & Major, 1964) model for spheres of phase 0 and phase 1 embedded in a mixture having the thermal conductivity λ of that being calculated.

$$\lambda = 1/4\left((3V_0 - 1)\lambda_0 + (3V_1 - 1)\lambda_1 + \left(\left((3V_0 - 1)\lambda_0 + (3V_1 - 1)\lambda_1\right)^2 + 8\lambda_0\lambda_1\right)^{0.5}\right) \tag{5}$$

The Brailsford and Major model should give a good estimate of the conductivity of a mixture if neither phase is continuous.

The theoretical λ / density relationship for a composite in Figure 2 is based on the models of Maxwell-Eucken (upper limit) and Brailsford & Major (lower limit), for a matrix of density 1610kg/m³ and λ=0.63W/(m·K). Two cases are presented in the figure, the first example showing air filled pore inclusions of at least 10µm in size where λ_{air} = 0.0254W/(m·K). The second example shows the theoretical relationship for 100nm (0.1µm) pore size with λ_{air} = 0. 0154W/(m·K), with the thermal conductivity reducing due to the decrease in pore size. The potential for improved insulating performance of nano-porous materials, with thermal conductivity values less than that for still air, is evident at low densities of the composite.

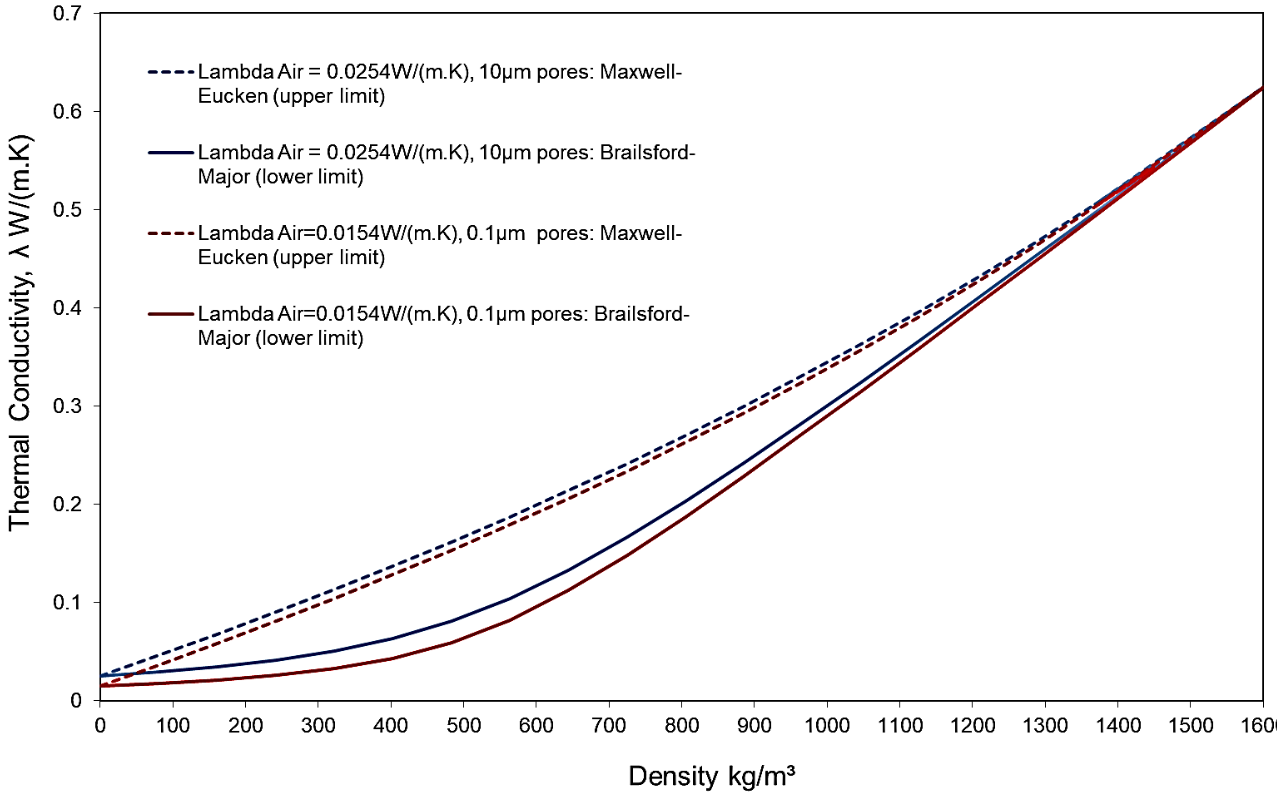

Figure 2 Theoretical thermal conductivity of composite based on models of Maxwell-Eucken (upper limit) and Brailsford & Major (lower limit) for air filled pores ~ 10 µm and 0.1 µm.

From the foregoing, it is evident that the thermal conductivity of air-filled pores may be effectively reduced below that of still air in materials with a predominantly nano-porous structure. It has been suggested that the microscopic hollow ceramic spheres in thermal paint additives have a nano-pore structure. It is also suggested that the pores in the ceramic spheres may be evacuated which raises the possibility of negligible gas conduction.

The parameter that defines how well a building element insulates is the U-value. A material can act as thermal insulation and lower the U-value in two ways:

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a) Increasing the intrinsic thermal resistance of the material and;
b) Reducing the emissivity ε and making surfaces more reflective thereby reducing radiant exchange and raising the thermal resistance of adjacent air layers within a structure.

Thermal resistance is a measure of resistance to heat flow and if the thickness of a material is increased there is a corresponding increase in resistance. Conventional thinking is that thin surface coatings, usually less than 1mm thick, are limited in their ability to resist heat flow and provide significant increases in thermal insulation levels of buildings. Some marketing literature suggests that thermal paints do not perform like conventional insulation materials as they contain a reflective additive, as well as possessing enhanced intrinsic insulating properties.

The reflective property of thermal paint coatings is effective on external surfaces where the goal is reducing solar radiation absorption to decrease air conditioning loads. However, the effectiveness to long wave radiation under ambient indoor conditions, is not the same as that for short wave solar radiation. The amount of thermal radiation emitted depends on the emissivity ε of the object's surface. Emissivity is the ratio of the energy radiated from a material's surface to that radiated from a blackbody (a perfect emitter) at the same temperature and wavelength and under the same viewing conditions. It is a dimensionless number between 0 (for a perfect reflector) and 1 (for a perfect emitter). The emissivity depends on the nature and temperature of the surface as well as wavelength and angle.

In the following section the material characteristics of pore structure, as well as coating emissivity and thickness of the thermal paint coatings at temperatures appropriate to indoor surfaces under domestic heating conditions, have been examined.

4. Material Characteristics

The theoretical models in the previous section describe the heat transfer implications for purported nano-pore and evacuated pore structures in insulating paint additives. Electron microscopy techniques have been used to determine the actual pore structure. The pore structure of the powdered insulating paint additives 1 and 2, and thermal paint coatings 1 to 6 was examined using high resolution Scanning Electron Microscopy (SEM). The elemental composition the particles of the additives was examined using Energy Dispersive X-ray Analysis (EDX).

The emissivity and the thickness of the coatings has been determined at 16^{o}C in order to test the effectiveness under ambient indoor surface conditions.

4.1 Scanning Electron Microscopy & Analysis

4.1.1 Additive 1 Powder

The SEM micrograph as shown in figure 3 was obtained using a system magnification of 300x. The micrograph demonstrates that the sample has a spherical morphology with a broad particle size range from 10µm to 200µm in diameter. Figure 4, represents an SEM micrograph obtained from a fractured particle using a system magnification of 2,500x. The micrograph shows the particle to have a smooth hollow internal morphology with variable outer wall thickness between 2µm to 6µm.

The internal wall structure observed from the particles is shown to contain spherical voids typically 0.5µm to 7µm in diameter. From the fractured areas examined only a small percentage of the voids are seen to be present below 1µm implying these particles are mainly micro-porous. In some cases, the wall structure was perforated, indicating that a vacuum could not be contained in the voids.

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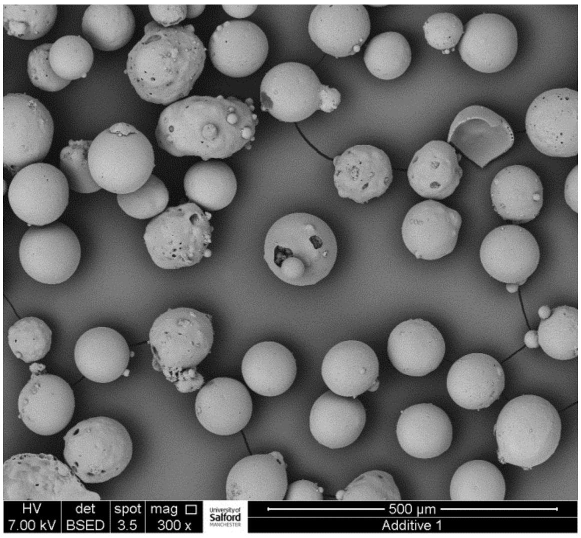

Figure 3 Loose ceramic beads in Additive 1

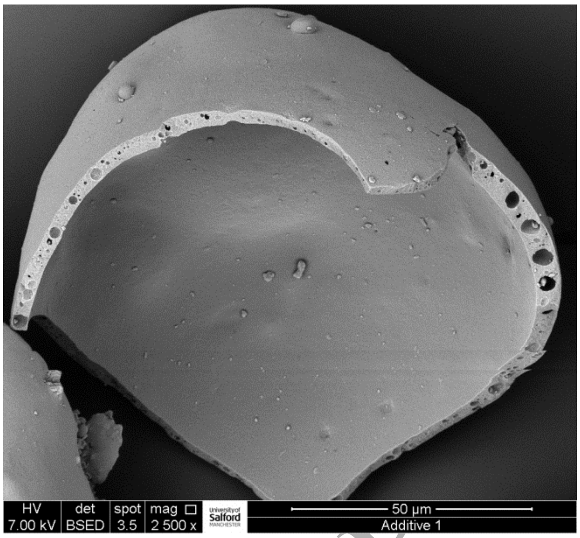

Figure 4 Fractured ceramic bead in Additive 1

The resulting EDX spectrum demonstrate that the particles contain high levels of aluminium, silicon, and oxygen. The X-ray Diffractogram illustrates a good match for Mullite $Al_6Si_2O_{13}$.

4.1.2 Additive 2 Powder

The SEM micrograph as shown in figure 5 below was obtained using a system magnification of 300x. The micrograph shows that the particles have a spherical morphology with a particle size range from 1µm to 150µm in diameter. Figure 6 represents an SEM micrograph obtained from a fractured particle, using a system magnification of 1,900x. The micrograph shows that additional smaller spherical particles are encapsulated within the larger fractured particle. The particles have a smooth surface morphology, containing some small voids existing between 100nm-600nm in diameter. The outer wall thickness obtained from the fractured particles is seen to be thin with measurements observed between 400nm to 1.2µm. The particles are predominantly micro-porous, and in some cases the wall structure was perforated.

