Construction Process and Measuring Initial Dryout of PCM Mortar in Energy Activated ETICS Façade

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ABSTRACT

For both newly built and renovated nearly zero energy buildings, installing photo-voltaic (PV) panels on building façades vertically is a growing trend. To develop reasonably priced and aesthetically satisfying energy activated façades, adding flexible PV (FPV) panels to traditional external thermal insulation composite system ETICS façades is under consideration. To prevent the FPV from overheating, phase change material (PCM) granules, encapsulated in the thick layer of mortar, were installed behind the FPV. As FPV is vapor tight, it is necessary to allow the moisture to dry out behind the FPV and to prevent frost damage of the moist PCM mortar.

A full scale test wall was built in a climate chamber with three versions of energy activated ETICS sections with traditional ETICS separating them. Also, a PCM mortar composite was investigated in small-scale experiments to calibrate the soil moisture sensors used for measuring moisture content in the overhygroscopic range. Measured results from the climate chamber were compared with hygrothermal model calculation results.

The function for calibrating the soil moisture sensors to measure moisture content in PCM mortar was defined, as well as formulas to eliminate the temperature error caused by specifics of the sensor. A double steel sheet joint solution was developed to make it possible for excess moisture to dry out behind the vapor-tight PV panel. It turned out that 12 days at room temperature was enough for 35 mm (1-3/8") thick mortar with PCM granules to dry out enough to cover it with a PV panel. Hygrothermal modelling showed a similar drying out process with several candidate materials.

INTRODUCTION

During times of geopolitical and economical instabilities, our world must move towards a green economy even faster and our dependency on fossil energy sources must be reduced drastically. Easy and economically justified integration of photovoltaic with building envelope can be a reasonable solution towards low and zero energy buildings.

Building-integrated photovoltaics (BIPV) is becoming more and more widespread on rooftops. But as the available area is often limited by the size of the roof, shading must be taken into account and therefore it is not always possible to reach near-zero energy levels. More solutions with PV panels integrated into façades are coming onto the market. But most of the solutions have an air gap behind the PV panels on the façade, which keeps the back side of the PV panels ventilated and makes it possible for excess moisture to dry out (Quesada et al., 2012).

According to technical requirements provided by many producers the exploitation temperature of PV panel should not exceed 85°C (185°F). In case of unventilated photovoltaic integrated with building facades this critical value can be exceeded due to the high solar absorptivity of PV. The concept of keeping the PV panels temperature under control by using phase change material (PCM) has been studied before (Ilomets et al., 2020). Previous calculations have shown that adding a thick layer of

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mortar mixed with PCM granules helps to avoid severe overheating of PV panels, thereby avoiding physical damage, ageing effects and efficiency drop in electricity output (Heim et al., 2021; Talvik et al., 2021).

Studies have shown that using PCM for keeping the PV panel temperatures below critical values, helps to both increase the electricity output of PV panels and to decrease the risk of PV panels deteriorating prematurely due to extremely high temperatures. Direct integration of flexible PV with wide range applied External Thermal Insulation Composite System (ETICS) can be a reasonable alternative for BIPV in a form of ventilated façade. On the other hand, the risk of overheating is higher due to the insulation layer being in direct contact with PV from inside. For this specific combination of PCM cooled PV and traditional ETICS wall (En-ActivETICS), thermal modelling has shown that passive cooling with a 30 mm (1-3/16") thick layer of PCM mortar decreased the peak temperatures of the PV panel from 83°C (181°F) to 71°C (160°F) and resulted in a 2.2% increase of electricity output in Tallinn, Estonia (Talvik et al., 2021).

