

BiTs: Bispectral Camouflage System Based on Switchable Phase Change Materials (sPCM) and Thermo-chromic Coatings

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ABSTRACT

Traditional infrared (IR) signature management systems for camouflage are based on materials and systems with low emissivity or a high thermal convection coefficient. Combining these systems with phase change materials (PCM) opens new technical possibilities for camouflage systems in stationary and mobile applications. PCM are materials that store or release heat due to their melting or solidification enthalpy. Because of this phase change, PCM respond to heat input within a certain temperature range with minimal temperature change. This temperature range, usually only a few °C, is called the 'latent range.' The location of the latent range depends on the PCM used, and the amount of heat stored is in the order of 150 to 300 kJ/kg. When the melting and solidification behavior of PCM is only dependent on the ambient temperature and cannot be actively controlled, they are referred to as passive PCM.

In camouflage applications, PCM can be used to absorb heat to prevent unwanted heating of the surface of the object. This can be used to influence and reduce the IR signature of an object. The heat can originate from internal sources, such as electronic components, or external sources, such as solar radiation. The advantage of PCM technology over pure insulation materials is that it prevents the interior from overheating if there are internal heat sources.

The disadvantages of the passive PCM systems outlined are mainly that they cannot be actively controlled and that they are only effective in the IR wavelength. For this reason, this work focuses on actively controllable bispectral camouflage systems that are currently under development. These systems use switchable PCM (sPCM) instead of passive PCM. During melting, sPCM behave like passive PCM (i.e., they melt when their melting temperature is exceeded and absorb heat). However, when the temperature of PCM falls below the normal phase transition temperature, sPCM do not solidify but enter a supercooled state. Much of the absorbed heat is still stored in the material, but this is not apparent from the material temperature. The advantage: the camouflage system can adopt the temperature of the environment and is difficult to detect in an IR image. Since the temperature of the PCM is the same as the ambient temperature, there is no further heat loss. Crystallization of the supercooled PCM can then be triggered by an actuation system. When activated, the supercooled PCM heats up to its melting temperature and releases the heat of fusion to the environment. This can be useful, for example, if a weapon system or electrical device is generating waste heat during operation, which is stored in the PCM, and the mission is at a critical stage. The PCM can then be cooled to ambient temperature and the heat can be dissipated later when the mission is less critical. Another option is to use this technology in an active deception system.

1.0 INTRODUCTION

Infrared (IR) camouflage is an important part of military self-protection. A conspicuity in the IR range is usually caused by a temperature difference between different parts of an object or between the object itself and its background. Phase change materials (PCM) can be used to reduce these conspicuities. PCM store large amounts of thermal energy during their phase change from solid to liquid, which can be used to manipulate the IR signature of different objects. Since the material can be in a liquid state, encapsulation is required to prevent the liquid PCM from leaking. Therefore, microencapsulated PCM are used in many applications, having a diameter of a few μm and a PCM content of about 70 w% [1]. The advantage of microencapsulated PCM is that they are leak-proof. For this reason, microencapsulated PCM have already been used in various applications (e.g., to increase thermal comfort in buildings [2], [3] or to improve thermal protective clothing [4]). Some of the drawbacks of microencapsulated PCM are their lower heat storage capacity due to the high proportion of shell material and their inferior thermophysical properties, in particular the larger thermal hysteresis compared to the pure PCM [1]. In our previous work, we have therefore investigated macroencapsulated PCM for IR signature camouflage. We have shown that PCM can be used to improve the IR signature in this case [5].

So far, research has been limited to passive PCM. In this case, the phase change only takes place because of a change in the ambient temperature. The aim of this study is therefore to investigate and prove the basic functionality of an active and thus switchable new concept for deception and camouflage. For this purpose, switchable PCM (sPCM) will be used. Unlike the passive PCM used to date, sPCM are supercooled melts whose exothermic crystallization is triggered by a controllable actuator. This operating principle is also known from hand warmers [6] and has been investigated for other heat storage applications, such as building and greenhouse heat storage systems [7], [8]. In addition to sPCM, thermochromic coatings (TCC) will also be used to address both the IR and visible wavelength ranges. These TCC change color when a certain color change temperature is exceeded, which can be caused, for example, by the activation of the sPCM. The activation of the sPCM itself can be controlled in a variety of ways, making the system resilient to attacks on the electrical infrastructure. The charged system does not require an electrical power supply to operate, as the necessary heat is stored in the supercooled PCM.