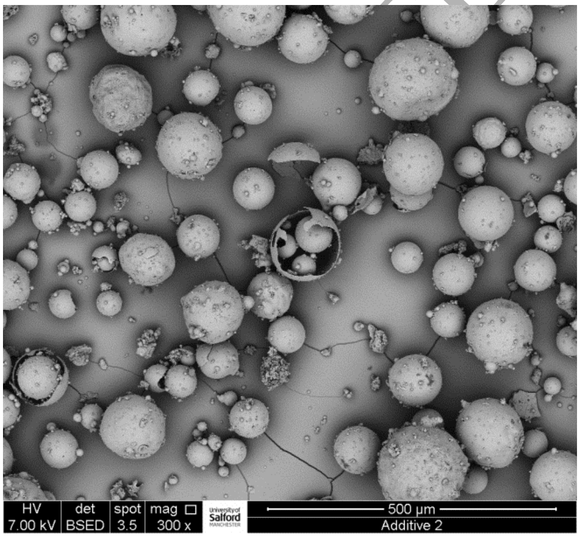

Figure 5 Loose ceramic beads in additive 2

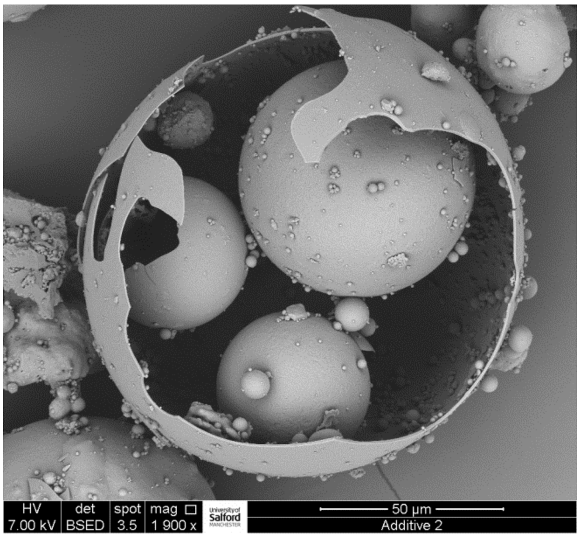

Figure 6 Fractured ceramic bead in additive 2

The EDX spectrum demonstrates that the particles contain high levels of aluminium, silicon, and oxygen, with trace levels of sodium, potassium, calcium and iron. The X-ray Diffractogram illustrates a good match for Mullite $Al_6Si_2O_{13.}$

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The bulk density the Additive 2 powder was measured at 393kg/m³.

4.1.3 Thermal Paint Coatings

The SEM examination of the thermal paint coatings clearly shows that, with the exception of Thermal Paint 5, they all were seen to exist as a mixture of spherical particles of additive embedded within a continuous, structure of fine, irregular shaped paint matrix material (Figures 7, 8, 9, 10 and 11).

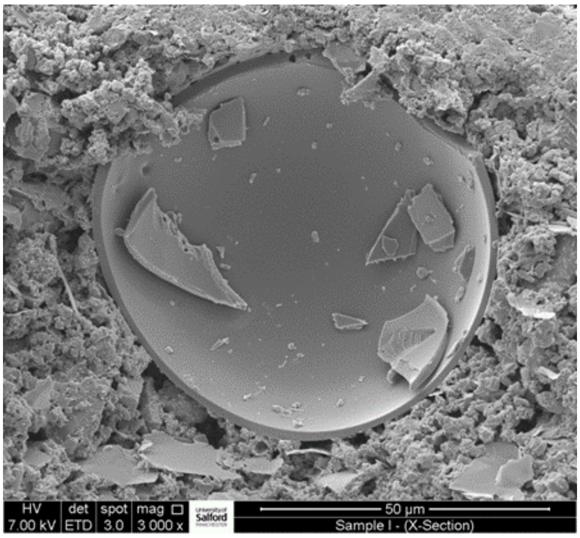

Figure 7 Thermal Paint 1

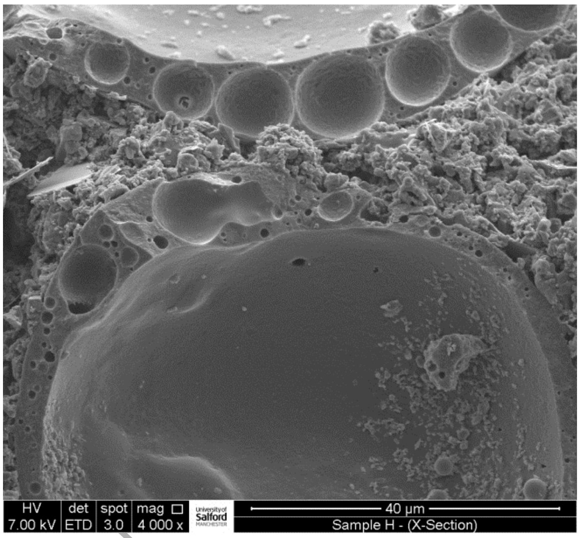

Figure 8 Thermal Paint 2

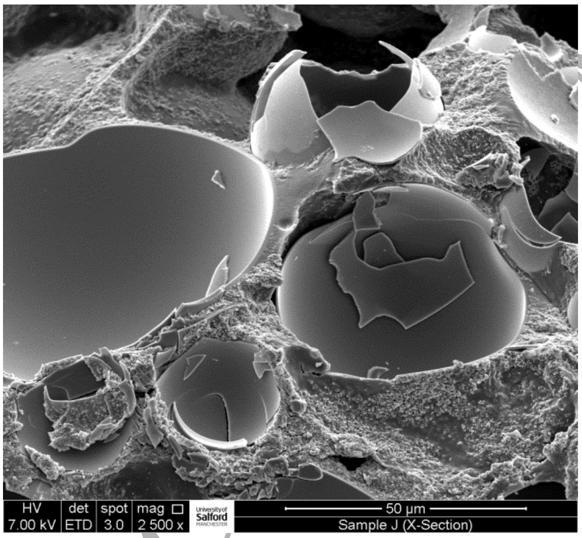

Figure 9 Thermal Paint 3

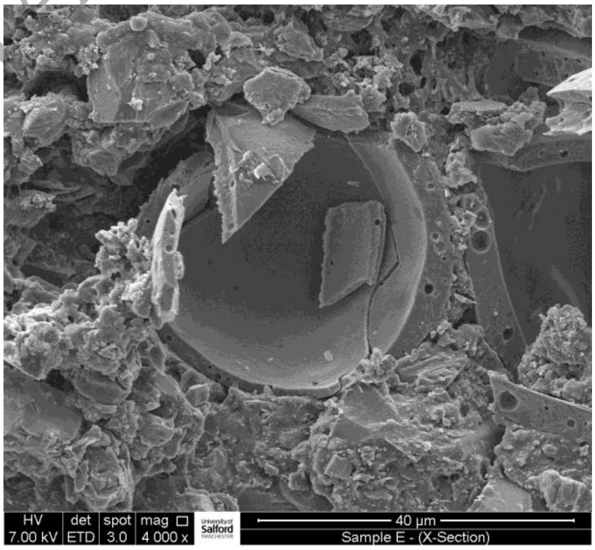

Figure 10 Thermal Paint 4

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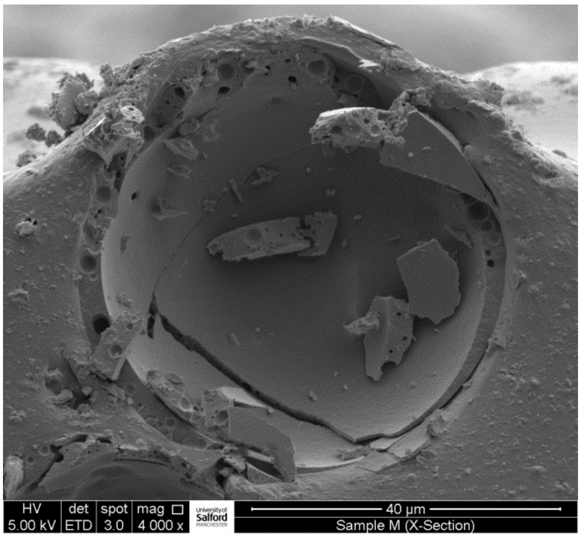

Figure 11 Thermal Paint 6

Thermal Paint 5 is described as a paintable, sprayable and printable paste with aerogel and glass micro spheres dispersed in an elastomeric polymer. As shown in Figure 12, the sample is seen to exist as spherical particles with a diameter between 10µm to 100µm. The spheres are held together by an amorphous binder forming a semi-continuous structure with very little inter particle matrix material.

A cross-section of the paint was obtained by cutting with a razor blade once frozen with liquid nitrogen. The internal morphology as shown in figure 13, reveals that the spheres are hollow with a very thin wall thickness. Many voids are present between the particles. The spheres are soft and thought to be polymeric rather than ceramic as seen in the previous samples examined.

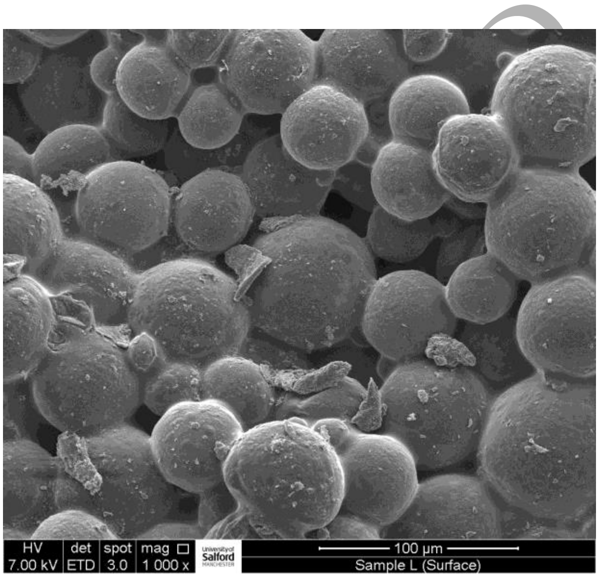

Figure 12 Thermal Paint 5

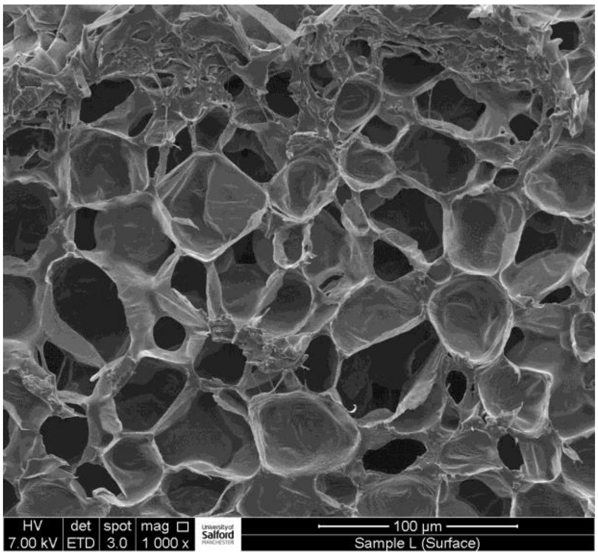

Figure 13 Thermal Paint 5

4.2. Emissivity and Thickness of Surface Coatings

The emissivity of all the surface coatings was determined using a calibrated emissometer Model AE1 supplied by Devices & Services Company, Texas. Sample surface emissivity was measured at a surface test temperature of 16°C, after calibrating the emissometer against a high emittance standard (ε = 0.88 ± 0.02) and a low emittance standard (ε = 0.06 ± 0.02), at the same temperature.

