Numerical and experimental evaluation of a granular PCM-enhanced plaster for historic building application

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Abstract
The construction sector represents more than one-third of the global energy consumption, and a consistent part of the building stock is made of historical buildings. The application of phase change materials (PCMs) mixed within the plaster represents a tangible possibility to improve the performances of historical buildings without violating any legal restriction. In this study experimental tests and numerical simulations were carried out with the focus on lime plaster, suitable and reliable for the restoration of historic buildings, and on granular PCM, recently introduced after the European project TESSe2b (TESSe2b).

Key Innovations
- PCMs for the energetic refurbishment of historical buildings
- dynamicity of the building envelope
- granular PCM addition to lime plaster

Practical Implications
When evaluating numerically the behavior of a building element, it is essential that the properties of the materials applied are as much reliable as possible.

Introduction
The building and construction sectors, according to the global status report of the United Nations Environment Programme, represent more than one-third of the global energy-related CO₂ emissions (UNEP, 2020). The energy demand for air conditioning is estimated to be about 40% of the total requirement, thus making it necessary to introduce legislative actions aimed at limiting the energy consumption while maintaining high indoor quality.

Internal comfort has always been pursued and, together with the constantly increasing concept of environmental sustainability, is leading to the design and execution of buildings with always higher performances, both in terms of energetic and economical consumptions. For this purpose, technological innovations are continuously improving the system performance even though the building envelope are slowed down due to a limited industrialization that too frequently restricts a systemic application of low cost and low impact strategies.

Further issues are due to a lack of regulations regarding the intervention on historical buildings, even though 30% of the buildings in Europe are considered historical (Eurostat). This problem is crucial in Italy where 20% of the total amount of buildings were built before 1919 (Bianco, 2015). A great number of buildings too frequently fails to combine with the most advanced technologies because of architectural and technological incompatibilities (Dalla Mora, 2015). This means that forthcoming efforts should concentrate more on existing buildings because of their energy-consuming asset as well as the tangible need to restore rather than build ex novo.

The pursuit of internal comfort can be achieved, for instance, through Thermal Energy Storage (TES) systems, which allow to accumulate energy for a delayed release and strategic in this sense can be the use of Phase Change Materials (PCMs). The use of PCM in the building envelope can make it dynamic and able to adapt to different conditions, an increasingly important feature in order to moderate the energy demand for air conditioning and improve resistance towards climate changes (Cabeza, 2011; Lachheb, 2017; Navarro, 2015). At the same time, the application of PCM can represent a valid solution for all those situations in which any other intervention is forbidden due to legislative restrictions. These do not consider only single buildings with relevant qualities in terms of aesthetics, history or culture, rather extend the supervision to larger areas, frequently coinciding with historical city centres.

This study is concentrated on the evaluation of the application on existing buildings’ external walls of lime-based plaster mixed with a granular PCM. The choice was of lime-based plaster as it was considered more suitable for the restoration of historical buildings than cement-based one, which is more common nowadays but that risks of damaging the wall on which it is applied. Moreover, even though it is not considered an insulator, lime plaster has good thermal properties (Stefanidou, 2010).

As PCM, granules of paraffin were selected (Figure 1). This type of PCM, supplied by PCM Products Ltd. (PCM Products) was recently introduced through the European project TESSe2b and its application has not been deeply studied yet. Among all the existing types of PCM, paraffin is the most used worldwide for the application on buildings with an incidence of 87.5% (Cui, 2017).
Figure 1: granular PCM supplied by PCM Products Ltd. Beside a melting point close to the temperature range for indoor comfort, paraffins are used for their chemical stability, non-corrosiveness, low cost, recyclability, low supercooling phenomenon and no phase segregation (Drissi, 2019; Pavlik, 2016).

In this paper, the application on the external side of historical building walls during summer is evaluated.

**Materials and Methods**

This study was conducted with preliminary experimental tests of two sample plasters in a climatic chamber under controlled conditions. The data acquired were used to calibrate a numerical model implemented with the commercial software COMSOL Multiphysics V5.5, followed by the simulation of the behaviour of a sample wall in terms of temperatures and heat flux during some summer days under real conditions.