The primary goal of this work is to create a first laboratory prototype of such a bispectral camouflage system (BiTs). Related fundamental work on materials and material models will also be carried out. In the first part of this report, we discuss the construction of BiTs consisting of different types of sPCM, the corresponding actuator, a macroencapsulation, and one or more TCC. In the second part of the report, the experimental testing of the constructed laboratory samples and their individual components is carried out.

2.0 MATERIALS AND SYSTEM DESIGN

This section discusses the overall construction of BiTs and the preparation of the materials and components used. Figure 1 gives a schematic overview of the constructed BiTs laboratory samples. Each BiTs consists of the sPCM placed inside a thermoformed macroencapsulation. The macroencapsulation is equipped with an activation mechanism to initiate the crystallization of the supercooled sPCM and at least one TCC that changes color when a certain temperature threshold is exceeded.

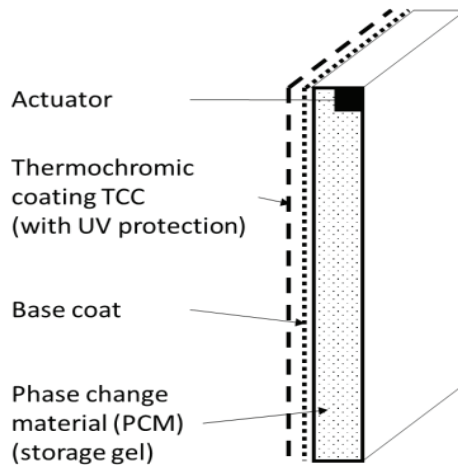


Figure 1: Schematic drawing of the laboratory sample.

2.1 Switchable Phase Change Materials (sPCM)

Materials whose phase change from liquid to solid can be used to store heat in technical applications are also referred to as phase change materials (PCM) [9]. Important properties of PCM include melting temperature, phase transition enthalpy, cycle stability, and supercooling tendency. In the melting temperature range of 0 to 100 °C, paraffins, fatty acid esters, and salt hydrates with a phase transition enthalpy of 150 to 280 kJ/kg are mainly used as PCM [10]. In contrast to many applications, where supercooling is an undesirable behavior, sPCM can only be made from materials that have a pronounced and stable supercooling tendency (i.e., the material can be cooled to a temperature well below its solidification temperature without crystallizing). This behavior is illustrated by an example in Figure 2, where spontaneous crystallization of the PCM starts when the material is cooled to a temperature ΔT_{sup} below the normal melting temperature T_m .

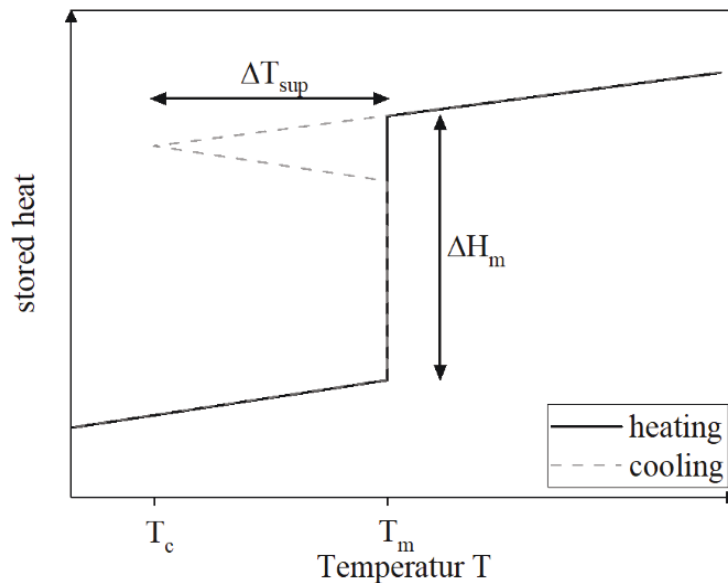


Figure 2: Exemplary plot of the stored heat against the material temperature of a sPCM with representation of the enthalpy of fusion ΔH_m and the supercooling during the cooling process ΔT_{sup} .