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The emissometer was also checked against the matt black plates of the single specimen heat flow meter ($\varepsilon = 0.87$). The emissivity of the plates had been determined using the procedure of European standard EN 1946-3:1999 Annexe A method (c).

The ten coatings described in Table 1 were each applied to the surface of 1mm thick steel plates, 100mm × 100mm square, to provide good thermal contact with an isothermal surface. The coated plates were conditioned in a constant temperature enclosure heat flow meter apparatus, to a similar temperature (16°C) to the surface of the coated plasterboard samples in the thermal resistance tests. The emissivity of each coating was measured with the emissometer mounted perpendicular to the surface as shown in Figure 14.

The thickness of the ten surface coatings on plasterboard panels was also determined by measuring the thickness of the test samples, before and after coating, in the heat flow meter apparatus.

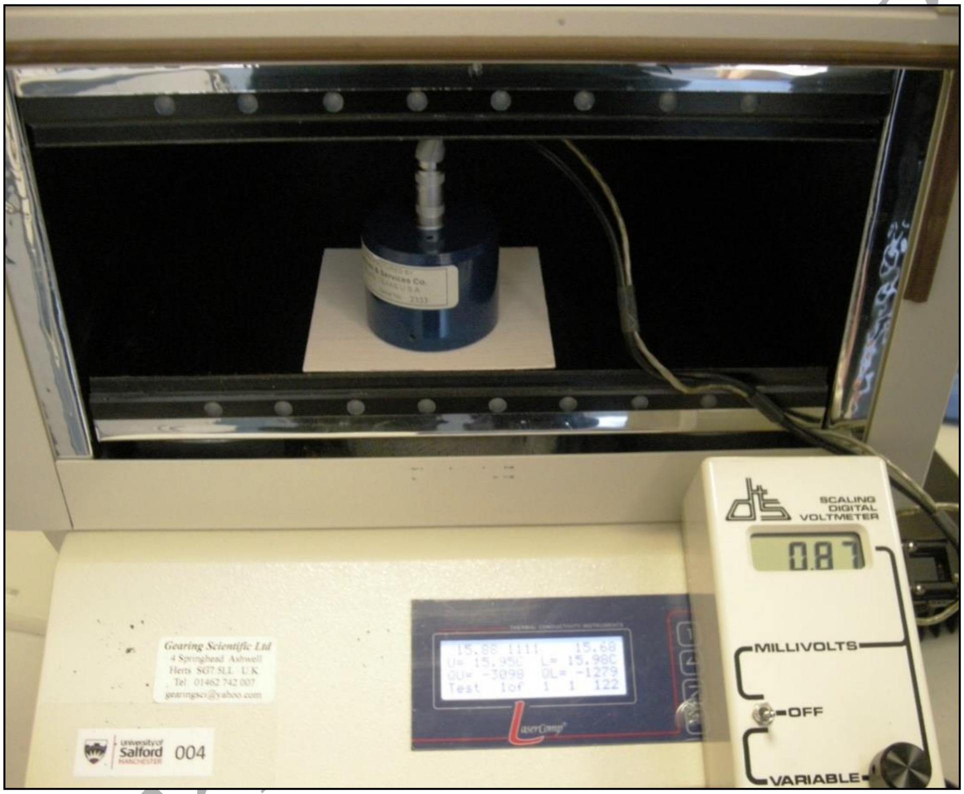

Figure 14 Emissometer mounted on a coated sample in constant temperature heat flow meter apparatus

The measured emissivity and thickness of the coatings are summarised in Table 2. The light coloured Emulsion Paint ($\varepsilon = 0.85$) reflects heat to a limited degree and is just as effective as the majority of thermal paint coatings. Surprisingly, conventional Textured Vinyl and Lining Paper were found to be slightly more reflective ($\varepsilon = 0.80$ to 0.82). All of the thermal paint coatings were very thin ranging from 0.28mm to 1.00mm in thickness. Of all the thermal paints the Thermal Paint 5 product was the thickest, and the emissivity of $\varepsilon = 0.72$ suggests an improvement in reflective properties. The EPS liner was much thicker (3.39mm) than all the other coatings.

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Coating	Thickness mm	Emissivity
Emulsion	0.07	0.85
Thermal Paint 6	0.28	0.89
Lining Paper	0.17	0.80
Thermal Paint 4	0.28	0.88
Textured Vinyl	0.88	0.82
Thermal Paint 3	0.55	0.86
Thermal Paint 2	0.37	0.87
Thermal Paint 1	0.31	0.87
Thermal Paint 5	1.00	0.72
EPS + Liner	3.39	0.80

Table 2 Emissivity and thickness results at 16^{o}C

4.3 Discussion of Material Characteristics Results

X-ray diffractograms suggests that the insulating additive particles are a good match for Mullite $Al_6Si_2O_{13.}$ Mullite is a refractory ceramic with a high maximum use temperature of 1650^{o}C, high density 2800 kg/m^3 and a high thermal conductivity of about 6 W/(m·K). The powdered insulating paint additive appears to be air filled spherical Mullite particles. The bulk density of Additive 2 powder was found to be 393kg/m^3, which is not consistent with low density insulating materials which are normally less than <100 kg/m^3. The density is more characteristic of a lightweight masonry material such as aerated concrete.

Classification of cellular materials broadly divides them into closed cell and open cell structures. In closed cell structure the gas is kept inside the pores so the material presents a continuous solid phase and a discontinuous gaseous phase. An open cell structure is characterised by a continuously dispersed gas phase into the solid one. In practice materials often present intermediate structures

The Scanning Electron Microscopy examination of the thermal paint coatings generally shows that they exist as a mixture of spherical particles of additive embedded within a continuous, structure of fine, irregular shaped paint matrix material. It has been suggested that since the microscopic hollow ceramic spheres in thermal paint additives have been developed from nano technology, that they have a nano-pore structure, and that the pores may be evacuated. However, SEM indicates that the additives are predominantly micro-porous with pore sizes between 0.1 and 100 μm. Microscopy also suggests that although they appear to be closed cell, the particles of additive are not sufficiently robust to maintain a vacuum and are probably air filled.

Insulating paint additives are marketed as making almost any paint insulate, but the bulk density of the additive is high, and it appears to have an air filled micro-porous structure, which suggests that it is not a low thermal conductivity material.

The emissivity results demonstrated that thermal paint products are generally poor inhibitors of infrared radiant heat loss on indoor surfaces appropriate to domestic heating conditions. The surface

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emissivities of five of the six thermal paint and the emulsion paint coatings were only slightly less than the value of $\varepsilon = 0.9$ which is conventionally assumed for building materials (BRE, 2006), (BSI, 2007). Of all the thermal paints the thickest product, Thermal Paint 5, indicated a significant improvement in reflective properties ($\varepsilon = 0.72$) suggesting some potential for reduced radiant heat transfer. The conventional EPS liner was much thicker (3.39mm) than all the other coatings. Under ambient indoor residential conditions, none of the thermal paint coatings could be considered reflective or of low-e classification, comparable to aluminium foil ($\varepsilon < 0.1$). Consequently, the results suggest that emissivity is unlikely be a significant factor in the thermal insulation properties of thermal paints. Choice of colour is unlikely to improve this unless it can be demonstrated that it is reflective or of low-e classification.

Thermal paint coatings, emulsion and paper linings were found to be very thin, between 0.07 and 1mm thick. The EPS liner was much thicker at 3.39mm than all the other coatings. The thermal resistance R of a material is directly proportional to the thickness d and inversely proportional to thermal conductivity λ, ($R = d / \lambda$). On this basis the potential for any improvement in thermal resistance by thermal paints is limited by the thin coatings, usually less than 1mm thick, applied to indoor surfaces. The thicker EPS liner is likely to provide a significantly greater increase in thermal resistance.

The measurement of the thermal properties of the coatings has been described in the following sections.

5. Thermal Properties

The thermal resistance of the thin coatings on the skimmed plasterboard panels has been determined under steady state indoor conditions typical of a poorly insulated building under UK winter conditions. Separately, thicker samples of Thermal Paint 2 and its components of Additive 2 and Emulsion paint have been prepared, and the thermal conductivity measured.

5. 1 Method of Measurement

Determination of accurate thermal property data for individual component materials, using objective and traceable thermal measurement techniques, is important for the evaluation of the U-value of complex multi-material building elements. Steady state thermal property data determined by UK, European and international standard procedures under controlled laboratory conditions are an accurate and accepted means of determining energy savings in buildings. Results obtained under dynamic / cyclic conditions, or simulated solar irradiation can be misleading, especially if determined at temperatures that are inappropriate to indoor ambient conditions.

U-value measurements under steady state conditions on multiple layer building elements using a guarded or calibrated hot box apparatus are generally more time consuming and require larger samples than standard thermal resistance tests. Thermal resistance measurements by heat flow meter or guarded hot plate methods are usually quicker, more accurate and repeatable as the test sample is sandwiched between hot and cold metal plates, which can readily maintain constant temperature and heat flow conditions. U values determined for large test samples sandwiched between temperature controlled circulating air flow, are generally subject to larger errors in determining temperature difference and the heat flow through the sample.

In view of the large number of samples and tests examined in this project the thermal resistance or thermal conductivity of test samples was measured using a single specimen heat flow meter apparatus 305 × 305mm square, with an actual central measuring area of 105 × 105mm square. The heat flow meter method complies with test standards ISO 8301:1991/ BS EN 12667:2001 / BS EN 12664: 2001. The Thermal Measurement Laboratory is a UKAS accredited laboratory and a European Notified Body for the measurement of thermal resistance / thermal conductivity to EN

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12664 / 12667 and ISO 8301 / 8302. All calibrations were traceable to international standards. The documented in-house method “FOX304 Modified EN12664” used for the tests is accredited by UKAS.

The scope of the thermal resistance test standard EN12664:2001 includes test samples with resistances between 0.1 and 0.5 m²K/W. Test standard EN12667:2001 covers measurements for thermal resistances greater than 0.5 m²K/W. Since the thermal resistance of the rigid coated plasterboard composite samples was slightly less than, and in some cases slightly greater than, 0.5 m²K/W, the same procedure was followed for all the test samples using thermal contact sheets and surface thermocouples, in order to minimize errors arising from any flatness deviations and to maintain accurate repeatability of measurement.

An in-house method was developed for determining the increase in thermal resistance resulting from the application of thermal paints and coatings used on various substrates such as plasterboard. The increase was determined by measuring the difference between the measured thermal resistance of the substrate before and after coating, following conditioning to constant mass at 23°C / 50% rh, using the methods in standard test standards EN12664:2001 / EN12667:2001.