**Experimental set up**

The apparatus consists of a 0.20x0.15x0.020 m plaster sample and a 0.20x0.15x0.028 m masonry tile positioned on a refrigeration plate made by a 0.003 m aluminium foil under which four Peltier cells are fixed. The thermoelectric cells are coupled with air exchangers and small fans to dissipate the heat on the warmer side. All the system is wrapped in XPS insulation to limit heat transfer on the edges and wooden frame and supports are used to stiffen the set up. All the tests were taken in a climatic chamber (Memmert CTC 256), with temperature, humidity and fan speed controlled.

As depicted in Figure 2, temperature and heat flux sensors were used to monitor the experimental test. T-type thermocouples (accuracy: 0.5 K), and heat flow plates (thickness 1.5 mm, accuracy: 5% at 23 °C) were connected to a datalogger ALMEMO 5690 (AHLBORN) and data were acquired with a time step of 30 s. To avoid any interference of the heat flux plates, on both the surfaces of the masonry tile were realized shallow indentations to allocate the sensors within the thickness of the tile. Moreover, in order to limit the thermal contact resistance due to the roughness of the plaster and the tile surface, some thermal paste was applied in correspondence of each layer. Beside the sensors in Figure 2, another T-type thermocouple was used to monitor the temperature inside the climatic chamber (Tair).

Two different plaster samples were realised, one with reference plaster (REFp) and one with reference plaster mixed with 10% by mass of granular PCM (PCMp). The plaster used was a bio-plaster based on hydraulic lime NHL 3.5 for interiors and exteriors supplied by Fassa S.r.l. (Fassa). The phase change material used was a granular PCM provided by PCM Products Ltd. with a melting point of 28 °C. The masonry tile was recovered from the restoration of a historical building and its thermal properties were object of the research.

The density of each material used was calculated by Eq. (1):

\[ \rho = \frac{m}{V} \]  

where \( m \) is the mass [kg] and \( V \) the volume [m³]. Table 1 reports the densities calculated:

<table>
<thead>
<tr>
<th>Material</th>
<th>( \rho ) [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>REFp</td>
<td>1517</td>
</tr>
<tr>
<td>PCMp</td>
<td>1278</td>
</tr>
<tr>
<td>Masonry tile</td>
<td>1607</td>
</tr>
</tbody>
</table>

![Table 1: densities of the materials used](https://doi.org/10.26868/25222708.2021.30578)
Experimental tests

The set up realised was tested in the climatic chamber under different and controlled conditions in order to obtain experimentally the thermal properties of the materials and use them in the numerical model. Figure 3 show the experimental set up in the climatic chamber.

![Image](image_url)

Figure 3: experimental set up inside the climatic chamber

First tests were conducted in steady-state to evaluate the thermal conductivity $\lambda$ [W/mK] of the samples and the masonry tile. Both the samples were placed in the climatic chamber with constant air temperature ($T_{air}$) at 25 °C and fan speed at 80% (the fan speed in the climatic chamber can be set in 10 different speeds, from 0% to 100%). Three different powers to the Peltier cells were supplied through a multi-range DC power supply (PSW 80-27, GWInstek) so that three different temperatures were set on the aluminium plate ($T_{down}$). The $T_{down}$ temperatures set were low to have high heat fluxes and so reduce the possibility of errors in the data acquisition. Table 2 summarizes the results of the test conducted.

The thermal conductivity of both the sample plasters and of the masonry tile was estimated through the following Eq. (2):

$$\lambda = \frac{d \bar{q}}{dT}$$  \hspace{1cm} (2)

where $d$ is the thickness of the sample [m], $\bar{q}$ is the average heat flux [W/m²] and $\Delta T$ [K] is the difference between the temperatures on the surfaces ($T_{up}$, $T_{down}$; Bianco, 2015; Li, 2019). The results are reported in Table 3.