In the temperature range from 0 to 100 °C, almost exclusively salt hydrates show a sufficient supercooling tendency to be used as sPCM. Supercooling can be explained by classical crystallization theory (see Figure 3). In general, a spontaneous reaction occurs when its Gibbs free energy is negative. The Gibbs free energy of initial crystal growth is positive due to surface effects, even though the material temperature has decreased below the normal melting temperature. Before spontaneous crystallization can take place, at least one nucleus larger than the critical radius r_{crit} must occur. ΔG_{crit} and again r_{crit} are material-specific parameters and depend also on the degree of supercooling [11]. In consequence, by increasing ΔT_{sup} , a point can be reached where spontaneous crystallization occurs. For technically relevant sPCM, this ΔT_{sup} must be at least 20 K.

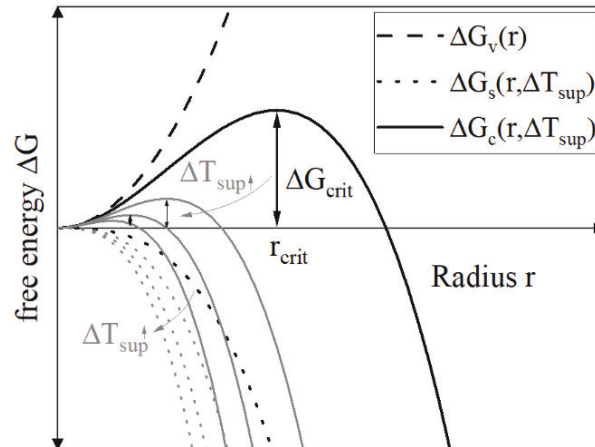


Figure 3: Plot of the critical enthalpy difference ΔG_{crit} and its dependence on the amount of supercooling ΔT_{sup} (according to Ref. [11]).

By manipulating the sPCM with additives, it is possible to reduce the supercooling tendency of the material through heterogeneous nucleation. Such additives are also known as nucleating agents. The knowledge of individual, suitable nucleating agents forms the basis for the use of salt hydrates as sPCM in BiTs. The crystallization of the heat storage based on sPCM can then be actively controlled by local manipulation of the supercooling behavior. For this purpose, the modified, non-supercooling PCM is stored in a separate volume in an actuation mechanism. If the crystallization in the supercooled sPCM is to be activated, the storage is connected to the actuator, which initializes the crystallization in the supercooled sPCM. The actuation system used for this purpose is described in Section 2.3.

In this work, the two salt hydrates, sodium acetate trihydrate (SAT) and calcium chloride hexahydrate (CCH), are selected as sPCM for use in BiTs. The material properties are summarized in Table 1. The phase change temperatures and enthalpies were measured with different calorimeters (DSC, 3-layer calorimeter, T-history calorimeter), and the degree of supercooling was measured with a screening setup for controlled temperature control of several material samples.

The tendency to phase separation and semi-congruent melting is a challenge when using salt hydrates as PCM. This reduces the cycle stability of the PCM, since the material decomposes into different phases with different, undesirable thermophysical properties. It is known from the literature that this can be suppressed by adding suitable gelling agents [12], [13]. When adding gelling agents, special care must be taken not to affect the supercoolability, as well as the heat storage capacity, of the PCM.

Table 1: Thermophysical properties of the used sPCM. Data from Refs. [7], [9], confirmed by own measurements (#).