5.1.1 Thermal Resistance of Coated Panels

5.1.1.1 Thermal Resistance Test Samples

Ten panels of 300mm square plasterboard were cut from the same original stock board 12mm thick, after skimming the entire board with a nominal 2mm thickness of skim material. Table 1 gives descriptions of the coating samples tested as applied to the skimmed 12mm plasterboard samples, including information about how the products were applied, before re-conditioning to constant mass at 23°C and 50% RH. The coatings were applied using a standard paint brush according to the instructions on each of the products packaging.

Before testing the uncoated and coated samples they were conditioned to constant mass at 23°C and 50% RH, according to BS EN 12429:1998**.** Mass equilibrium is considered to have been established when the change in mass of the test specimen over a 24 hour period is less than 0.05% of the total mass.

5.1.1.2 Thermal Resistance Measurement

The thermal resistance of each test panel was measured using a single specimen heat flow meter apparatus 305 × 305mm square, with an actual central measuring area of 105 × 105mm square. Documented in-house procedure “FOX304 Modified EN12664” was followed. The heat flow meter method complies with test standards ISO 8301:1991/ BS EN 12667:2001 / BS EN 12664: 2001. The Thermal Measurement Laboratory is a UKAS accredited laboratory and a European Notified Body for the measurement of thermal resistance / thermal conductivity to EN 12664 / 12667 / ISO 8301 and ISO 8302.

Measurements were conducted under steady state conditions, in line with UK and European procedures, which is an accepted way of evaluating heat loss savings in buildings. The literature on environmental conditions in buildings located in UK climates was reviewed in order to develop a suitable test temperature regime of a poorly insulated building under winter conditions.

5.1.1.3 Internal Test Temperature Condition

The Warm Front Study Group provided one of the most comprehensive sets of dwelling-related humidity and mould data for low income English homes in urban areas (Oreszczyn et al, 2006). The

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survey of living rooms in more than 3,000 dwellings, over the winters of 2001-2 and 2002-3, was based on the daytime hours of 8 a.m. to 8 p.m, during the heating period. The median standardised living room temperature was 19.1°C, with 90% of the dwellings between 13.5 to 23.0°C.

The Welsh School of Architecture (Jian et al, 2015) carried out a household monitoring study of 99 dwellings in Wales, in the heating season of 2013-14. The internal conditions were monitored in hard-to-heat, hard-to-treat houses during the winter. It was found that 87% of spot-measured indoor air temperatures were in the range 19 ± 3°C.

The studies by Warm Front and WSA provide a realistic base on which to model indoor conditions for low income housing stock during the winter. Public Health and World Health Organisation recommend maintaining a minimum indoor air temperature of 18°C for healthy sedentary occupants, and a minimum temperature of 20°C for rooms occupied by vulnerable groups (Wookey et al, 2014). A survey by (BRE, 2013) derived a mean dwelling temperature of 19°C during the heating season (October to April).

For test purposes a simulated steady state air temperature of 19°C has been taken to represent indoor conditions.

5.1.1.4 External Test Temperature Condition

International standard (BS EN ISO 13788, 2012), for the calculation of surface temperatures and mould growth, requires monthly mean values of external temperature derived from national standards. Table D.1 in (BSI, 2011) summarizes long term mean temperature and relative humidity for London, Manchester and Edinburgh. The values are considered to be appropriate for assessing the risk in most buildings if a correction of -1°C is applied to the mean temperature to allow for the worst climate to occur in 10 years. Based on the data in Table D.1 for the winter months, a temperature of 4°C is assumed to represent external conditions. A cold plate temperature of 4°C has been applied for test purposes.

5.1.1.5 Thermal Resistance Test Stages

Test samples of skimmed plasterboard (with and without coatings as in Table 1) were attached to a retained 25mm rigid sample of honeycomb insulation board of well-established constant thermal resistance, to give a total sample thermal resistance of about 0.465 m²K/W. The effective U value of about 1.6 W/m^{2}K, including the air surface resistances, is similar to that for poorly insulated external building elements such as double leaf solid brick wall typical of older terraced housing in the UK.

Consider the temperatures of an uninsulated plastered double brick wall having a U-value of about 1.6 W/m²K under steady state winter conditions. For an indoor air temperature of 19°C and outdoor temperature 4°C, the plaster surface temperature would be depressed below that of air to some temperature between 16 and 17°C, depending on surface resistance values.

Three stages of thermal resistance tests were performed at a constant temperature difference on each of the ten test samples under the following temperature regimes:-

1) Skimmed plasterboard (uncoated) / 25mm retained insulation rigid board - cold face 4 ± 0.2°C, hot face in the range 16.5 ± 0.5°C.
2) Coated skimmed plasterboard / 25mm retained insulation rigid board - cold face 4 ± 0.2°C, hot face in the range 16.5 ± 0.5°C.
3) 50mm air space / coated skimmed plasterboard / 25mm retained insulation rigid board - cold face 4 ± 0.2°C, air temperature in the centre of the air space maintained constant in the

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range 19.2 ± 0.2°C. This resulted in plasterboard surface temperatures in the range 16.3 to 17.1°C, depending on the degree of additional thermal resistance from the coatings.

Under these conditions the mean temperature of the test samples was maintained in the range 10.3 ± 0.3°C. It is estimated that the variation of thermal conductivity with temperature is < 0.1% for a 0.3°C temperature change, which is negligible compared to the accuracy of measurement.

5.1.1.6 Experimental Procedure

Thin calibrated thermocouples (0.2mm thick junctions) were attached to the faces of the sample to measure temperature difference. 3mm thick foamed silicone rubber contact / interface sheets were used to establish good thermal contact between the sample and the test plates. All temperature, dimensional and heat flow measurements were traceable to national standards. The laboratory / apparatus is accredited by UKAS for the documented in-house method "FOX304 Modified EN12664".

EN 12664 specifies that for sample thermal resistances of less than 0.3 m^2K/W, or if a rigid sample is not sufficiently flat, thin contact sheets of an adequately compressible material shall be inserted between the sample surfaces and the plates of the apparatus to establish good thermal contact between them, and minimise errors arising from deviations from flatness. The thin sheets also insulate electrically the thermocouples which are placed on the specimen surfaces to determine the temperature difference.

Deviations from sample flatness means there is potential for small air gaps between sample surfaces and plate surfaces, which would be included in the thermal resistance measurement. For example, a rigid sample of thermal resistance 0.5 m^2K/W with a 0.1mm continuous air gap, could result in a 0.8% increase in the apparent thermal resistance. The use of compressible contact sheets reduces the potential for contact errors on rigid materials. Imperfect contact/contact sheet errors associated with the same sample, are estimated to be less than 0.3%. The error can be further reduced by ensuring that thermocouple junctions are in good thermal contact with the sample surfaces by applying a small quantity of heat sink compound.

The contact sheet procedure was followed for all thermal resistance measurements, where test sample surfaces were in contact with the plate surfaces, to minimise the potential for comparative errors between the samples. The composite sample is shown in Figure 15 being assembled in the heat flow meter apparatus, with thermocouples on both faces and contact sheet on the hot plate. When fully assembled with a contact sheet on the cold plate the clamping pressure of the apparatus (7kPa) is applied. This pressure has been shown by measurements using a Guarded Hot Plate at the same pressure to achieve the required surface contact between apparatus surface, thermocouples, thermal contact sheets and specimens.

Figure 15 Composite sample being assembled in the heat flow meter apparatus, with thermocouples on both faces and contact sheet on hot plate

Using the contact sheet procedure, repeatability errors for the thermal resistance of the ten skimmed plasterboard samples cut from the same parent board, were reduced to less than 0.4% (see Figure 16). Similarly, repeatability errors for each of the three stages of thermal resistance measurement were less than 0.4%.

Stage 3 type measurements were conducted in the horizontal heat flow mode and included the effects of air surface layer adjacent to the coating in order to determine any effects of surface emissivity on radiant exchange. The procedure involved maintaining a mean temperature of about 19°C in the center of a 50mm air space adjacent to the surface of the coated composite sample. In effect a half cavity (25mm airspace) was included in the measured thermal resistance of the composite. Unventilated normal (high) emissivity air spaces, with horizontal heat flow in wall constructions, are conventionally taken to have a resistance of 0.18 m^2K/W. Thus, if the thermal resistance of a half cavity is significantly greater than 0.09 m^2K/W then it is likely that radiant exchange is reduced by low surface emissivity effects.

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5.1.2 Thermal Conductivity Measurements of the Components of Thermal Paint 2

Derivation of the thermal conductivity of the coatings from the measured thickness d and the thermal resistance of the coating $R_{coating}$ was found to be unrealistic, since the derived coating conductivity would be subject to further large errors in the thickness. Coating thickness values were very small, usually less than 1mm, and repeatability errors in measuring the difference between the thickness before and after coating was found to be less than 0.1mm. Consequently, the thermal conductivity was determined on larger thicknesses of the components of Thermal Paint 2, prepared in the laboratory i.e.. 24.4mm Additive 2, 3.3mm Emulsion Paint layer, and 21.9mm of a mixture of Emulsion Paint and Additive 2.

5.1.2.1 Experimental Procedure

The test methods of EN12664:2001 as described in section 5.1.6 were used to measure thermal conductivity.

In order to obtain a realistic thermal conductivity sample of Thermal Paint 2 a 22mm × 220mm square sample of powdered insulating paint Additive 2 mixed in standard Emulsion was cast in a 21mm deep extruded polystyrene frame of external dimensions 300mm square and allowed to cure. The thermal resistance of emulsion was obtained on a 3.3mm coating by building up in layers on a 26mm rigid structural sandwich panel of known resistance and stability. The increase in thermal resistance and thickness of the composite panel was used to determine the thermal conductivity of emulsion. The rigid samples were machined flat and parallel and then conditioned to constant mass at 23°C / 50% RH before testing at a mean temperature of 16°C.

The thermal conductivity of the 24.4mm sample of loose fill Additive 2 was sealed in a vapour proof plastic envelope and tested at mean temperatures of 10, 16, 22°C, thereby covering the possible range of conditions likely to be present on wall surfaces in dwellings. The powdered Additive 2 was very compressible which resulted in good thermal contact being maintained during test.

5.2 Thermal Properties Results & Discussion

5.2.1 Thermal Resistance of Coatings

The results for thermal resistance tests at stages 1, 2 and 3, coating thicknesses and the emissivity of the ten samples are given in Table 3. Also included are the derived resistance increase for the coatings and the coatings plus air surface layer, and the relative increases compared to standard emulsion.