Moreover, as assumed in En-ActivETICS (Heim et al., 2020), adding the vapor-tight PV panel to the outermost material layer of the wall causes significant hygrothermal risks behind the PV panel (Ilomets et al., 2020). As the PV panel is watertight and vapor tight, it creates a situation where moisture is not able to transfer through the wall system by diffusion. It could lead to moisture accumulation behind the PV panels, potentially allowing the thick layer of mortar to reach high levels of moisture content and thereby leading to physical deterioration of the material when freezing or corrosion of PV. Many traditional ETICS façades have problems with deterioration (Sulakatko, 2019). Adding PV panels to the façade makes the system more complicated and the probability of cracks appearing in the façade plaster (mainly on the border of two materials) and the risk of moisture deterioration rises. One option to reduce the risk of moisture accumulation is to let the excess moisture dry out with diffusion channels located behind the vapor tight PV panel and connected to the external environment via dedicated inlets.

Moreover, it is necessary to let the PCM mortar dry out enough before installing the PV panels to control the built-in moisture inside the wall. This study tries to define the necessary time needed for a thick layer of PCM mortar to dry out, before the PV panel could be applied to the wall.

METHODS

Tests in climatic chamber with experimental wall

A test wall was built in the climatic chamber of Tallinn University of Technology, Estonia. The climate chamber has two separately controlled environments (simulating indoor and outdoor environments), separated by the test wall. The test wall was built using traditional ETICS with three sections of energy activated ETICS inset into the main construction (Figure 1 and 2). Two thirds of the traditional ETICS were assembled using expanded polystyrene (EPS) insulation and one third using mineral wool (MW).

Measuring moisture content of materials in the overhygroscopic range with soil moisture sensors

As it is impractical and imprecise to measure the relative humidity of porous building materials when they reach the overhygroscopic range, soil moisture sensors were used side-by-side with temperature and humidity sensors to measure moisture content. Researchers (Klõšeiko et al., 2017) have found the soil moisture sensors could be useful in hygrothermal experiments with mineral construction materials if the layer thickness is enough. In this case, the PCM mortar layer was 35 mm *(1-3/8")* thick which allows the application of soil moisture sensors into the specimen. Used soil moisture sensors have a measuring range between 0 m^3/m^3 (0 ft^3/ft^3) to 1 m^3/m^3 (1 ft^3/ft^3) and an accuracy of ±0.02 m^3/m^3 (±0.02 ft^3/ft^3) for any porous mediums (METER Group, 2021). It has been stated (Varda, 2017) that calibrating by weighing the measured specimen is necessary for each specific material.

For calibrating the soil moisture sensor, the same PCM mortar was applied onto the EPS around a pre-attached sensor. As well as the soil moisture sensor, there were capsules inside the mortar to measure temperature and RH with conventional sensors. The specimen was regularly placed into a water-vapor tight case for stabilizing the moisture levels. During the 2-month period, drying out and soaking cycles were conducted with a small-scale test specimen.

The specimen was weighed regularly to find the connection function between sensor output voltage and measured moisture content inside the PCM mortar. The function for converting soil moisture sensor output into volumetric moisture content at a temperature of 20°C (68°F) for this specific PCM mortar is shown below (Formula 1):

$$\psi = 2.27{U_{20}}^3 - 5.346{U_{20}}^2 + 4.378U_{20} - 0.981 \quad (1)$$

Where U_{20} is the voltage output of the soil moisture sensor (V) measured at 20°C (68°F) and ψ is volumetric moisture content of the PCM mortar around the sensor (m^3/m^3). This function could be used for measuring moisture content in PCM mortar in the overhygroscopic range. In the hygroscopic range, humidity could be measured with conventional RH sensors.

