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DSC analysis for the evaluation of an energy storing wallboard[1]

D. Feldman*, D. Banu

Centre for Building Studies, Concordia University, 1455 de Maisonneuve Blvd. West, Montreal, Quebec, H3G 1M8, Canada

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Abstract

Sensible heat storage in building materials has been practiced for thousands of years. Recent work at the Centre for Building Studies of Concordia University on the incorporation of various phase change materials (PCMs) in gypsum wallboard has resulted in the addition of their latent heat values to the sensible heat storage value of wallboard. In this way its heat storage capacity can be increased by at least eightfold. PCM-wallboard development tests were conducted on a small scale using DSC analysis for selecting the PCMs; evaluating PCM-wallboard prototypes; to ascertain the reproducibility of PCM thermal characteristics in wallboard, to verify the spatial uniformity of PCM and to ascertain the effects of temperature cycling on the thermal characteristics of PCM-wallboard.

Keywords: DSC; Wallboard; Heat storage

1. Introduction

The concept of using building materials for thermal storage has been known for a very long time. However, the storage of heat in sensible form requires a large mass of a building material and prolonged excursions of temperature above and below the human comfort zone can render such a building extremely uncomfortable.

To solve this problem, the concept of using latent heat storage in building materials was introduced about 45 years ago [1]. This was achieved by the use of PCMs which

* Corresponding author.

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absorb heat in changing from the solid phase to the liquid phase and release it when going from liquid to solid. PCMs selected for thermal storage applications normally perform these functions within a few degrees and at an appropriate range in the temperature scale. The development of thermal storage is important for the following reasons:

- time shifting of maximum demand in energy supply systems which renders feasible the use of low-cost off-peak power;
- use of internal heat gain which would otherwise be wasted (e.g. from solar radiation, lights and appliances, periodic building load surges, etc.);
- improving the efficiencies of burners, chillers and heat pumps by the reduction of short cycle operation.

To provide a simple and relatively low cost thermal storage system, an energy storing building material was developed at the Centre for Building Studies of Concordia University by incorporation of a phase change material (PCM) in gypsum wallboard.

The reasons for selecting wallboard for thermal storage with PCMs were described elsewhere [2].

The selection of PCM in our study was directed towards the use of organic materials in an effort to avoid some of the problems inherent in inorganic materials such as the need for special containers due to their corrosivity, tendency of super-cooling, segregation, etc. Special attention has been given to the products separated from vegetable oils and fats produced from renewable sources.

Several desirable characteristics were considered when selecting these organic PCMs as the preferred area of research. These include: the required range of melting and freezing; high latent heat of transition; acceptable density, specific heat and thermal conductivity; little or no supercooling during freezing; chemical stability; melting/freezing point congruency; low vapor pressure at room temperature; non-toxicity.

Using DSC we have investigated many organic PCMs and those selected for further studies are shown in Table 1.

2. Experimental

PCM-wallboard samples were prepared on laboratory scale by immersion of a 20 cm ordinary wallboard square sample in a bath of melted PCM. The temperature of the PCM bath was constant (lower than 80°C) and the immersion time was correlated with the temperature of the bath.

Another method of obtaining PCM-wallboard samples was by the incorporation of PCM directly into the gypsum paste formulated as in the production of commercial wallboard. The resulting mixture was poured in a 20 × 20 × 1.2 cm mold between two sheets of paperboard and after stiffening and demolding, dried for 2 h at 105°C. Details regarding this method are given elsewhere [3]. The PCM loading was between 20 and 25% of the weight of wallboard.

The DSC measurements were performed using a 912 DuPont DSC provided with DuPont Mechanical Cooling Accessory and connected to a 2100 DuPont Thermal Analyst. DSC runs were carried out on about 5 mg specimens for PCMs and on about 20 mg specimens for PCM-wallboard in covered aluminum sample holders, in most cases at a heating/cooling rate of 2°C min^{-1}. The purge gas used was dry nitrogen at a flow rate of 20 ml min^{-1}.