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Coating	**Thickness mm**	**Emissivity**	**Thermal Resistance m²K/W**						
			Skimmed Board (Stage 1)	**Coated Board (Stage 2)**	**Coating Only**		**Coated Board + Air Surface (Stage 3)**	**Coating + Air Surface**	
					Increase compared to skimmed	**Increase compared to emulsion**		**Increase compared to skimmed**	**Increase compared to emulsion**
Emulsion	0.07	0.85	0.466	0.464	-0.001	0.000	0.557	0.091	0.000
Thermal Paint 6	0.28	0.89	0.465	0.467	0.003	0.004	0.556	0.091	0.000
Lining Paper	0.17	0.80	0.466	0.470	0.003	0.004	0.563	0.097	0.006
Thermal Paint 4	0.28	0.88	0.465	0.469	0.004	0.005	0.559	0.094	0.003
Textured Vinyl	0.88	0.82	0.464	0.470	0.006	0.007	0.563	0.099	0.008
Thermal Paint 3	0.55	0.86	0.464	0.471	0.007	0.008	0.561	0.097	0.006
Thermal Paint 2	0.37	0.87	0.463	0.470	0.007	0.008	0.561	0.098	0.007
Thermal Paint 1	0.31	0.87	0.463	0.473	0.010	0.011	0.561	0.097	0.006
Thermal Paint 5	1.00	0.72	0.464	0.488	0.024	0.025	0.581	0.117	0.026
EPS + Liner	3.39	0.80	0.463	0.574	0.112	0.113	0.667	0.204	0.113

Table 3 Thermal resistance / thickness and emissivity results

The overall uncertainty associated with absolute measurement using the heat flow meter apparatus according to the test standards was estimated to be ± 2.5%. However, due to the tightly controlled hot and cold plate temperatures of ± 0.01 to 0.2°C, the repeatability uncertainty of thermal resistance measurement was much less.

The repeatability errors for the thermal resistance of the ten skimmed plasterboard samples cut from the same parent board, were found to be reduced to less than 0.4% by using the contact sheet / surface thermocouple method (see Figure 16). Similarly, the repeatability was less than 0.4% for each of the three stages of thermal resistance measurement, where contact sheets were also used.

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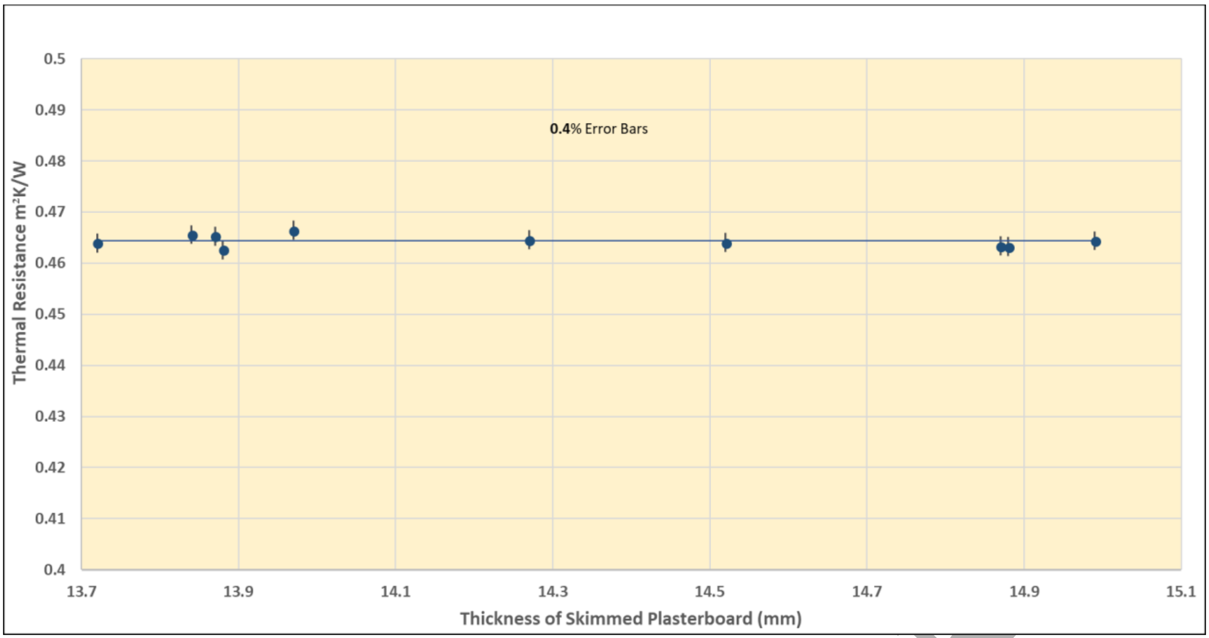

Figure 16 Thermal resistance of composite of skimmed plasterboard samples + 25mm rigid retained sample

The increase in thermal resistance in rank order for all the coatings compared to standard emulsion is shown in Figure 17.

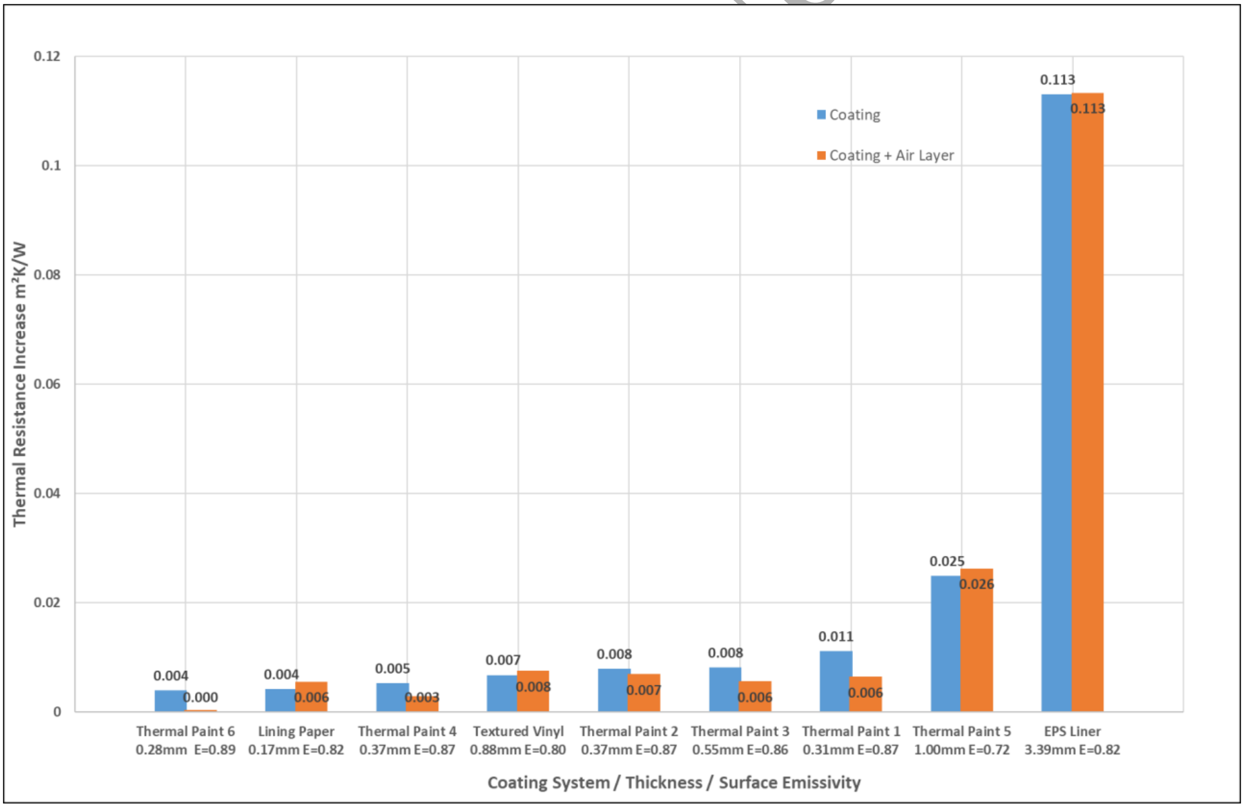

Figure 17 Thermal resistance of coatings compared to emulsion

The increase in thermal resistance for thermal paint coatings less than 0.55mm thick, as well as the for the wall paper linings, was found to be very small ranging from 0.004 to 0.011 m²K/W. When the increases are used in conjunction with other materials which provide the bulk of insulation in a building element, the improvements in the overall thermal insulation levels were not significant. For example, compared to the resistance of a poorly insulated structure of U value 1.6 W/m²K the relative improvement would only be about 0.6 to 1.8%. See Figure 18. The percentage improvement becomes progressively smaller as insulation levels increase and the U value decreases.

For larger coating thicknesses of 1.00mm for Thermal Paint 5, and 3.39mm for EPS liner, the thermal resistance increase is more significant at 0.025 and 0.113 m²K/W respectively. These correspond to relative increases of 4.0% and 18.1% for the above structure. Thermal Paint 5 is applied in a paste like form, which results a thicker coating than for the other thermal paints.

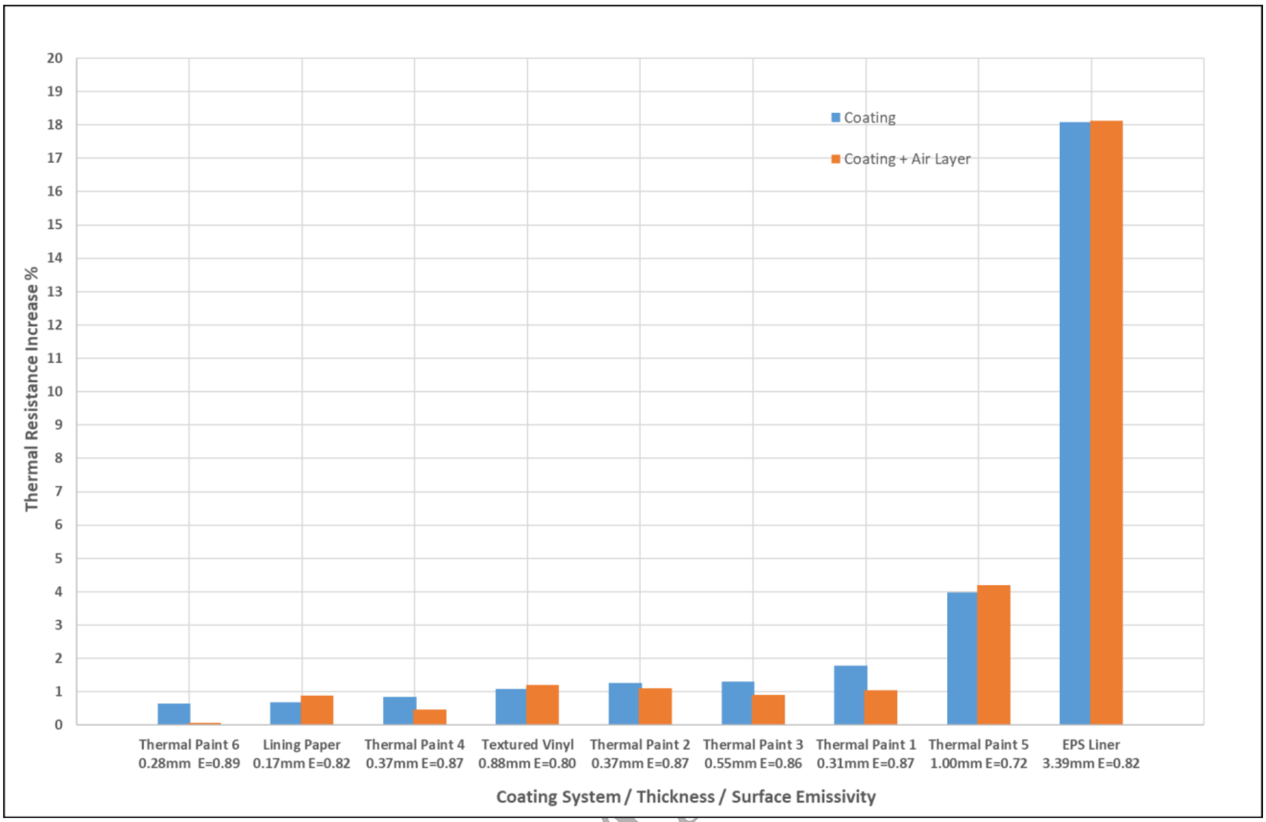

Figure 18 Percentage Increase in thermal resistance for a structure U value 1.6m²K/W

The repeatability was less than 0.4% for each thermal resistance measurement using contact sheets. Since the derived coating thermal resistance is the small difference between two large measurement results (before and after coating the boards), the resultant coating resistance is subject to a large error. This is particularly true for the low resistance coatings (excluding Thermal Paint 5 and the EPS liner).