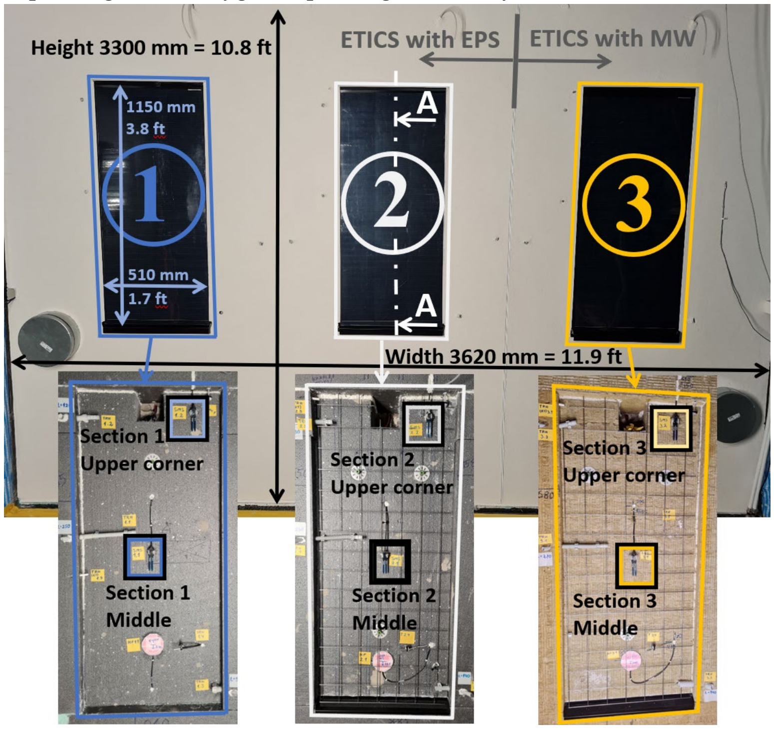


Figure 1 Overview of the test façade. Reference section 1, without diffusion channels; Reference section 2, PV panel on EPS with diffusion channels behind PV (2); Reference section 3, PCM mortar with diffusion channels on MW (3). Below are photos before the application of PCM mortar. Highlighted are the soil moisture sensors.

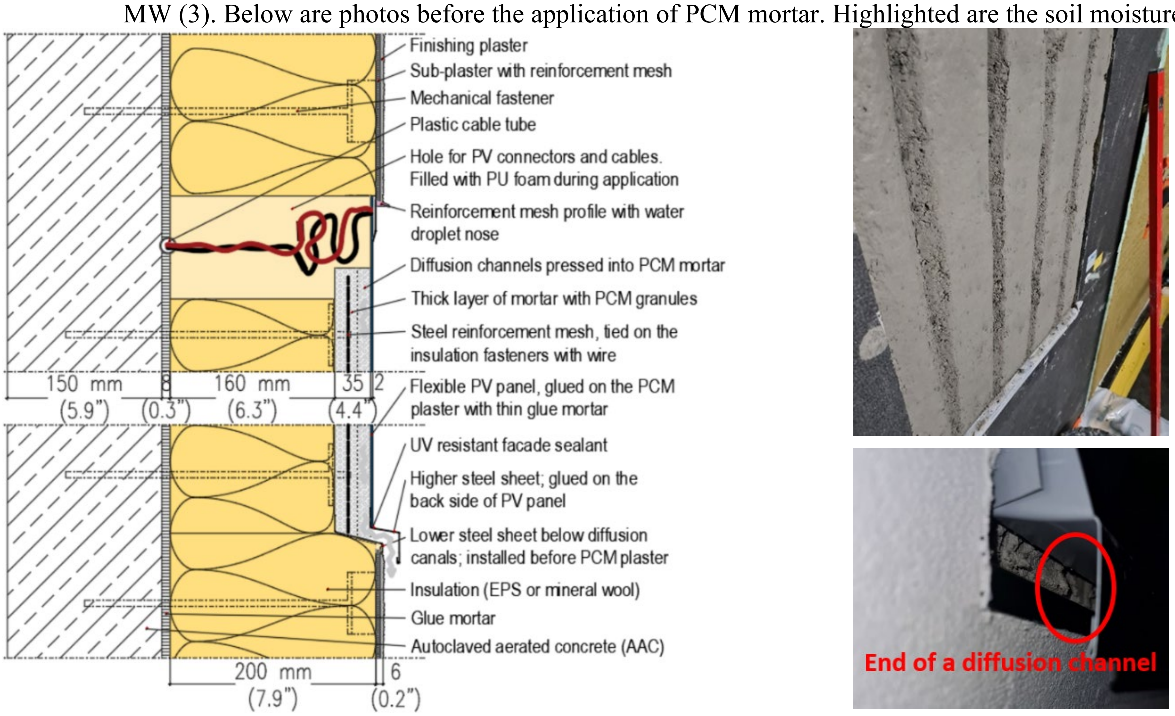
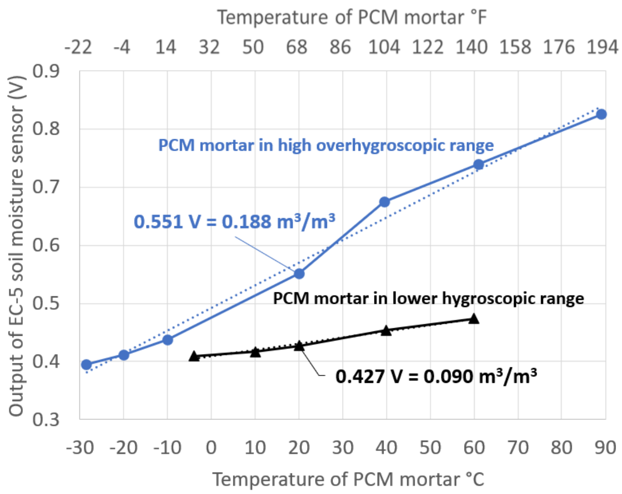


