NEW ENERGY EFFICIENT ROOFING MATERIALS WITH PHASE CHANGE MATERIAL (PCM) TREATMENT

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Abstract

With regard to a building's thermal performance, the roof system often is a significant weak point. During the day, most of the heat provided by solar radiation penetrates through the roof system into the building. On hot days, the living area below the roof system often overheats which leads to a substantial decrease in thermal comfort. In order to cool the living space many buildings are equipped with air-conditioning systems, which consume a lot of energy. Overnight, most of the heat stored inside the building during the day is lost through the roof. On cold days, this substantial heat loss through the roof system significantly influences the building's heating demands.

In order to improve the thermal comfort and make buildings more energy-efficient, new roofing materials have been developed. These building products are textile composites equipped with highly-efficient thermal storage means - phase change materials (PCMs). The PCM is integrated in a polymeric compound which is topically applied to a textile substrate.

In a roof application, the PCM controls the heat flux into and out of the building through the roof system components by either absorption or release of latent heat as soon as its temperature increases above a certain value or decreases below a certain value. By controlling the heat flux through the roof, the PCM adapts the roof system's thermal insulation to prevailing needs. Because of the temperature initiated change in their thermal insulation properties, the building materials treated with PCM are considered to be "smart" materials.

The heat flux control feature has a significant influence on the thermal management of the entire building. As a result, the thermal comfort of the enclosure will be enhanced, the facility's overall heating and air-conditioning demands of the facility will decrease and the construction becomes more energy efficient. Specifically, the PCM application in the roof system eliminates peak energy demands which would otherwise arise on very hot and very cold days.

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Barbara Pause earned her master's degree in physics at the University of Leipzig, Leipzig, Germany and holds a doctorate in engineering science from the University of Wuppertal, Wuppertal, Germany. She has been working in the field of material research and development for more than 20 years. In May 2000, she founded her own company Textile Testing & Innovation, LLC, which specializes in the transfer of cutting-edge technologies, such as the phase change material (PCM)-technology into textiles and polymers that can be used in various end-use products. Dr. Pause holds several patents related to the PCM-technology. She has been an active member of ASTM International.

Introduction

The roof system is perhaps the weakest part of a building's thermal performance. During the day, most of the heat provided by solar radiation penetrates through the roof system into the building. In a hot climate, the living area below the roof system often overheats, which leads to a substantial decrease in thermal comfort and a subsequent cooling demand. On the other hand in a cold climate, most of the heat stored inside the building during the day is lost overnight through the roof system. This substantial heat loss through the roof significantly influences the building's heating demands. The problem can be solved by applying newly-developed composite building products with thermo-regulating properties in the roof structure. These thermo-regulating properties are obtained by the application of phase change material (PCM) - a highly productive thermal storage medium.

Phase Change Material (PCM)

PCM changes its physical state within certain temperature ranges. When the melting temperature is reached in a heating process, the phase change from solid to liquid occurs. During this melting process, the PCM absorbs and stores a large amount of latent heat. The temperature of the PCM and its surroundings remains nearly constant throughout the entire process.

In the cooling process, the latent heat stored in the PCM is released into the environment in a certain temperature range, and a reverse phase change from liquid to solid takes place. During this crystallization process, the temperature of the PCM and its surroundings remains also nearly constant. When the phase change is complete, a continued heating / cooling process leads to a further temperature increase / decrease.

The absorption or release of high amounts of latent heat without a change in the material's temperature is the reason why the use of PCM as a heat storage medium offers great potential.

As an example of a phase change, consider the melting of ice into water. When ice melts, it absorbs an amount of latent heat of about 335 joules per gram (J/g) or 144 Btu per pound (Btu/lb). When the water is further heated, it absorbs an amount of sensible heat of only 4 joules per gram (J/g) or 1.7 Btu per pound (Btu/lb) for every one-degree Celsius rise in its temperature. Therefore, water must be heated from about 1 degree Celsius (34 degrees Fahrenheit) to about 84 degree Celsius (183 degrees Fahrenheit) in order to absorb the same amount of heat that is absorbed during ice melting into water. In addition to ice (water), there are more than 500 natural and synthetic PCMs, such as paraffins, salt hydrates, or salt eutectics. These materials differ from one another in their phase change temperature ranges and their latent heat storage capacities.

Thermo-regulating effect

For roof systems, the PCM controls the heat flux into and out of the building through the roof components by either absorption or release of latent heat as soon as the PCM's temperature increases above a certain value or decreases below a certain value. By controlling the heat flux through the roof, the PCM adapts the roof's thermal insulation to prevailing needs. For instance, the PCM's latent heat absorption feature decreases the heat flux into the building when a given temperature is exceeded leading to a temporary increase of thermal insulation provided by the roof's components. Because of the temperature-initiated change in their thermal insulation properties, the building materials treated with PCM can be considered "smart" materials.