Table 2: steady-state experimental test

<table>
<thead>
<tr>
<th></th>
<th>REFp</th>
<th>PCMp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{air}$ [°C]</td>
<td>25.0</td>
<td>25.0</td>
</tr>
<tr>
<td>$T_{up}$ [°C]</td>
<td>21.8</td>
<td>21.1</td>
</tr>
<tr>
<td>$T_{mid}$ [°C]</td>
<td>16.8</td>
<td>15.0</td>
</tr>
<tr>
<td>$T_{down}$ [°C]</td>
<td>12.6</td>
<td>9.6</td>
</tr>
<tr>
<td>$H_{mid}$ [W/m²]</td>
<td>76.1</td>
<td>95.4</td>
</tr>
</tbody>
</table>

Table 3: thermal conductivities estimated experimentally

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda$ [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>REFp</td>
<td>0.31</td>
</tr>
<tr>
<td>PCMp</td>
<td>0.24</td>
</tr>
<tr>
<td>Masonry tile</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Figure 4: temperatures of the air ($T_{air}$) and of the samples ($T_{up}$, $T_{mid}$) inside the climatic chamber. $T_{down}$ was the same for both the samples. The red line is the difference between $T_{mid}$ REFp and $T_{mid}$ PCMp

The value for REFp is lower than what is frequently reported in literature, whose values are around 0.7-0.8 W/mK (Cerny, 2006; Walker 2015). Moreover, the addition of PCM to the reference plaster brings to a reduction of the thermal conductivity of 22.5%.

In order to monitor the behavior of the plaster samples and evaluate the effect of the PCM, other tests were conducted in unsteady-state. Both the samples were placed in the climatic chamber as in Figure 3 with constant fan speed at 80% and an initial temperature of 20 °C. Once the system was in steady state, the temperature inside the chamber ($T_{air}$) was changed and set at 40 °C for 3 hours and then again at 20 °C. In Figure 4 the temperature inside the chamber is depicted, and the temperatures on the upper and lower surfaces of the plaster samples are reported. Although the amount of PCM added into the reference plaster was limited (10% by mass), differences between the two samples are visible. This can be seen in Figure 4 as the temperature between the plaster sample and the masonry tile ($T_{mid}$) changes slower for PCMp than REFp. In this regard, the difference between the two samples at each acquisition step is depicted with the red line: during the melting of the PCM, there was a peak of 2 K, while during the solidification of the PCM the peak was of 1.4 K.

Figure 5: heat fluxes of the samples ($H_{mid}$) inside the climatic chamber. The red line is the difference between $H_{mid}$ REFp and $H_{mid}$ PCMp
Greater differences are clearly visible in Figure 5, where the heat flux between the plaster sample and the masonry tile (HFmid) of the two cases are depicted, together with the difference between them step by step (the red line). During heating, the heat flux through PCMp was much lower than REFp with a peak reduction of nearly 45% and values close to 0 W/m² in correspondence of the peak melting temperature. During cooling there was a lower reduction of the peak heat flux, which was about 15%, but during the phase change the values even changed the sign with a peak of -15.3 W/m² in correspondence of the solidification temperature (at the same time, REFp had values of 3.5 W/m²).

During heating, the convective heat flux coefficient was estimated at 25 W/m²K, which was imposed on the upper surface of the plaster. The value of the convective heat flux coefficient was estimated by means of the experimental data by the following Eq (4):

\[
h = \frac{\tilde{q}}{(T_{\text{up}} - T_{\text{air}})}
\]

where \(\tilde{q}\) is the average heat flux [W/m²], \(T_{\text{air}}\) and \(T_{\text{up}}\) are the temperature inside the climatic chamber and of the plaster sample surface [°C], respectively. The value was obtained as average of the values calculated in the above-mentioned steady-state experimental tests.

The simulation of the experimental tests led first to the estimation of the specific heat of the reference plaster, then of the specific heat of the PCM plaster by means of Eq (5):

\[
c_{p,\text{PCM}}(T) = (1 - r) \cdot c_{p,\text{REF}} + r \cdot (1 - H(T)) \cdot (c_{p,\text{PCMs}} + h_{sl} \cdot D_s(T)) + r \cdot H(T) \cdot (c_{p,\text{PCMl}} + h_{sl} \cdot D_l(T))
\]

where \(c_{p,\text{REF}}\) is the reference plaster specific heat [J/kgK], \(c_{p,\text{PCMs}}\) is solid PCM specific heat [J/kgK], \(c_{p,\text{PCMl}}\) is liquid PCM specific heat [J/kgK], \(r\) is the PCM mass ratio in plaster, \(H(T)\) is a dimensionless variable which is the liquid fraction of the PCM in a range between 0 and 1, \(h_{sl}\) is the latent heat of fusion [kJ/kg] and \(D_{t}(T)\)