Certified indium metal (American National Bureau of Standards) was used as standard for temperature and cell calibration at scanning rates of 2 or 0.2°C min^{-1}. For the DSC evaluation, 20 cm^2 samples of PCM-wallboard prepared at laboratory scale were cut in four 5 cm squares and each square was cut into three slices. Two specimens of 4 mm diameter (the same diameter as the DSC sample holder) were punched from each slice (specimen weight ~20 mg) and scanned on DSC in most of cases at a heating/cooling rate of 2°C min^{-1}. Then, when the desired characteristics were achieved, a test rate closer to the actual rise and fall of temperature normally experienced in buildings was used, i.e. 0.2°C min^{-1} for final tests.

The sources for all materials investigated as potential PCMs are shown in Table 1; except propyl palmitate which was synthesized in our laboratory, all the materials were commercial products and were used as obtained in all cases.

3. Results and discussions

DSC analysis was one of the important methods of testing in the development of PCM-wallboard. It was used for selecting the PCMs, evaluation of PCM-wallboard prototypes, finding out the reproducibility of PCM thermal characteristics in wallboard, verify-

Table 1
Final selection of PCM candidates

Candidate	m.p./°C	ΔH_m/J g^{-1}	Disposition	Reason for rejection
Polyglycol E 600 (Dow Chemical)	20	130	Rejected	Melting range too large
Alfol 12–dodecanol (Vista Chemical)	20	200	Rejected	Too flammable
Hexadecane (Anachemia)	19	230	Rejected	Too expensive
Eutectic capric–lauric acid Emery 659 (67%)–Emery 651 (33%) (Henkel)	20	137	Rejected	Oily exudation
Emery 659 (45%)–Emery 651 (55%) (Henkel) + 10% fire retarder	21	120	Rejected	Cannot be directly introduced into gypsum paste
Eutectic capric–palmitic acid Emery 659 (85%)–Emersol 6340 (15%) (Henkel)	21	150	Rejected	Quite strong odor
Coconut fatty acid Emery 626 (Henkel)	19	120	Rejected	Melting range too large
Propyl palmitate (synthesized in laboratory)	20	190	Rejected	Not on the market for the moment
Butyl palmitate (49%)			Accepted	
Butyl stearate 48%	17	140		
Emerest 2326 (Henkel)				

ing the spatial uniformity of PCM in wallboard and ascertaining the effect of temperature cycling on the thermal characteristics of PCM-wallboard. The evaluation process of PCM-wallboard began with DSC tests to ascertain the latent heats, melting and freezing points for the candidate PCMs and then for wallboard impregnated with these materials. These were followed by tests for thermal conductivity, thermal diffusivity, flexural strength and compatibility with selected wall covering, preliminary tests for flame spread and fire resistance and finally exposure to the effects of temperature cycling. From these tests only one PCM material from those presented in Table 1 was judged a worthy candidate for further development. This is Emerest 2326 a mixture of butyl esters of stearic and palmitic acids.

Figs. 1 and 2 present the thermal characteristics of PCM Emerest 2326 alone at a scanning rate of 2°C min^{-1} and 0.2°C min^{-1} and in Figs. 3 and 4 the thermal characteristics of wallboard loaded with 25.7% and 24.6% Emerest 2326 scanned at 2°C min^{-1} and 0.2°C min^{-1}, respectively.

From these figures it may be seen that the thermal characteristics of PCM-wallboard are very close to those of PCM alone and that there is no significant difference between the testing at scanning rates of 2°C min^{-1} and 0.2°C min^{-1}. As can be seen from Figs. 1–4, the melting and freezing curves are quite broad due to the impurities present in the commercial product. The entire latent heat is evolved in a quite large temperature interval. For a smaller temperature interval, i.e. 4°C which is of greater interest for thermal exchange, the evolved latent heat is lower and corresponds to the partial area of the entire curve in this temperature interval. The partial area, or the useful latent heat in a 4°C temperature interval, down from the melting or freezing point is about 70–72% of the total latent heat of freezing and about 65–67% of the total latent heat of melting as can be seen in the example presented in Fig. 4.