Figure 2 Cross section A-A (see Figure 1 section 2) of the test wall (left); diffusion channels pressed into fresh PCM mortar during application (right, above); air gap between steel sheets where diffusion channels reach to external environment (right, below)

It has been found that soil moisture sensors are sensitive to changes in temperature (Seyfried & Grant, 2007) (Fares et al., 2016). For applications in agriculture and forestry, the necessary corrections are in the reasonable limits, as soil temperatures are relatively stable during the vegetation period, compared to temperature fluctuations of a building façade. A study referencing 19 different soil types found that the temperature sensitivity depends significantly on the soil type (Seyfried & Grant, 2007). Therefore, it was decided to verify the corrections for this specific PCM mortar used in the test wall.

To compensate for the temperature dependency, the same test specimen with a known moisture content was sealed into a water-tight container and kept at different temperatures. Two experiments were conducted – the first with the specimen at a relatively low moisture content and the second at a higher moisture content (Figure 3). The results were different for different moisture contents, but the graphs were linear, as was expected based on other studies (Seyfried & Grant, 2007). The phase change area between 20ºC (68°F) and 40ºC (104°F) showed a slight additional increase in readings which could be explained by the phase change effect, but the amount of increase is in the margins of error. It is possible to adjust the sensor output for any temperature between -30ºC (-22°F) and 90ºC (194°F) to voltage output at 20ºC (68°F) with the formulas presented in Figure 3. After temperature correction, the U_{20} value could be used in the Formula 1 to calculate volumetric moisture content of PCM mortar.



Volumetric moisture content 0.185 m^3/m^3

Condition	*Formula for correcting the voltage*
t<20	U_{20}=U+U*(20-t)*0.0032
20<t<=40	U_{20}=U-U*(t-20)*0.0064
t>40	U_{20}=U-U*(t-40)*0.0030-0.128

Volumetric moisture content 0.097 m^3/m^3

Condition	*Formula for correcting the voltage*
t<20	U_{20}=U+U*(20-t)*0.00073
20<t<=40	U_{20}=U-U*(t-20)*0.0013
t>40	U_{20}=U-U*(t-40)*0.0010-0.026

U - Voltage output of soil moisture sensor (V)
U_{20} - Voltage output equivalent if it were measured at 20°C (V)
t - PMC mortar internal temperature in Celsius scale (°C)
*Use °C=(°F-32)*5/9 to convert Fahrenheit temperatures to Celcius scale*

Figure 3 Temperature correction graphs for soil moisture sensors in PCM mortar (left) and formulas for correcting the sensor output voltage if the material temperature varies from 20°C (68°F) (right). The black (triangular) line on the left graph is just at the boundary between the hygroscopic and overhygroscopic range. The blue (dotted) line represents the moisture content three days after taking the soaked specimen out of the water.