For low resistance coatings, the combined error for the difference between the uncoated and uncoated boards is estimated to be 25 to 90%, increasing with decreasing levels of coating thermal resistance. For example, allowing for the potential uncertainties the thermal resistance of Thermal Paint 1 can be said to be in the range 0.008 to 0.014 m²K/W. For Thermal Paint 6 with the smallest coating resistance, the range would be within 0.000 to 0.008 m²K/W. Generally, for the majority of thermal paints the derived coating resistance was found to represent an almost insignificant improvement. The absolute value of the increases cannot be expressed with a great degree of confidence. However, in the case of the higher resistance coatings EPS liner and Thermal Paint 5, it is estimated that the uncertainties associated with the coatings were significantly more acceptable at 3% and 11% respectively.

Overall, the results show a general increase in thermal resistance with increasing thickness of coating, when compared to a much thinner layer of emulsion paint. This provides some validation for the method of measuring boards before and after coating, but due regard must be given to the potential uncertainties in the results.

The thermal resistance of the air surface layer $R_{s,}$ was determined from the difference between the mean airspace temperature T_a and the coating surface temperature T_s, and heat flux φ, where:

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$$R_s = (T_a - T_s)/\varphi \tag{6}$$

Unventilated cavities 50mm wide with normal (high) emissivities and horizontal heat flow in wall constructions, are conventionally taken to have a resistance of 0.18 m²K/W (BRE, 2006), (BSI, 2007). If the thermal resistance of a half cavity is greater than 0.09 m²K/W then it is possible that surface emissivity effects are contributing to reducing radiant exchange. As shown in Table 4, there was a general trend for the derived value of R_s to increase with decreasing emissivity. R_s was found to increase marginally above 0.09m²K/W for coating surface emissivities less than 0.85. For Thermal Paint 5 (ε =0.72) an increase in R_s to 0.094 m²K/W was determined.

Coating	**Thickness d mm**	**Thermal Resistance of Coating** $R_{coating}$ **m²K/W**	**Emissivity ε**	**Thermal Resistance of Air Surface Layer** R_s **m²K/W**
Emulsion	0.07	-0.001	0.85	0.092
Thermal Paint 6	0.28	0.003	0.89	0.089
Lining Paper	0.17	0.003	0.80	0.093
Thermal Paint 4	0.28	0.004	0.88	0.090
Textured Vinyl	0.88	0.06	0.82	0.093
Thermal Paint 3	0.55	0.007	0.86	0.090
Thermal Paint 2	0.37	0.007	0.87	0.091
Thermal Paint 1	0.31	0.010	0.87	0.088
Thermal Paint 5	1.00	0.024	0.72	0.094
EPS + Liner	3.39	0.112	0.80	0.093

Table 4 Emissivity and surface resistance results

Conventional values for surface resistance R_{si} of walls adjacent to the internal environment of a large volume room are taken to be 0.13m²K/W using BR 446 (BRE, 2006). Although the stage 3 type surface resistance values R_s measured in this project are in a more restricted air space of 50mm, they are still representative of the relative changes with surface coating emissivity. The changes in R_s were largely insignificant and did little to contribute to the effective resistance of surface coatings. None of the coatings qualified as low emissivity surfaces.

A low-emissivity surface (e.g. aluminium foil) reduces the radiation transfer across an airspace so that the airspace has a higher thermal resistance compared to one bounded by surfaces of normal (high) emissivity. Subsidiary tests in this study, with a low emissivity (ε < 0.1) aluminium foil covered plasterboard, were found to support this indicating a significant change in the R_s value to 0.26 m²K/W. For foil-faced products, with the foil adjacent to an unventilated airspace of width at least 25 mm, the conventional airspace thermal resistance for heat flow horizontal (wall applications) is accepted to be 0.44 m²K/W again using BR 446 (BRE, 2006) which implies a half cavity resistance of 0.22 m²K/W.

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5.2.2 Thermal Conductivity of Additive 2 and Emulsion Paint Mixture (Thermal Paint 2)

The thermal conductivity results at a mean temperature of 16°C for the Emulsion, Thermal Paint 2 mixture and Additive 2 are summarised in Table 5.

Coating	**Thickness d mm**	**Thermal Resistance m^2K/W**	**Mean Temperature °C**	**Thermal Conductivity W/(m·K)**	**Density Kg/m^3**
Emulsion	3.26	0.00518	16.0	0.63	1610
Thermal Paint 2 Emulsion & Additive 2 mixture	21.88	0.0455	16.1	0.481	1330
Additive 2	24.4	0.214	16.0	0.114	393

Table 5 Thermal conductivity results on Thermal Paint 2 and components at 16°C

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The results for the thermal conductivity of the sample of loose fill Additive 2 tested at mean temperatures of 10, 16, 22°C, are shown in Figure 19.

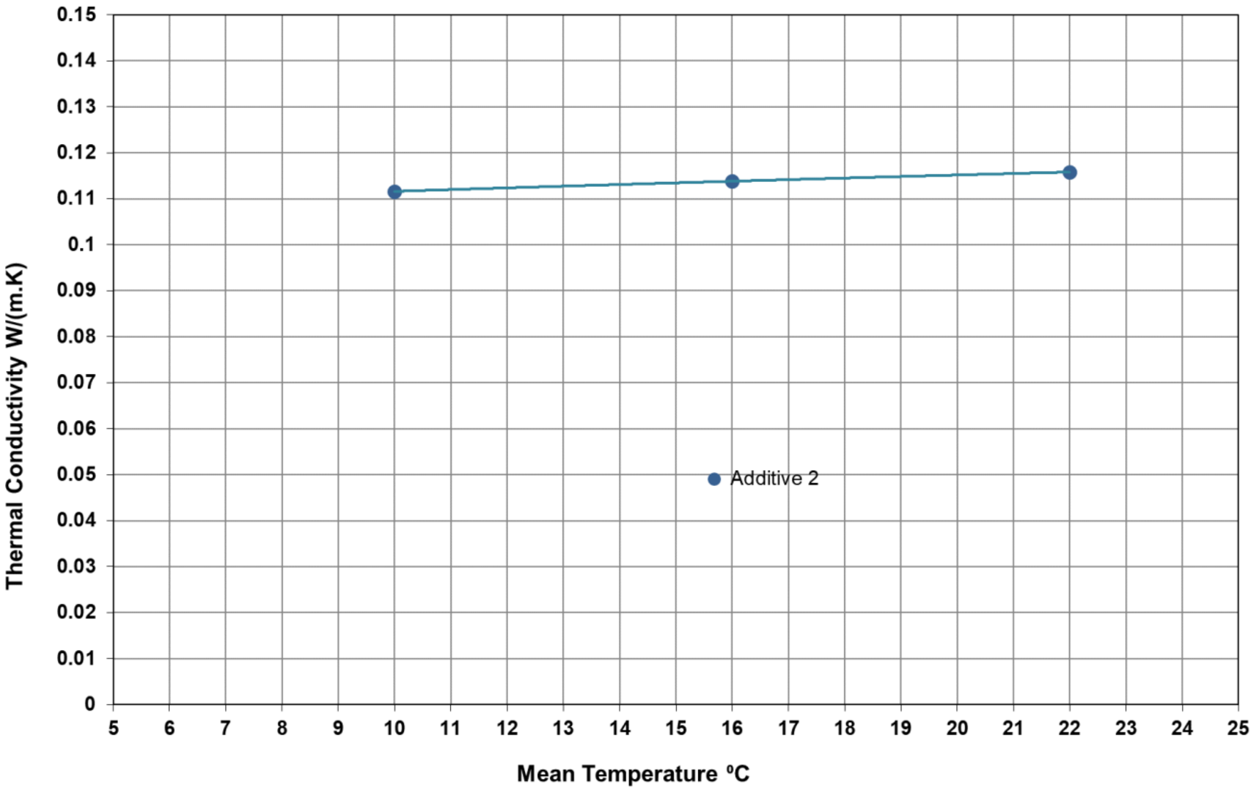

Figure 19 Thermal conductivity of Powdered Insulating Paint Additive 2

Both the density ($393kg/m^3$) and thermal conductivity (0.114W/(m·K) at 16°C) of powdered insulating paint Additive 2 were found to be much higher than those normally associated with conventional insulants, usually in the range $<100kg/m^3$ and <0.06W/(m·K). The high density and the thermal conductivity properties are more characteristic of aerated concrete than of a low density insulation material. Effectively this means that the conductivity at a surface temperature of 16°C of any mixture of Additive 2 and paint must always be greater than 0.114W/(m·K), as the density and

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thermal conductivity of the paint matrix will always be greater. This limits the resistance of thin thermal paint coatings containing the additive.

For comparison the EPS liner, which had a thickness of 3.4mm, a more appropriate thermal conductivity value of about 0.03W/(m·K) was determined from the data in Table 4. Consequently, the insulating performance of an EPS liner of equivalent thickness is likely to be about four times that of any paint coating containing additive. Insulating paint additives are marketed as making almost any paint insulate, but the results clearly show that potential for any improvement is very limited due to the high conductivity of the additive.

The following two theoretical modelling assumptions have been applied to the thermal conductivity results.

Assumption 1 – Air pore inclusions dispersed in a paint matrix. The theoretical λ / density relationship for Thermal Paint 2 mixture of Additive 2 + Emulsion, in Figure 20, is based on the models of Maxwell-Eucken (upper limit) and Brailsford & Major (lower limit), for a matrix of density 1610kg/m³ and λ=0.63W/(m·K), containing air filled pore inclusions of at least 10µm in size where $\lambda_{air} =$ 0.0254W/(m·K).