When a PCM impregnated wallboard is cut, it is to be expected that the greater concentration of PCM lies in the outer third of the wallboard thickness near each face, because of the diffusion process. The spatial distribution was evaluated from the ΔH_m and ΔH_f of DSC specimens obtained from the two 1/3 outer slices and the inner 1/3 slice cut as described above. The results are indicated in Table 2. From the data presented in Table 2 for a PCM-wallboard sample with 23.5% PCM loading, it can be seen that the average latent heat is 34.5 J g^{-1} for the edges samples and 28.4 J g^{-1} for the center samples. The difference in latent heats between the edge and center samples indicated that, as expected, outside edges absorbed more PCM than the interior portions of the wallboard. The average latent heat for all PCM wallboard samples, outer and inner slices, was 32.5 J g^{-1} for melting with a standard deviation of 3.07 J g^{-1} and a coefficient of variation of 9.4% and 32.2 J g^{-1} for freezing with a standard deviation of 3.18 J g^{-1} and a coefficient of variation of 9.8%.

DSC testing of less specimens from other samples with different PCM loading (always between 22 and 25%) gave similar results concerning PCM distribution and calculated versus experimental latent heat; the coefficient of variations of the average latent heats was never higher than 9.5%. DSC results for melting and freezing points were much closer for the specimens of the same samples or different samples. The average melting and freezing points were 17.0°C and 19.3°C respectively with a standard deviation of

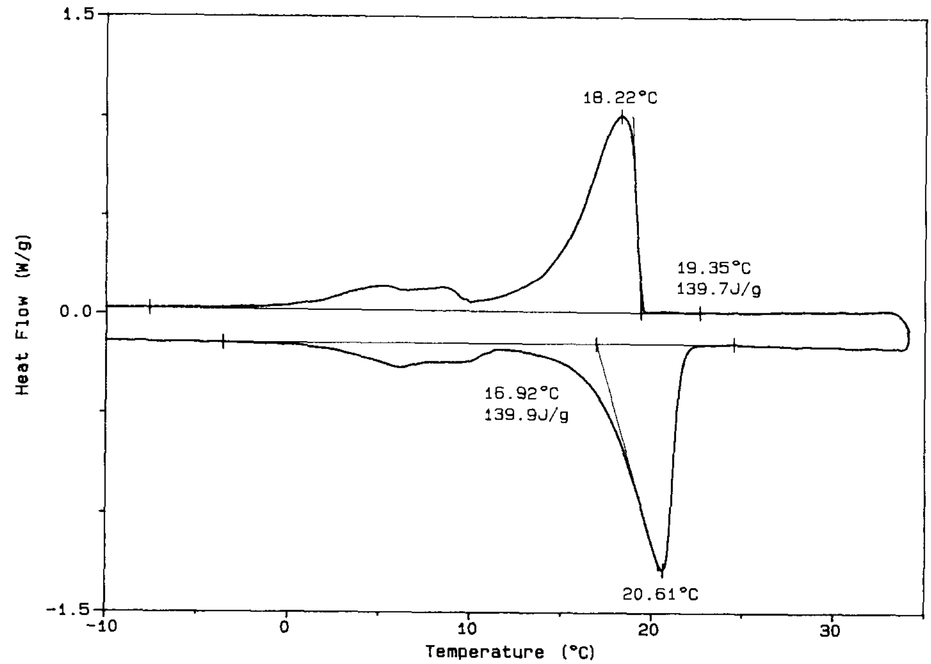

Fig. 1. DSC curve of Emerest 2326 scanned at 2°C min^{-1}.