As there are probably many different temperature dependency graphs between those two lines, this method for correcting the voltage results has some inaccuracies. During future experiments, more temperature dependency graphs could be researched to further increase the accuracy of temperature correction functions.

Hygrothermal modelling

Coupled heat, air, moisture, and matter transfer software Delphin 6 was used to model the hygrothermal performance of the wall. 1D model was used for calculations, as initial drying out process is not affected by the presence of diffusion channels. After 25 days, virtual PV panel was installed by adding boundary condition S_d=10 000 m (0.0003 Perm). Materials used in model besides PCM mortar were Autoclaved Aerated Concrete (database material no 1); Glue Mortar I (90); Polystyrene Foam Board – Expanded (186) and Lime Cement Mortar (143).

For hygrothermal modelling several small scale tests were conducted. Results from sorption curve measurements, wet cup experiment and water uptake tests were used to create a final material file. Measured material properties of PCM mortar were: bulk density ρ=1150 kg/m^3; thermal conductivity λ=0.63 W/m*K=0.364 Btu/(h·ft^2·°F); water uptake coefficient A_w=0.045 kg/($m^2s^{0.5}$)=0.00922 lb/($ft^2s^{0.5}$); water vapor diffusion resistance factor μ=154 and effective saturation moisture content 0.28 m^3/m^3 (0.28 ft^3/ft^3).

To compare the new created material with other mineral, mostly cement based, mortars, 9 different materials from the library were chosen to compare newly developed PCM mortar material. For all the models, measured data from the climate chamber was added as boundary conditions and the PV panel was added into the model at the same time as it was installed on the test wall. Initial moisture content of all the materials were taken equal to effective saturation moisture content.

BUILDING THE TEST WALL

Most of the test wall was built as a standard ETICS according to technical guidelines (ETAG 004, 2013) and data sheets of material producers. More effort was put into developing a new solution of a thick mortar layer with PCM granules and a new joint design to make it possible for the excess moisture to dry out behind the PV panel.

Reinforcement and anchoring of the thick PCM mortar

The PCM mortar consists of two main ingredients – a mixture of PCM granules with different melting temperatures and cement-based mortar. The mortar itself contains fibers and does not require any additional reinforcement and could be applied as a thick layer of up to 30 mm (1 3/16”). However, as this mortar was transformed into a new composite material by adding the PCM granules, it was hard to apply the PCM mortar on a vertical surface without additional reinforcement mesh and there was a tendency for the mortar to fall down some minutes after the application. The problem was solved with 75x75x2,5 mm (3” x 3” x 0.1”) steel reinforcement mesh which can be seen in Figure 1.

To avoid the PCM mortar separating from the wall during the service period, the reinforcement mesh was tied to the mechanical fixing of the ETICS system. Mechanical anchors are fixed on the structural layer of the wall system and thereby failure of the chemical bonding between the PCM mortar and insulation material does not result in a collapse of the PCM mortar and PV panel.

Pressing the diffusion channels into PCM mortar

One test wall section was constructed as a reference wall without any way for excess moisture to escape other than drying out on the sides of the PV panel through the façade plaster of ETICS. Two test wall sections were constructed with diffusion channels to make it possible for excess moisture to dry out behind the vapor tight PV panel by diffusion, micro-convection or dripping down by gravity.

There were 4 vertical diffusion channels for each section with PV panels (Figure 2). The channels were pressed into the PCM mortar right after application and were finished with an orthogonal masonry trowel. The results were triangular shaped diffusion channels with an average cross-sectional area of 400 mm^2 (0.62 in^2). The spacing between diffusion channels was 120 mm (4.7”).

Diffusion channels were open at the bottom. Below the PCM mortar there was a steel sheet installed with a 1:10 slope (Figure 2). If excess moisture condenses on the surface of the PV, it drips down on the steel sheet, which leads the water out from the wall system. The opening is covered with another steel sheet, fixed on the back side of the PV panel. The second steel sheet has a lengthened vertical part to protect the diffusion channels from wind-driven rain. All the diffusion channels were closed at the top. Therefore, only micro convection could occur in the channels, with no stack or convection effect as would be seen with a traditional air cavity. Creating similar rain-protected joints at the top of the PV would have resulted in the steel sheets leaning too far away from the main façade and potentially shading the very top photovoltaic cells of the PV, resulting in a significant efficiency loss of the whole PV panel.