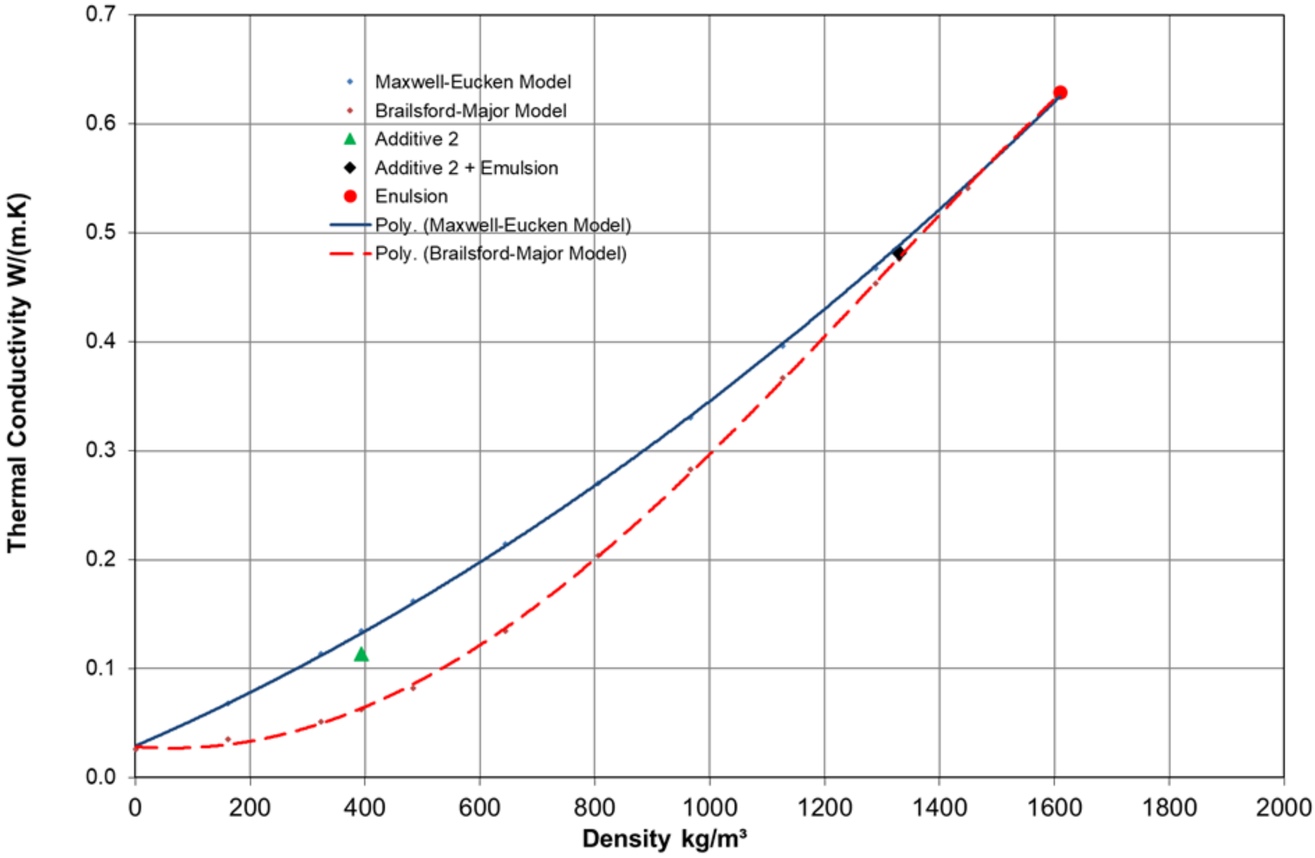

Figure 20 Thermal conductivity vs density of a mixture of Emulsion and Additive 2. Theoretical models assuming air filled pores > 10 µm.

The thermal conductivity of the Thermal Paint 2 mixture falls within the bounds of the two models. The result for the Additive 2 falls roughly midway between the bounds, consistent with the microscopic hollow ceramic spheres in the additive being air filled.

The thermal results and microscopic evidence do not support the claim that the hollow ceramic spheres maintain a vacuum. For evacuated beads where $\lambda_{air} \rightarrow 0$, the predictions would place the experimental result for the thermal conductivity of Additive 2 outside of the bounds of the Maxwell-Eucken / Brailsford-Major models. Contrary to the claims of some suppliers, there is no evidence of the ceramic beads being evacuated. Even if the beads were evacuated it would have little effect on the thermal conductivity of the mixture of additive and emulsion, as the high density and thermal conductivity of the continuous solid components would tend to dominate the thermal field within the mixture.

Furthermore, microscopic analysis indicates little evidence of a nano-porous structure (<1μm), and there is unlikely be suppression of the thermal conductivity of the air within the pores to below that of still air.

Assumption 2 – A lumped parameter assumption for insulating additive inclusions dispersed in a paint matrix. The theoretical λ / density relationship for Thermal Paint 2 composite in Figure 21 is based on the models of Maxwell-Eucken (upper limit) and Brailsford & Major (lower limit), for a matrix of density 1610kg/m³ and λ=0.63W/(m·K), containing Additive 2 inclusions (density 393kg/m³ and λ 0.114W/(m·K).

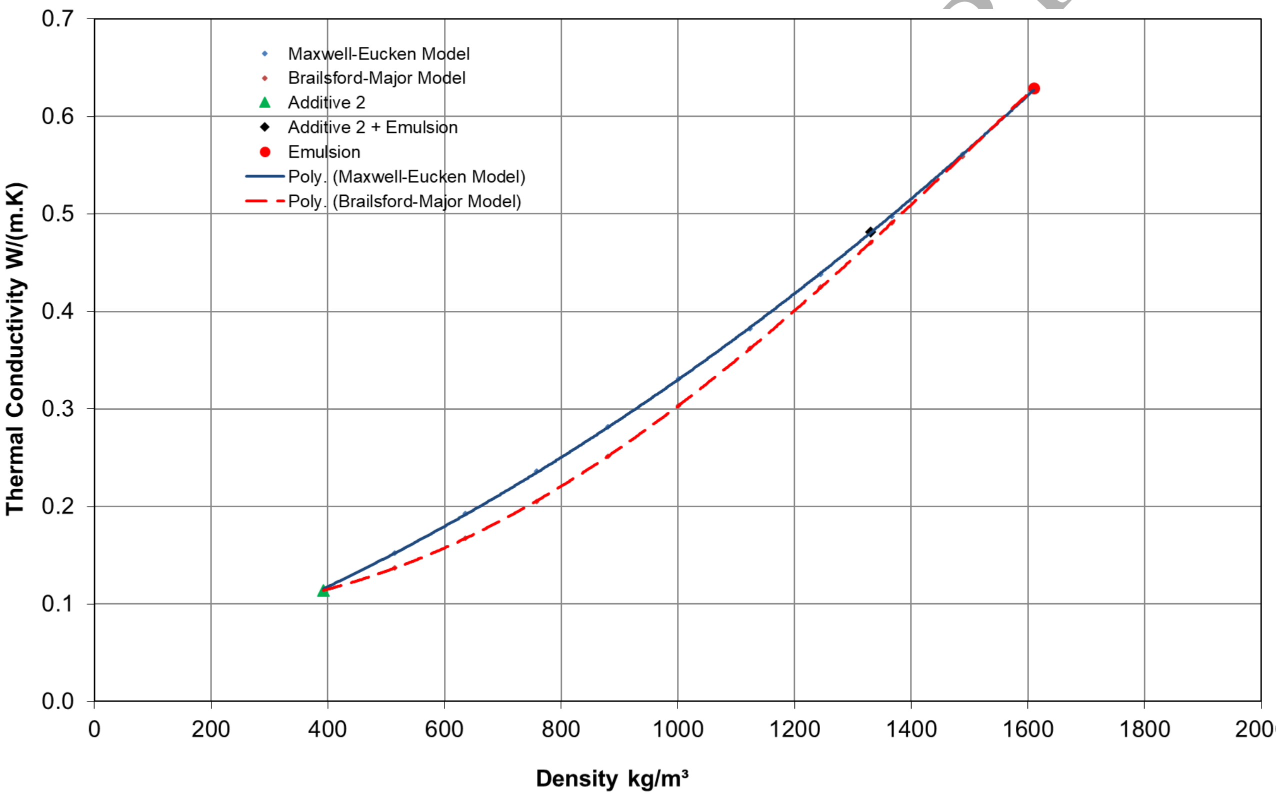

Figure 21 Thermal conductivity vs density of a mixture of Emulsion and Additive 2. Theoretical models assuming Additive 2 inclusions.

The theoretical predictions of thermal conductivity from both Maxwell-Eucken and Brailsford-Major models, as well as the mean of the two models, are summarised in Table 6 for the two assumptions for dispersed phase inclusions. The mean result of the Maxwell-Eucken and Brailsford- Major models has been included as it should provide a more realistic model intermediate between the upper and lower cases of i) inclusions dispersed in continuous paint phase and ii) inclusions and paint phase embedded in a mixture having the λ of that being calculated.

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Assumption for Dispersed Phase inclusions in continuous phase of Emulsion Paint Density = 1610kg/m^3 λ = 0.63W/(m·K)	**Model Predictions**			**Experimental**
	Maxwell-Eucken (inclusions dispersed in continuous paint phase) W/(m·K)	**Brailsford-Major (inclusions and paint phase embedded in a mixture having the λ of that being calculated) W/(m·K)**	**Mean Maxwell-Eucken & Brailsford-Major W/(m·K)**	**Thermal Paint 2 (Mixture of Emulsion & Additive 2) W/(m·K)**
Assumption 1) - Air filled pore inclusions > 10μm. Density = 1.2kg/m^3 λ_{air} = 0.0254W/(m·K)	0.487	0.476	0.481	0.481
Assumption 2) -Additive 2 inclusions. Density= 393kg/m³. λ = 0.114W/mK)	0.479	0.471	0.475	0.481

Table 6 Thermal conductivity model predictions and results on Thermal Paint 2 at 16°C

It is evident that there is good agreement of less than 1.3% between the experiment and the more realistic mean model for both sets of assumptions for the dispersed phase inclusion. The agreement is well within experimental uncertainty. This not only gives credence to the accuracy of measurement but provides a good model by which the thermal conductivity of thermal paint mixtures may predicted, given that the conductivity and density of the components are known, whether it is assumed that the dispersed phase inclusions are air filled pores or insulating additive.

If air filled pore inclusions are assumed, knowledge of the pore sizes and the effective thermal conductivity of the air component, along with the conductivity and density the paint matrix would be required in order to predict the performance of the thermal paint mixture at any given proportions and resultant density.

For a lumped parameter assumption of dispersed insulating additive inclusions in the paint matrix, knowledge of the thermal conductivity and density of both insulating additive and the paint matrix would be required in order to predict the performance of the thermal paint mixture at any given proportions and resultant density.

For Thermal Paint 2 mixture it is clear that a nominal mixture of 21% additive by volume in emulsion paint only reduces the thermal conductivity by 24% from 0.630W/(m·K) to 0.481W/(m·K). It should be noted that even if the proportion of additive in the mixture was increased to nearly 100%, well in excess of the supplier’s instructions, the thermal conductivity could never be less than that of the additive. The high density and the thermal conductivity of the additive and the paint matrix restricts the performance of thermal paint mixtures to being in the range 0.114 to 0.630W/(m·K), whatever the proportions.

Thermal or insulating paint additives made up of microscopic hollow ceramic spheres, are claimed to make almost any paint or coating insulate. The experimental measurements show that the degree to which this can be achieved is clearly very limited and does not compare with the typical thermal conductivities <0.06W/mK and densities <100kg/m³ normally associated with conventional insulants. The thickness of Thermal Paint 2, on skimmed plasterboard, was a mere 0.37mm. Based on the thermal conductivity results for the mixture described above, this would equate to an insignificant coating thermal resistance of less than 0.001 m^2·K/W. This again underlines the poor

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insulation effectiveness of thermal paint coatings. The thermal conductivity of the paint mixture matches the theory, but the coatings are too thin and the thermal conductivity is too high to be effective.