Suitable PCM Arrangement in a Roof System

Based on thermal tests in a common roof structure and the use of a computer modelling procedure, PCM should be arranged in the following two locations in a cathedral ceiling or warm roof structure:

1. in the upper part of the roof system between the roof tiles and the thermal insulation layer,

2. in the lower part of the roof system between the thermal insulation layer and the drywall (ceiling).

Figure 1 illustrates the PCM arrangement in a common roof system.

PCM locations

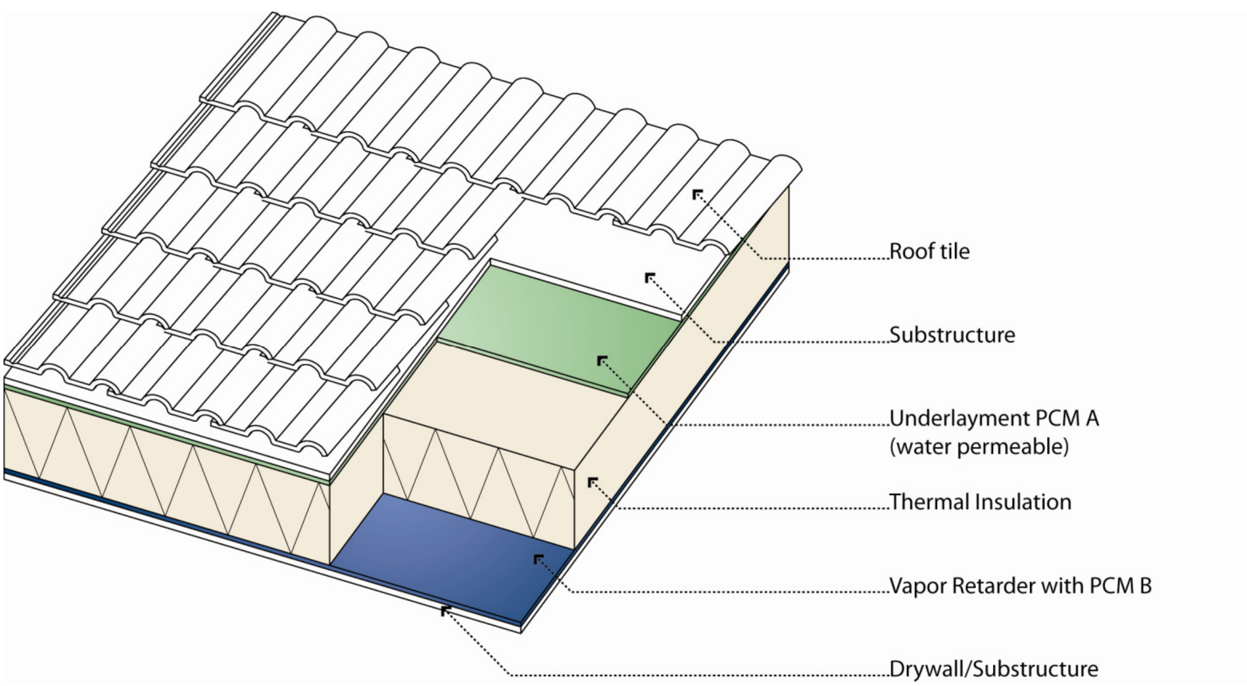

Figure 1: Arrangements of the PCM-treated building materials in the roof system

The main purpose of this PCM arrangement in the upper part of the roof system is the heat protection on hot summer days. The PCM will absorb the heat provided by solar radiation, which has penetrated through the roof tiles, as soon as the temperature of the PCM and its surrounding containment structure reaches a certain se point. During the latent heat absorption by the PCM, the temperature of the PCM and its surrounding containment structure will remain nearly constant. Therefore, the heat flux into the building during the day will be minimized; and, consequently, the temperature in the living space underneath the roof will not rise as much as it would without the PCM application. Furthermore, the PCM arrangement in the upper part of the roof construction prevents the solar radiation heat from penetrating into other roof components such as the thermal insulation layer where removing heat would be more difficult. Moreover, the selected PCM location ensures that the stored latent heat could be completely removed overnight and, therefore, the PCM could be recharged and ready for reuse the next day.