RESULTS

Drying out process of the PCM mortar

According to the producer, a 35 mm *(1-3/8")* thick mortar layer would need 35 days to dry out but this is affected by boundary conditions. In the climate chamber experiment, different dry out times were used to cover the PCM mortar. For wall section 1 it was 25 days, for section 2, 17 days and for section 3 it was 12 days.

It can be seen from Figure 4 that in all three wall sections, the PCM mortar moisture level balanced after approximately 2 weeks. However, it could be stated that the PCM dried out slightly faster on the mineral wool (wall section 3) than it did on EPS (wall no. 1 and 2). The difference is small because during the drying out process, the PCM mortar was in contact with air up until the application of PV panels. As all wall sections had dried out for a relatively long time, there were no significant differences between the solutions with diffusion channels and those without, after installing the PV panels. There is a small amount of increase just after the PV panels were installed, which is caused by the initial moisture content of the glue mortar used for fixing the PV panels.

It could be concluded from Figure 4 that a drying out time of 12 days was sufficient to allow covering the PCM mortar with a PV panel. There was some additional drying process on the test area on the mineral wool after covering, but it was not significant enough to conclude whether diffusion channels made it faster or not.

Boundary conditions in the climate chamber during the dry out period (Figure 5) were favorable. The temperature was mostly between 20°C (68°F) and 25°C (77°F) and RH between 30% and 60%. An increase in RH is noticeable on the days when new wall sections were covered with PCM mortar (days 1, 9 and 14).

To test out the temperature correction formulas developed with small scale experiments (Figure 3), the climate chamber temperature was dropped to 7°C (45°F) on day 29 (Figure 5). Initial data from soil moisture sensors showed a drop in readings, but after the temperature correction formula for lower moisture content was used, the change in PCM mortar temperature does not stand out in the graphed moisture content of PCM mortar (Figure 4).

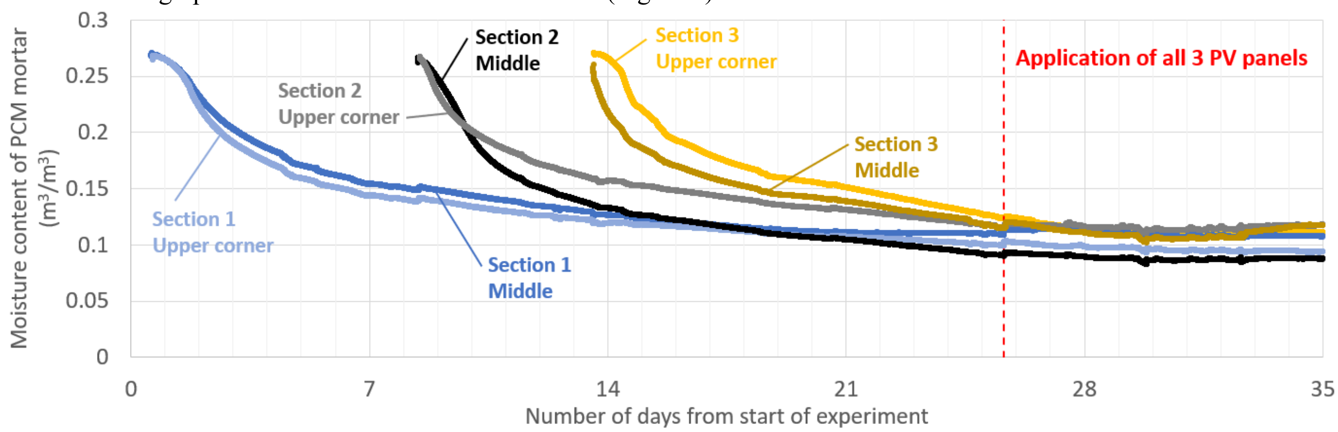


Figure 4 Initial drying out process of PCM mortar. Measured with calibrated soil moisture sensor.