**Numerical simulation**

The numerical simulations were carried out through the commercial software COMSOL Multiphysics V5.5 (COMSOL, 2019). A first model of the experimental set up was implemented in a “Heat Transfer in Solids” 3D domain with time-varying boundary conditions. Considering that in steady-state the two heat flux meters applied on the set up (HFmid – HFdown) had the same values, in the simulation the XPS frame was not modeled and adiabatic boundaries were set. The mesh was made of hexahedra and was limited to 2200 elements. The mesh independence of the solutions was checked with the simulation of the same problem with a much greater number of elements, and negligible changes in the solution were found. The boundary conditions set were the temperature inside the climatic chamber (Tair), the temperature of the aluminium plate (Tdown) and the convective heat flux coefficient, estimated at 25 W/m²K, which was imposed on the upper surface of the plaster.

The value of the convective heat flux coefficient was estimated by means of the experimental data by the following Eq (4):

\[
h = \frac{\tilde{q}}{(T_{\text{up}} - T_{\text{air}})}
\]

where \(\tilde{q}\) is the average heat flux [W/m²], \(T_{\text{air}}\) and \(T_{\text{up}}\) are the temperature inside the climatic chamber and of the plaster sample surface [°C], respectively. The value was obtained as average of the values calculated in the above-mentioned steady-state experimental tests.

The simulation of the experimental tests led first to the estimation of the specific heat of the reference plaster, then of the specific heat of the PCM plaster by means of Eq (5):

\[
c_{p,\text{PCM}}(T) = (1 - r) \cdot c_{p,\text{REF}} + r \cdot (1 - H(T)) \cdot (c_{p,\text{PCMs}} + h_{sl} \cdot D_s(T)) + r \cdot H(T) \cdot (c_{p,\text{PCMl}} + h_{sl} \cdot D_l(T))
\]

where \(c_{p,\text{REF}}\) is the reference plaster specific heat [J/kgK], \(c_{p,\text{PCMs}}\) is solid PCM specific heat [J/kgK], \(c_{p,\text{PCMl}}\) is liquid PCM specific heat [J/kgK], \(r\) is the PCM mass ratio in plaster, \(H(T)\) is a dimensionless variable which is the liquid fraction of the PCM in a range between 0 and 1, \(h_{sl}\) is the latent heat of fusion [kJ/kg] and \(D_{t}(T)\)

**Table 4: thermal properties of the masonry tile estimated experimentally**

<table>
<thead>
<tr>
<th>(\rho) [kg/m³]</th>
<th>(\lambda) [W/mK]</th>
<th>(c_{p}) [J/kgK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1607</td>
<td>0.49</td>
<td>800</td>
</tr>
</tbody>
</table>

**Figure 6: portion of the set up of the test on masonry tile**

In parallel, another test was realized to estimate the specific heat of the masonry tile. The set up, a 0.30x0.15x0.028 m tile wrapped in XPS insulation, was placed inside the climatic chamber with fixed air temperature and fan speed at 80%. The tile was completely dried before carrying on the tests. In Figure 6 a portion of the set up is depicted.

Once in steady-state at 20 °C, the system was brought to a higher temperature, at 40 °C, until no more consistent changes in terms of temperature and heat flux were seen. It was then brought again to the initial temperature. A heat flux meter (accuracy: 5% at 23 °C) and a T-type thermocouple was inserted into a hole in the middle of the tile. The specific heat of the masonry tile \((c_{p,\text{tile}})\) was estimated through the following Eq (3):

\[
c_{p,\text{tile}} = \frac{\tilde{q}}{m_{\Delta T}} = \frac{\int_{t_1}^{t_2} \tilde{q} \, dt}{\rho (T_{\text{end}} - T_{\text{init}})}
\]

where \(\tilde{q}\) is the average heat flux [W/m²], \(\rho\) is the density of the tile [kg/m³], \(d\) is the thickness of the tile [m], \(T_{\text{end}}\) and \(T_{\text{init}}\) are the initial and final temperatures of the surface, respectively [K] (Li, 2019).