The purpose of the second PCM placement, in the lower level of the roof structure just above the dry wall (ceiling), is to provide a temporary, additional thermal insulation on cold winter nights. In this case, the PCM will store the heat generated in the living space below the roof system during the day after penetrating through the dry wall. When the temperature of the PCM and its surrounding containment structure drops overnight below a certain set point, the latent heat will be released. The PCM arrangement directly above the dry wall (ceiling) ensures that the heat, which is generated in the living space underneath the roof during the day and usually rises to the ceiling, is preserved and available to use in order to reduce the heat flux through the roof overnight. In addition, the heat absorption, without a substantial rise in the ceiling's temperature during the day, leads to a reduction in the temperature gradient between the living space's floor and ceiling, which further enhances the room's thermal comfort. The PCM arrangement underneath the thermal insulation layer is also advantageous for the following reason: the latent heat released by the PCM will first penetrate into the insulation layer, from which it slowly dissipates.

Building Products with PCM Treatment

PCM must be properly contained in order to prevent dissolution while in its liquid state. Although PCM often is difficult to contain, silicone rubber was found to be an appropriate containment material. The silicone rubber matrix with the PCM is topically applied as a coating to a textile carrier material. In their roof application, the PCM- silicone-rubber coated textiles will replace either the underlayment or the water vapour retarder, which are commonly arranged above and below the insulation package.

The PCMs used in both arrangements need to be carefully selected in order to provide the desired thermal benefits. Temperature development studies and computer simulations have been used to determine the temperatures at which the latent heat absorption and the latent heat release should start in each of the building products. The PCM A located in the upper part of the roof (see Figure 1) should absorb latent heat when its temperature rises above 55 degrees Celsius (131 degrees Fahrenheit). On the other hand, the PCM B located above the dry wall (see also Figure 1) will release latent heat when its temperature falls below 20 degrees Celsius (68 degrees Fahrenheit). Because of the differences in the phase change temperature ranges between the two PCMs, they will both act separately without interfering with each other.

The selected PCMs are both non-combustible salt hydrates that have high latent heat storage capacities. Using non-combustible salt hydrates in the roofing materials allows for compliance with the fire resistance codes for building products. The necessary latent heat storage capacity of both PCMs has been determined from solar radiation incidences, the heat absorption of the roof components of model buildings, and the heat flux through the roof into and out of the buildings.

For instance, heat protection on hot days, especially during the summer, requires a latent heat storage capacity of about 450 kilojoules per square meter (kJ/m^2) or 355 Btu per square yard (Btu/yd^2). Based on a latent heat storage capacity of 340 joules per gram (J/g) or 146 Btu per pound (Btu/lb) of the selected PCM A, a PCM quantity of about 1.3 kilograms per square meter (kg/m^2) or 2.4 pound per square yard (lb/yd^2) is necessary. Applying about 60 percent PCM to the silicone rubber matrix leads to a thickness of a closed PCM silicone rubber layer of about 2 millimetres (mm) or 0.08 inch. Because an underlay structure must provide a sufficient water vapour transfer, the silicone rubber matrix with PCM is bonded to the carrier fabric in a mesh-like form. The resulting surface reduction leads to an increase in the material thickness to about 3 millimetres (mm) or 0.12 inch.

On the other hand, in order to prevent a substantial heat loss through the roof during cold nights, especially during winter, a latent heat storage capacity of about 300 kilojoules per square meter (kJ/m^2) or 237 Btu per square yard (Btu/yd^2) is required. Based on a latent heat storage capacity of the selected PCM of about 280 joules per gram (J/g) or 120 Btu per pound (Btu/lb), a PCM quantity of about 1.1 kilograms per square meter (kg/m^2) or 2 pound per square yard (lb/yd^2) is necessary in this case. Applying about 60 percent PCM to the silicone rubber matrix leads to a thickness of about 1.5 millimetres (mm) or 0.06 inch for the PCM silicone rubber layer. In this arrangement, the silicone rubber matrix with PCM covers the surface of the textile carrier material completely. The silicone rubber itself provides the required water vapour barrier and the necessary air tightness. The technical parameter are summarized in Table 1.

The fabrics with the PCM silicone rubber coating are dimensional stable. The coated fabrics can be laminated to the insulation material as well as to each other. The fabrics can also be connected to other materials by fasteners. Putting holes in the PCM silicone rubber matrix will not lead to a leakage of the PCM, because the PCM is cross-linked into the silicone rubber matrix. However, the use of fasteners is not recommended when water vapor barrier properties of the materials are required.

The PCMs are stable when subjected to repeated thermo-cycles. The use of non-combustible salt hydrate PCMs in the developed building products leads to an improvement in their fire-resistance properties.