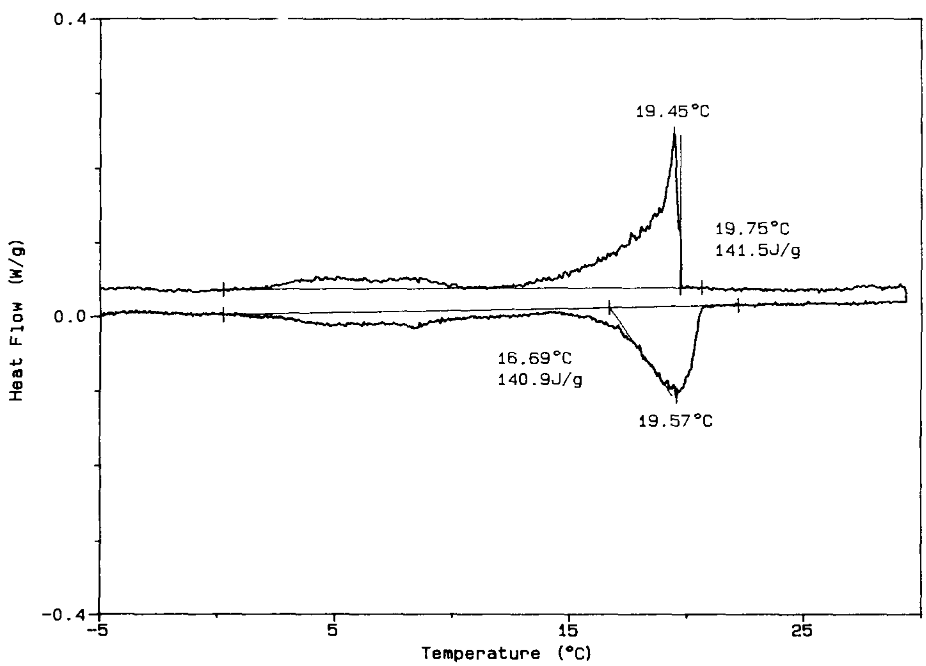

Fig. 2. DSC curve of Emerest 2326 scanned at 0.2°C min^{-1}.

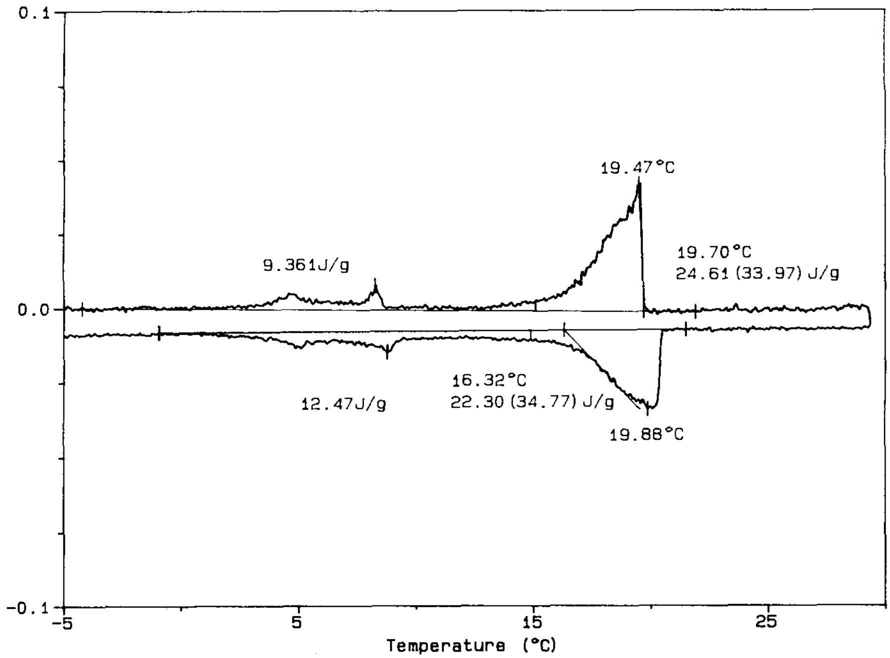

Fig. 3. DSC curve of PCM-wallboard scanned at 2°C min^{-1}; PCM, Emerest 2326; loading, 25.7%.