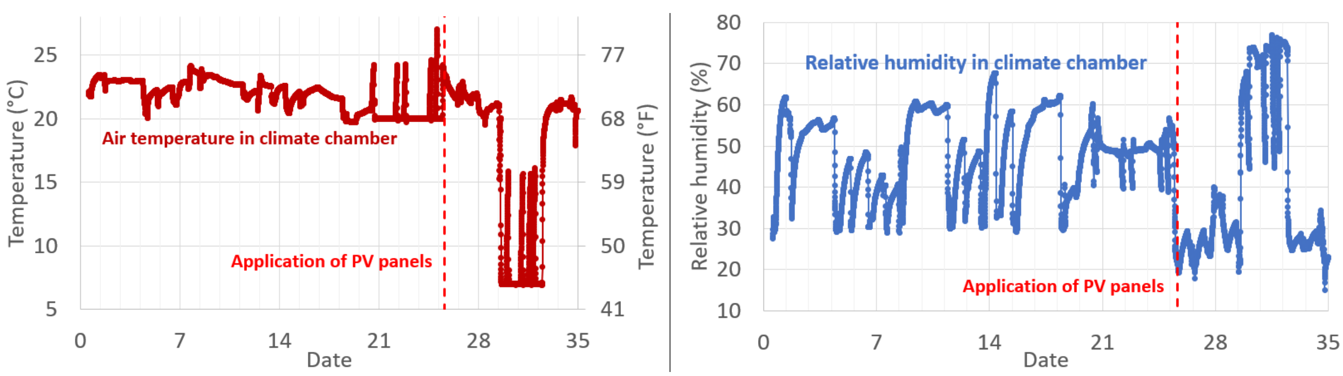


Figure 5 Boundary conditions during the PCM mortar drying out process. Air temperature (left) and relative humidity (right) inside the climate chamber during the measurement period.

Modelling the drying out process

Hygrothermal modelling was carried out with PCM mortar material file, which properties were measured during small scale experiments. To get an idea, whether measured material properties correlate with existing material files in the software, modelled results were compared with 9 mineral materials. All those modelled results were compared to measured data of wall section 1 – PCM mortar on EPS without diffusion channels (see Figure 6).

There is a correlation in moisture content between modelled and measured results. Only at the very beginning there is some difference, but as the material is expected to be at lower moisture content than 0.15 m^3/m^3, the difference is not very significant. Other plasters and cement-based materials showed great differences in modelled results. Therefore, it could be stated that measuring exact hygrothermal properties of new building materials makes modelling results much more accurate than just picking materials from the database that seem to be similar from the first look.