Thermal Benefits and Energy Savings

The heat flux control feature has a significant influence on the thermal management of the entire building. As a result, the thermal comfort of the enclosure will be increased, the overall heating and air-conditioning demands of the facility will decrease, and the structure becomes more energy efficient. Specifically, the PCM application in the roof system smoothes and reduces peak energy demands. Computer modelling procedures have been carried out in order to determine the extent to which thermal comfort improvements and energy savings can be expected by replacing the commonly used underlay and water vapour barrier materials by the composite building materials containing PCM. Using a two-story residential home located in Germany as a model, with total living space of about 160 square meters (m^2) or 1,722 square foot (ft^2) and a roof area of 130 square meters (m^2) or 1400 square foot (ft^2), the latent heat storage capacity of the PCM applied to the roof totalled 97,500 kilojoules (kJ) or 92, 412 Btu. 60 percent of the latent heat storage capacity is used for heat protection on hot summer days. The remaining 40 percent is used to support the roof system's thermal insulation function during cold winter nights.

Thermal Comfort Improvement

Further calculations quantify the thermal comfort improvement, by observing the temperature development in the living space underneath the roof of the residential home, with and without the PCM application in the roof system. The calculations are based on real measurements of the ambient temperature and the room temperature on hot summer days, and on the expected heat transfer effects through the roof. Figure 2 shows the ambient temperature development and the temperature development inside the room for each version (with and without PCM) during the course of an entire day.

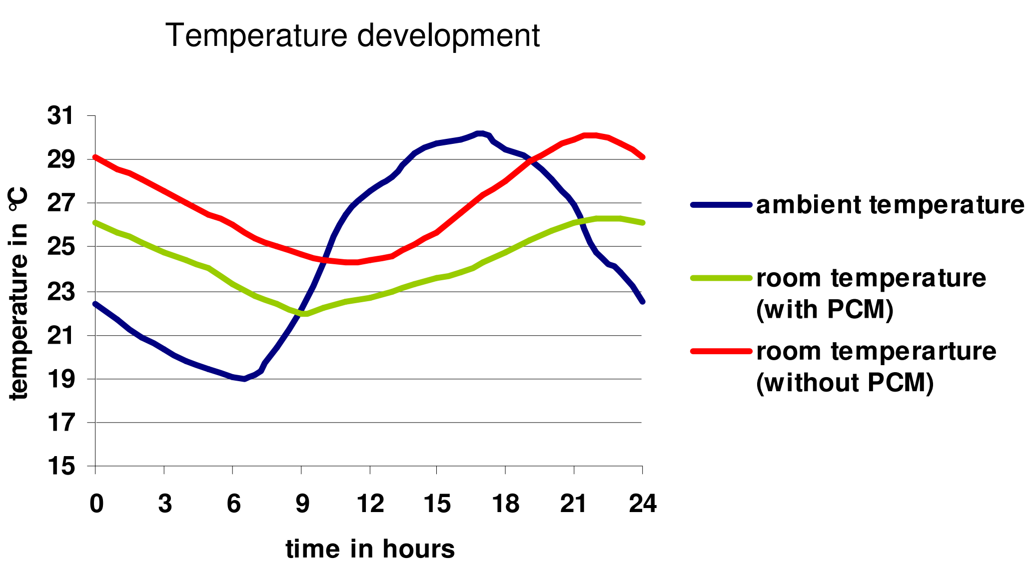

Figure 2: Temperature development in the living area of a house on a hot day

When PCM is applied to a building's roof system, the temperature increase in the living space of the second floor is reduced significantly. During the evening hours, temperature differences of up to 4 degrees Celsius are obtained in the living space of the second floor when comparing the buildings with and without PCM. Furthermore, because of the prevention of the heat flux increase through the roof system into the building during the day caused by the latent heat absorption of the PCM, the room temperature can be kept in a comfort range between 22 degrees Celsius (72 degrees Fahrenheit) and 26 degrees Celsius (79 degrees Fahrenheit) even on a very hot summer day without the use of an external air-conditioning system.

Energy Savings

The annual heating demand of the residential building in question is about 13,500 kilowatt-hours (kWh) or 90 kilowatt-hours (kWh) per square meter of living space. With the PCM application in the roof, the heating demand can be reduced by 25 percent to about 10,200 kilowatt-hours (kWh) or 68 kilowatt-hours (kWh) per one square meter living space. Furthermore, if an air-conditioning system is used during the summer months, the overall energy savings could increase up to about 40 percent.

Conclusions

The newly-developed composite building products with PCM offer enhanced thermal performance capabilities previously unattainable. These capabilities will permit a substantial improvement in the thermal management of buildings where these composite building products with PCM are applied. The improved thermal management leads to enhanced comfort and reduces the building's heating and air-conditioning demands. In sum, the PCM application in the enclosure makes the building more energy-efficient, i.e. it makes energy savings possible.

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