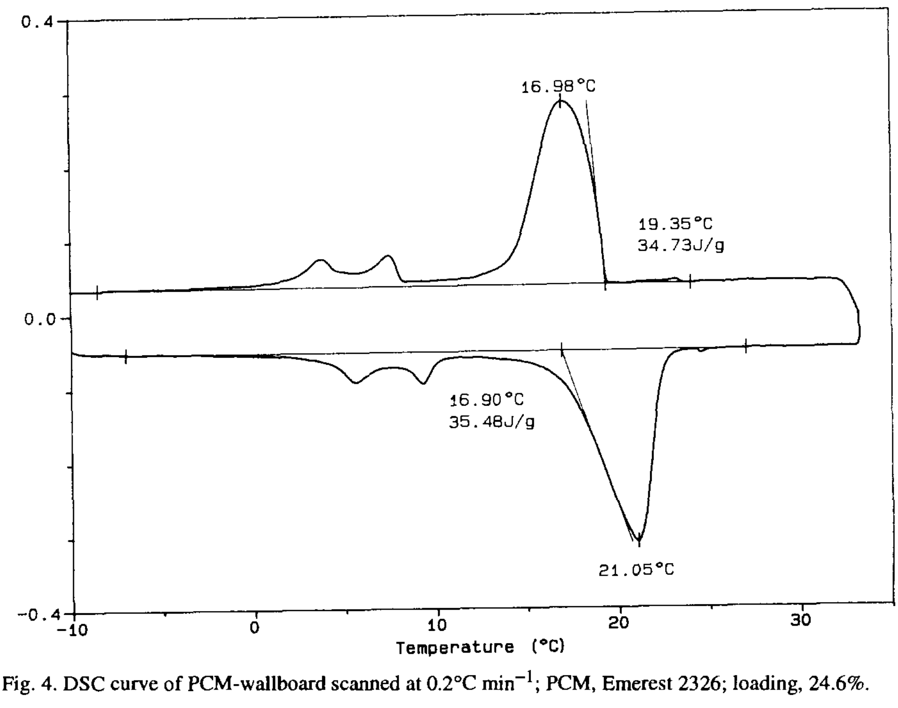

Fig. 4. DSC curve of PCM-wallboard scanned at 0.2°C min^{-1}; PCM, Emerest 2326; loading, 24.6%.

0.3°C and 0.4°C, respectively, depicting the accuracy of DSC tests for PCM-wallboard samples.

For samples obtained by direct incorporation of PCM into the gypsum paste, the values of ΔH_m and ΔH_f were very close for edge and center specimens indicating, as expected, an even distribution of PCM in wallboard. Average melting and freezing points were the same as in samples obtained by immersion.

The effect of temperature cycling on the thermal characteristics of PCM-wallboard was ascertained also by DSC analysis after about of 400 temperature cycles between −28 and 32°C. The cycling frequency was 4 cycles per day which corresponds to a heating or cooling rate of about 0.2°C min^{-1}. DSC analyses indicated that more than 400 freezing-melting cycles did not affect the thermal characteristics of PCM in wallboard. The values of the melting and freezing points were practically unchanged and the coefficient of variation of the average latent heats was 6.9%.

Based on DSC data, it was possible to estimate the storage capacity of 1 m^2 of PCM-wallboard. The calculation was done using the data from Table 3. It can be seen that for a temperature change of 4°C the heat storage capacity of 1 m^2 of ordinary wallboard is 36 kJ m^{-2} and the heat storage capacity of 1 m^2 wallboard with 25% PCM (Emerest 2326) is 314 kJ m^{-2}. It should be noted that only 70% of the total latent heat capacity of PCM wallboard was taken into consideration, respectively the latent heat capacity in the useful 4°C temperature interval as mentioned above.