Unfortunately, performance claims for insulating paint are frequently overestimated. The study by Azemati et al. (2013), for example, assumed a 0.4mm thick ceramic mineral paint coating has a thermal resistance of 1.06 $m^2 \cdot K/W$, which is about a thousand times greater than that obtained for the Thermal Paint 2 mixture with Additive 2 described above.

Marketing of thermal paints is generally sparing of published independent scientific evidence, frequently relying on non-standard methods of detection and anonymous customer testimonials. It has been shown that commercial claims for the additives creating an effective thermal barrier in thin coatings, reducing heating bills in buildings by 20 to 25% or more, are not substantiated by standard methods. A typical reduction in heat transfer through an external uninsulated solid brick wall for a thermal paint coating of up to 0.5mm thick is estimated to be nearer to 1%. The overall reduction in heating bills could be significantly less when heat losses from all the non-coated building elements are considered in the calculation.

6. Energy House Modelling of Energy and Cost Savings

Designbuilder has been used to create a model of the Energy House research facility, located at the University of Salford. The software is a dynamic energy simulation package based around the widely used Energy Plus application (Crawley et al., 2000), which conforms to EN ISO 13790:2008 (ISO, 2008) for calculations of energy for space heating. The facility houses a fully functioning, to scale, pre-1919 Victorian end terrace property within an environmentally controlled chamber. The solid brick building is split across two levels, with 7 windows (3 from bay window), 2 external doors, and suspended timber floors. A gas boiler has been installed in the Energy House to heat the building using a wet central heating system. Rigorous testing of the thermal properties of this building led to accurate calibration being carried out on the model of that building (Marshall et al, 2017) – with U-values of the external walls measured at 1.56W/m^2K. As such, the model is highly representative of the thermal performance of this type of domestic property in the field; accurate predictions of the thermal performance are therefore possible.

Potential savings for energy consumption and fuel cost have been predicted using this calibrated model. From that, further predictions of payback period have also been calculated, along with estimations of the required thickness of each coating material to achieve the same regulatory thermal resistance for new constructions. Annual simulations were performed in order to predict the total yearly energy consumption for space heating – a number of assumptions were made during this modelling exercise:

- Heating, occupancy and lighting schedules follow domestic schedules used by UK NCM (NCM, 2008). This is also used for the adjacent building.
- Location and weather data were representative of Manchester in the UK, the weather file is provided by ASHRAE’s IWEC (ASHRAE, 2002).
- Coatings were applied to all wall surfaces that make up the thermal envelope of the dwelling, including the party wall. The total covered wall area was 117.63m^2 across the entire building; this consisted of 27 individual surfaces around a total volume of 169m^3.
- U-values for external walls were recalculated using (BRE, 2006), by augmenting the existing calibrated values of thermal resistance with additional resistances as listed in Table 6.

The difference in energy consumption from the baseline model using emulsion coating only indicates the predicted savings for each subsequent coating type.

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Table 7 shows the predicted annual energy consumptions for space heating with each of the coatings, the respective fuel cost, savings relative to the baseline scenario, decorating cost and payback period. Note that payback period is rounded to the nearest 10 years.

Fuel costs were calculated using an estimated quote for gas from British Gas at 4.14p/kWh, priced as of 15/10/18 – costs exclude the standing charge. Decorating costs were advised using schedules of rate from BCIS Painting and Decorating Prices 2018 and average prices for thermal paint, lining paper, textured vinyl and EPS + Liner (£4.46/m^2, £0.27/m^2, £2.00/m^2, and £3.64/m^2 respectively).

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Coating	Space Heating Consumption (kWh/m^2/year)	Annual Heating Fuel Cost	Annual Energy Savings over Baseline	Annual Cost Savings over Baseline	Decorating Cost	Payback Period (Years)
Emulsion	127	£314.66	-	-	-	-
Thermal Paint 6	126	£313.57	0.35%	£1.09	£1,131.97	1040
Lining Paper	126	£311.99	0.85%	£2.67	£779.89	290
Thermal Paint 4	126	£313.20	0.46%	£1.45	£1,131.97	780
Textured Vinyl	125	£311.04	1.15%	£3.62	£983.39	272
Thermal Paint 3	126	£312.14	0.80%	£2.51	£1,131.97	450
Thermal Paint 2	126	£312.31	0.75%	£2.34	£1,131.97	480
Thermal Paint 1	125	£311.60	0.97%	£3.05	£1,131.97	370
Thermal Paint 5	123	£305.54	2.90%	£9.11	£1,131.97	124
EPS + Liner	116	£289.06	8.13%	£25.59	£1,176.30	50

Table 7 – Dynamic annual simulation results for each coating.

These predictions offer an unfavourable payback period for the majority of coatings. Coatings that are inherently thicker lend to better savings predictions (EPS + Liner), however, thermal paints and lining paper alone have relatively small savings. All predictions are based on the manufacturers' recommendations (two coats of thermal paint in each case).

The standards for new building elements as given in the UK government's L1B document for conservation of fuel and power in existing dwellings (HM Government, 2008) give a U-value of 0.28W/m^{2}K. The overall required thermal resistance is calculated to be 3.57m^{2}K/W, which is much greater than the 0.64m^{2}K/W measured for the external solid walls.

The required additional thermal resistance in all cases is much larger than the overall thermal resistance of external walls with each of the coatings. The model indicates that several hundred additional thermal paint applications, would be required to meet the recommendations of the current Building Regulations L1B document. The number of additional coatings of thermal paint would correspond to additional thicknesses of up to 200mm which is prohibitively expensive in terms of material cost, time and safety. The replenishment of the paints during its lifetime must also be considered as it increases the necessary cost.

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Conclusions

The six thermal paint products prepared to according to instructions on each of the products packaging did not show significant improvements in thermal insulation when compared to standard emulsion paint. Claims that insulating additive powders of microscopic hollow ceramic spheres can create an effective thermal barrier which significantly reduces heating bills in buildings, sometimes by as much as 20 to 25%, cannot be justified.

Objective standard thermal measurement techniques, combined with modelling on a solid wall Victorian end terrace dwelling, show that for five of the six products each containing hollow ceramic spheres as insulation additives, and coatings less than 0.55mm thick, energy savings are less than 1% when heat losses from all the building elements are considered. For a sixth product - a thicker coating of 1mm of paste containing hollow polymeric spheres - larger savings of 2.9% were predicted.

The increase in thermal resistance for thermal paint coatings less than 0.55mm thick, as well as the for the wall paper linings, was found to be very small ranging from 0.004 to 0.011 m²·K/W. For an uninsulated solid brick wall structure of U-value 1.6 W/(m²·K) the relative thermal resistance improvement of a coated wall would only be about 0.6 to 1.8%. For the thermal paint product with a larger coating thicknesses of 1mm, the thermal resistance increase was more significant at 0.025 m²K/W or an improvement of 4.0% when applied to the wall structure.

In general, the performance of the thermal paints was found to be not much better than that of conventional vinyl textured wallpapers and lining paper. However, a conventional 3.4mm EPS liner was found to be substantially more effective, with a thermal resistance increase of 0.113 m²·K/W corresponding to a relative increase of 18.1% for the above structure.

The surface emissivity results demonstrated that five of the thermal paint products were generally poor inhibitors of infrared radiant heat loss, no better than conventional building surfaces. The paste product with aerogel and glass micro spheres dispersed in an elastomeric polymer, indicated some improvement in reflective properties with an emissivity of 0.72, suggesting some potential for reduced radiant heat transfer. However, none of the coatings could be considered as low emissivity surfaces. Overall, the changes in the air to surface thermal resistance of the six products was insignificant and did little to contribute to the effective resistance of thermal paint coatings.

Thermal conductivity measurements on laboratory made thick specimens of one of the thermal paint products, as well as its additive and emulsion paint components, demonstrated the limited degree to which hollow ceramic sphere additives can make any paint or coating insulate. The high density (393kg/m³) and the thermal conductivity (0.114 W/(m·K)) of the additive was found to be more characteristic of aerated concrete, much higher than that normally associated with conventional insulants. Prepared according to supplier’s instructions, a mixture of 21% additive by volume in emulsion paint only reduces the thermal conductivity by 24% from 0.63W/(m·K) to 0.481W/(m·K). The thermal conductivity of any mixture of the additive and paint must always be greater than that of the additive, since the high density and thermal conductivity of the paint matrix will tend to predominate. X ray analysis of the powdered insulating paint additive shows that it is air filled spherical Mullite particles, a high thermal conductivity refractory material. The refractory properties of the additives may be valuable in the aerospace industry, but this is not of primary importance in built environments

Theoretical models of porous or multi-phase materials have been applied to the thermal conductivity results. Given accurate data for thermal conductivity and density of the components, the performance of the paint mixture matches the theory, but the coatings were found to be too thin and the thermal conductivity too high to be effective thermal barriers. The evidence from the measurements and models, as well as scanning electron microscopy, do not support commercial

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claims of insulation effectiveness, or that the hollow ceramic beads contain a vacuum or a nano-porous structure.

Effective energy saving application of thermal paint would require considerably more than the two coatings suggested by the instructions on each of the products packaging. It is counter-intuitive to expect that a thin thermal paint coating, typically a few tenths of a millimetre thick, would provide significant increases in thermal insulation levels. Thermal resistance is a measure of resistance to heat flow and if the thickness of a material is increased there is a corresponding increase in thermal resistance. The application of two coats is already a costly process and technically more difficult than conventional paint.

The criteria for selecting either thermal paint coatings or conventional insulation materials is the comparison of the price and the energy bill savings. Modelling predictions of energy and cost savings have been based on the Energy House Victorian end terrace property at the University of Salford. The results indicate an unfavourable payback period of several hundred years for the thermal paint coatings and conventional wall coverings. The only payback period within human life span was found to be 50 years for a 3.4mm thick EPS insulation liner. The model indicates that a considerable number of thermal paint applications would be required to meet the recommendations of the current Building Regulations L1B document. The number of additional coatings of thermal paint would correspond to additional thicknesses of up to 200mm which is prohibitively expensive in terms of material cost, time and safety.

Although the insulating properties of thermal paint coatings in heated buildings have been shown to be limited, it is recognised that the coatings do have advantageous properties. The small thermal resistance increase of internal thermal paint coatings in buildings provides potential for wall surfaces being slightly warmer by a fraction of a degree for longer than for conventional painted surfaces. This can de-risk the incidence of mould growth and possibly condensation in a building. Also, heat gain reductions can be significant when coatings are applied to sun-bathed surfaces as they can reflect solar energy from roofs and external surfaces, keeping buildings cooler and reducing air conditioning loads. In industrial and maritime environments, there are advantages in coating high thermal conductivity metallic surfaces and pipes where there is little inherent thermal resistance, reducing heat losses, maintaining safe surface temperatures, and minimising corrosion.

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