The specific heat was estimated to be about 800 J/kgK. In Table 4 the thermal properties of the masonry tile are summarized, which are in accordance to Akkurt (2020) and Lucchi (2017).

**Figure 7: D & H functions indicating the melting and solidification of the PCM. The arrows indicate the reading direction of the curve**

https://doi.org/10.26868/25222708.2021.30578
is a normalized Dirac’s pulse \([K^{-1}]\). These functions (Bottarelli, 2015) are depicted in Figure 7.

As represented in Figure 8, basing on the heat flux curve (HFmid_PCMp), the properties of the PCM in terms of melting temperature and range were assumed. The coloured areas were identified considering the different trend with respect to the heat flux curve of the reference plaster (HFmid_REFp). It seems that the granular PCM charges at a higher temperature than discharge, and the melting range is wider than the solidification one. For this reason, different equations for \(H_i(T)\) and \(D_i(T)\) were implemented for melting and solidification, respectively.

\[
\begin{array}{c|c}
\text{Table 5: thermal properties obtained through calibrations. For the PCM, the properties were estimated when } & \\
\text{HF(T)=0 and HF(T)=1 (not during the phase change)} & \\
\text{REFp} & c_p \text{ [J/kgK]} \\
\text{PCM} & h_f \text{ [kJ/kg]} \\
800 & - \\
2220 & 75 \\
\end{array}
\]

The melting temperature was set at 28 °C with a range of 12 K, while the solidification temperature at 24 °C with a range of 6 K. After the simulations, the latent heat of fusion of the granular PCM was estimated to be 75 kJ/kg. The values obtained through the calibration of the experimental tests (Figure 9 and Figure 10) are summerized in Table 5. The PCM plaster has an increased specific heat than the reference one of 17%.

Extension of the numerical model

The experimental tests and the preliminary numerical simulations were used to define the thermal properties of the materials.

With the aim of evaluating the behavior of the plaster samples under real conditions, another model was realised and a portion of a perimeter wall was implemented.

The portion of the wall was 0.4x0.4 m\(^2\), made of a 0.25 m brick main structure with a 0.02 m lime-plaster layer both on the exterior and the interior side. As for the preliminary simulations, the mesh was made of a limited number of hexahedra (1500 elements, Figure 11), and the mesh independence of the solutions was checked both with a hexahedral mesh with a greater number of elements as well as with a physics-controlled mesh, made of tetrahedra, with an extra fine quality (290040 elements). Negligible changes were found. The behaviour of the building element was studied during some consecutive days of summer 2019. The model was implemented with “Heat Transfer in Solids” and “Surface-to-Surface Radiation” physics applied.

On the interior side a fixed temperature of 26 °C was set, while as regards the external one, the temperature and solar radiation from a database of a weather station at the TekneHub laboratory at the University of Ferrara were used. On both the interior and the exterior sides, a convective heat transfer coefficient of 10 W/m\(^2\)K was set.
as representative of the liminal coefficient of the wall. All the other surfaces were considered adiabatic. The days selected were characterized by high temperatures during the day and relevant differences of temperature between day and night, so that the PCM can charge and discharge completely. Figure 12 depicts the boundary conditions of the selected days in terms of temperature, solar radiation and $T_{\text{sol-air}}$, which was calculated following Eq (6) by means of the available data (Kheradmand, 2016; Sa, 2012):

$$T_{\text{sol-air}} = T_{\text{air}} + \alpha I_g R_{se}$$  \hspace{1cm} (6)

where $\alpha$ is the absorption coefficient of the surface set equal to 0.48 (Yao, 2011), $I_g$ is the global solar radiation [W/m$^2$] and $R_{se}$ is the external surface resistance [m$^2$K/W], supposing a convective heat transfer coefficient of 25 W/m$^2$K, in accordance to the recommendations of ISO 6946 (Kheradmand, 2014).

In Figure 13 the nomenclature and the position of the sensor considered is depicted. The simulations were carried out for a period of four consecutive days, but the results were considered reliable from the second day on to avoid any interference of the boundary conditions set.