Table 2

Spatial distribution of PCM in wallboard by DSC testing at a scanning rate of 2°C min^{-1}

	Outer 1/3 slice		Inner 1/3 slice		Outer 1/3 slice	
	ΔH_m/J g^{-1}	ΔH_f/J g^{-1}	ΔH_m/J g^{-1}	ΔH_f/J g^{-1}	ΔH_m/J g^{-1}	ΔH_f/J g^{-1}
Square No. 1						
Specimen 1	35.0	35.9	27.5	26.8	34.8	35.0
Specimen 2	36.4	36.7	28.3	27.7	35.1	34.2
Square No. 2						
Specimen 1	34.3	35.2	29.0	29.1	32.3	32.7
Specimen 2	32.5	31.9	28.1	27.5	35.1	35.7
Square No. 3						
Specimen 1	33.1	32.9	30.1	30.0	34.7	33.9
Specimen	34.8	33.7	29.7	29.2	34.4	34.0
Square No. 4						
Specimen 1	34.4	33.9	27.5	27.3	35.0	34.8
Specimen 2	35.4	34.2	27.4	27.7	33.9	33.5
Average	34.5	34.3	28.5	28.2	34.4	34.2

PCM loading in wallboard, 23.5%; calculated latent heat, 140 × 23.5% = 32.9 J g^{-1}; found by DSC testing, ΔH_m = 32.5 J g^{-1}; standard deviation = 3.07 J g^{-1}; coefficient of variations 9.4%; ΔH_f = 32.2 J g^{-1}; standard deviation = 3.18 J g^{-1}; coefficient of variation 9.8%.

Table 3
Estimation of the thermal storage capacity of 1 m^2 wallboard loaded with 25% Emerest 2326

Material	Weight/kg	Specific heat/ $kJ\ kg^{-1}\ {}^{\circ}C^{-1}$	Latent heat/ $kJ\ kg^{-1}$	Sensible heat[a] /$kJ\ m^{-2}$	Storage capacity/ $kJ\ m^{-2}$
Emerest 2326	2.06	2.41	140	–	–
Gypsum board	8.25	1.08	–	36	36
PCM-wallboard	10.31	1.41	35	58	360 + 58 = 418
			25[b]		256 + 58 = 314

[a]Sensible heat calculated for a 4°C temperature rise.
[b]The latent heat capacity in the temperature interval of interest.

According to DSC results, the heat storage capacity of PCM-wallboard is at least eight times (314/36 = 8.7) higher than the storage capacity of wallboard alone. Besides the laboratory evaluation, the heat storing characteristics of PCM-wallboard versus ordinary wallboard were measured in a 2.8 × 2.2 × 2.0 m outdoor test room whose walls were covered with impregnated or ordinary wallboard. Each wall was provided with a number of thermocouples connected to a data acquisition station. The test room was equipped with a computerized data acquisition and control system. Measured variables included front and back surface temperatures of the gypsum boards, air temperature, global temperature, outside temperature and solar radiation transmitted into the room. Details concerning this evaluation have been published elsewhere [4].

The test room was built with a large near-south facing window and a major objective of the investigation was to test the effectiveness of PCM wallboard with respect to storage of passive solar gains and reduction of room temperature swings.

Typical results collected during the 1992 winter, sunny cold days, indicated that between 1000 and 1300 h the front surface of the ordinary gypsum board rose to a maximum of 27°C, while at the same time the surface temperature of the PCM board adjacent to the ordinary one reached a maximum of 21°C, 6 degrees difference. Since in both locations approximately the same amount of solar radiation was received and the heat flow was definitely one-dimensional, we may conclude that the PCM gypsum board has a significant potential for reducing the maximum mean radiant temperature, and indirectly the air temperature thereby improving thermal comfort and providing an effective means for storage of passive solar gains.

For quantitative results concerning the heat storage capacity of PCM-wallboard, current research is now underway to comparatively test ordinary and PCM-wallboard in a twin room test facility for thermal performance, energy consumed and heat cycling rates.

4. Conclusion

In addition to the utility of DSC for selecting PCMs, it has proven to be a very useful method for evaluation of PCM-wallboard prototypes due to its accuracy in measuring temperatures and latent heats of transition of these prototypes. Using DSC, it was possible to verify the distribution of PCM in wallboard, to determine the effects of temperature cycling on the thermal characteristics of PCM in wallboard and to estimate the heat storage capacity of PCM-wallboard. If the heat storage capacity estimation based on DSC results is confirmed by full scale measurements, which are in progress, it may be concluded that expensive large scale testing need only be utilized in the commercialization of the material.

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