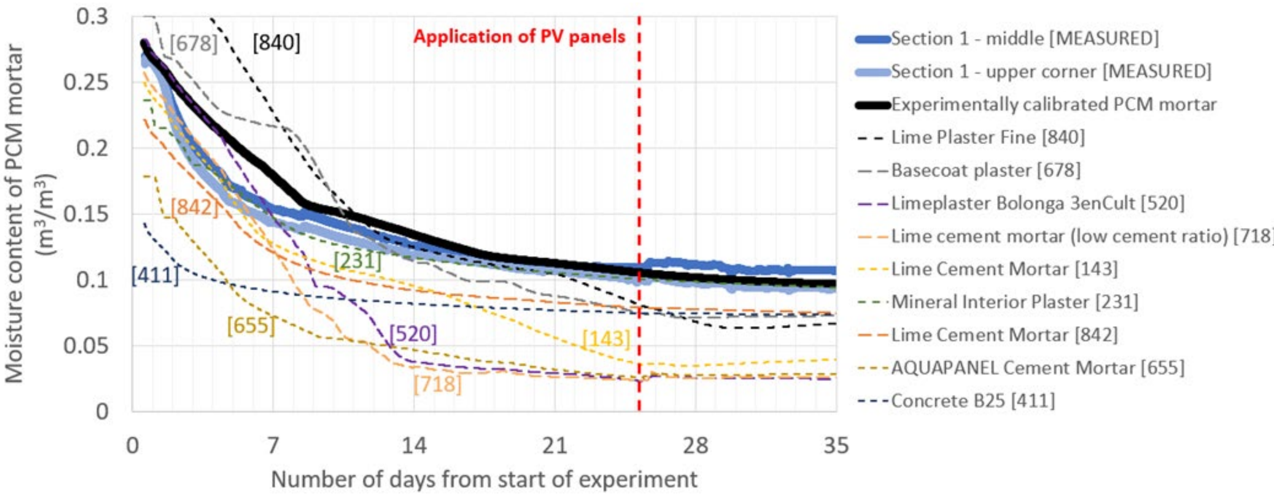


Figure 6 Drying out process modelled with experimentally calibrated material file (thick black line), compared with measured (blue lines) PCM mortar drying out on test wall section 1. Thin dashed lines are modelled results with different building materials with similar properties.

DISCUSSION

Using the soil moisture sensors

In general, using soil moisture sensors appeared to be appropriate for applications with high moisture content in the overhygroscopic range. Temperature correction formulas have been proven to work, but as there are more lines between the two measured formulas, then temperature dependency graphs for several different moisture contents should be studied in the future.

Voltage correction formulas presented in Figure 3 were calculated in three different temperature ranges because of the phase change effect, to get more exact results. However, it could be stated that the temperature dependency lines are linear all the way, as the differences are not tremendous.

Improving construction methods for the energy activated ETICS wall

The application process of the 35 mm *(1-3/8")* thick layer of mortar on the vertical surface was relatively time consuming and material intensive. It would not be the most economical way to build this wall on a real construction site. A future consideration would be to make the façade system partially prefabricated. PCM could be integrated with PV in form of a closed, thin-walled metal case for example.

A significant amount of time could have been saved by applying the PCM mortar if the PV panels were already covered with a rough-surfaced material layer to avoid the application of primer. Moreover, connection profiles for the application of the façade plaster system could have been pre-installed in the factory on the PV panels.

Drying out process of PCM mortar before covering with vapor tight PV panel

The time for covering the PCM mortar was selected according to material producer guidelines and common construction practices. So the available dry-out time for all the test areas was between 12 and 25 days which allowed enough dry-out time for all the sections, which means that the effects of covering the PCM before it is properly dried out are still unknown. During further experiments, it would be worthwhile to neglect the technically correct solutions and apply the PV panel onto wet mortar. Measurements could then be conducted after covering the PCM mortar at 3, 5 and 7 days at room temperature or 2 weeks under different external weather conditions.

CONCLUSIONS

During the study, a full-scale installation of energy activated ETICS façade was built in the climate chamber. Calibrated soil moisture sensors were installed in the layer of mortar with PCM granules. The initial drying out process of thick PCM mortar was investigated.

It was possible to apply PCM mortar to a vertical surface after steel reinforcement mesh was installed. Diffusion channels were able to be pressed into the fresh mortar and a lower joint detail with two layers of steel sheet was developed and built successfully. Soil moisture sensors proved trustworthy for measuring high moisture content in the overhygroscopic range after temperature corrections were made.

For 35 mm *(1-3/8")* thick PCM mortar, 2 weeks proved to be enough drying out time before covering with a vapor tight PV panel. Under conditions close to an indoor climate, the drying out process was relatively fast. In the future, the drying out process at lower temperatures should be studied and there should be a shorter time between the application of PCM mortar and installing the PV panels.

Hygrothermal properties of PCM mortar should be further calibrated during various climate chamber tests to increase the correlation between the measured and modelled results. Comparing the drying out process of different database materials and PCM mortar material with measured hygrothermal properties, it was clear that exact hygrothermal functions make a huge difference in calculated results.

Many other experiments could be conducted with the test wall in the climate chamber – various frost resistance, wind driven rain and solar experiments are planned for carrying out in the future with the energy-activated ETICS façade set up.

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