In Figure 14 the temperatures between the outer plaster and the brick layer (T2) are depicted. As expected, there are consistent differences in between the base lime plasters (REFp and LITp), which means that the product used for the experimental tests has fairly good thermal insulation properties. The addition of PCM brought to slight improvements if compared with REFp: the maximum temperatures are about 2 K lower, 42 °C instead of 44 °C, while the minimum ones are 1 K higher (red continuous line). Greater improvements are visible if comparing PCMp with LITp: maximum temperatures are 5-5.5 K lower while minimum temperatures are 2 K higher (red dashed line). Analog considerations can be made regarding the temperatures on the interior surface of the wall (T4, Figure 15). As the previous case, improvements are visible if comparing PCMp with the base lime ones. The wall on which PCM is applied has lower temperature fluctuations, with a difference of 0.2 K if compared to REFp (red continuous line), but that reaches 0.5 K if compared to LITp (red dashed line). These differences are clear on higher temperatures, while minimum temperatures are almost equal in all the walls with slightly higher values for PCMp.

### Results and discussion

The behavior of the above-described sample wall was simulated under real conditions. Considering the thermal properties of the reference plaster obtained, it seemed it would have not been representative of many of the existing buildings. For this reason, a third plaster that was compared to REFp and PCMp was simulated which thermal properties were found in literature (LITp): in Table 6 the values are depicted. In all the simulations, on the inner surface was applied lime plaster, while the PCM was applied on the outer side of the wall.
A major detail is depicted in Figure 16, where the temperatures on the interior wall of one day are presented together with sol-air temperature, and the peak temperature delay was evaluated. The maximum temperature outdoor was reached at 2pm, while on the interior wall the highest value was reached at 10:30pm for LITp, at 10:45pm for REFp and at 11:30pm for PCMp. This means that the addition of PCM delays the peak of one hour if compared to LITp, of 45° if compared to REFp. Regarding the heat flux through the inner wall, in Figure 16 the results are shown. As observed with temperatures, the addition of PCM show consistent improvements if compared to the base lime plasters.

During the whole period of simulation, a reduction of the total energy through the wall of 6% is obtained if compared to REFp. The reduction is even greater if compared to LITp, with a value nearly 21%. As shown in Figure 17, the fluctuations of the heat flux in LITp are wider than REFp and PCMp, with slightly lower values for PCMp. Focusing on highest daily values, the reduction of the peak heat flux of PCMp if compared to REFp is of nearly 7.5%, while between PCMp and LITp is of 26%. Thus, the application of PCM in lime plaster is a promising solution for the improvement of the thermal properties with consequent better performances of the building envelope. In fact, even though the reference plaster had good thermal insulation properties, the effect of PCM is certainly evident.

**Conclusion**

The enhancement of lime plaster with granular PCM was proposed as a possible solution for the energy refurbishment of historical buildings, which are frequently protected by legislative restrictions that hamper most of the common interventions. Lime plaster was chosen for its compatibility with historical structures, while paraffin PCM was selected as the most compliant PCM typology in building envelope applications. Samples of reference plaster and PCM-enhanced plaster were realized and studied under controlled conditions in a climatic chamber. Experimental tests were propaedeutic for the evaluation of density and thermal conductivity of the materials used. As expected, the addition of 10% by mass of granular PCM brought to a reduction of the density of the 16% and of the thermal conductivity of 22.5%, which means an increase of the thermal resistance. A first numerical 3D model of the experimental set up was implemented to estimate the specific heat of the reference plaster and, secondly, the latent heat of the granular PCM. All the properties were inserted in a 3D model in which the behavior of a sample wall under real conditions was simulated. Beside the reference lime plaster, whose thermal values might not be representative of many of the existing building, an additional lime plaster with thermal properties found in literature was considered and simulated. The results of the three simulations were compared. The addition of PCM slightly improved the performance of the reference plaster, with a reduction of the heat flux of 6%. Greater improvements are visible if comparing the base lime plaster found after the bibliographical research with the PCM-enhanced one: the heat flux was reduced of nearly 21% and the inner temperatures were more stable with maximum indoor temperatures 0.5 K lower. Further considerations might be concentrated both on the effect of PCM with increasing wall thicknesses as well as changing the melting and solidification temperatures.

**Acknowledgment**

The materials used during the experimental tests were gently provided by Fassa S.r.l. and PCM Products Ltd.

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