	Sodium acetate trihydrate (SAT)	calcium chloride hexahydrate (CCH)
Chemical formula	$\text{NaCH}_3\text{COO}\cdot 3\text{H}_2\text{O}$	$\text{CaCl}_2\cdot 6\text{H}_2\text{O}$
Phase change temperature [°C]	58 [#]	29 [#]
Phase change enthalpy [kJ/kg]	230 [#]	190 [#]
Degree of supercooling (stable) [K]	>50 [#]	>20 [#]
Thermal conductivity [W/(m·K)]	0,7 (solid) -	1,01 (solid) 0,54 (liquid)

In this work, we have used carboxymethyl cellulose (CMC) and xanthan gum as gelling agents. The PCM gels are prepared using a process shown in Figure 4. The individual process parameters are adapted to the salt hydrate used and the corresponding additives and can be summarized as follows: First, the salt hydrate is weighed and completely liquefied in a closed vessel in a washing bath with stirring. Nucleating and gelling agents are then added, the mixture is heated to the individual gelling temperature and then homogenized using a disperser. The modified PCM are filled into sample containers and, if necessary, post-annealed in a heating oven until the gel structures are completely formed. Each process step i takes place at a specific temperature T_i for a specific time t_i . The individual masses m_i of the respective chemicals are added at the beginning of each process step.

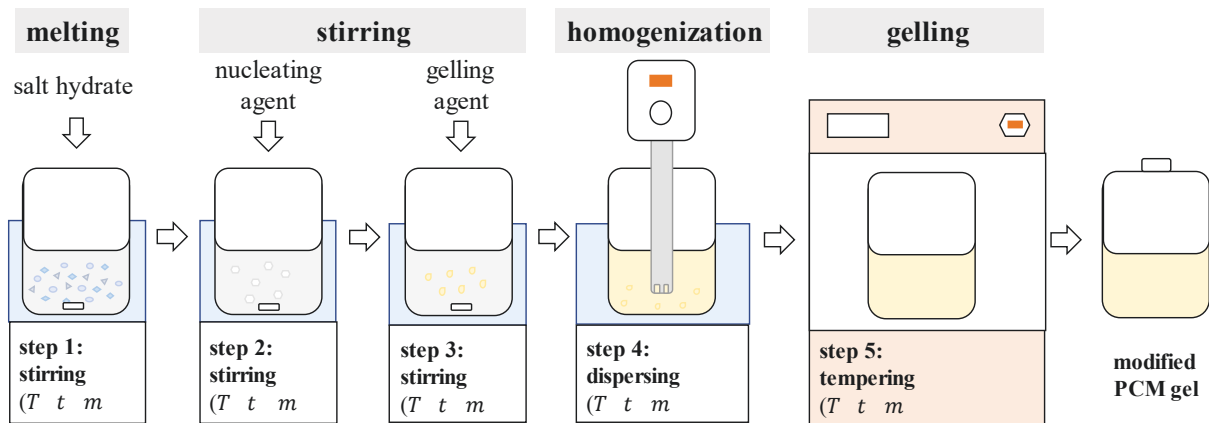


Figure 4: Schematic representation of the manufacturing process for salt hydrate based PCM gels developed at ICT.

Two different gels are produced for each of the two salt hydrates used in this work. One is the storage gel, which is used for thermal heat storage in the BiTs system. The storage gel is designed for high cycle stability, stable supercooling, and high storage capacity. The other gel is the nucleating gel, which is used in the actuator to initialize crystallization in the storage gel. The focus of the nucleating gel is on high dimensional stability, high cycle stability, and low supercooling tendency. This is achieved by adding nucleating agents to the nucleating gels, as well as higher amounts of gelling agents. The nomenclature for the prepared PCM is composed of the salt hydrate, the gel function, and the number of cycles to be run in the cycle stability tests (see Section 3.1 for cycle stability tests). Figure 5 illustrates the composition of the sample designation of the sodium acetate trihydrate (SAT) based storage gel, which is thermally analyzed in the first cycle.

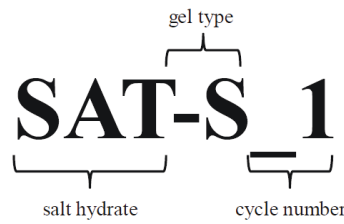


Figure 5: Explanation of the nomenclature for the PCM gel samples to be characterized.

2.2 Thermochromic Colors

Five commercially available thermochromic colors are selected to produce the TCC according to the manufacturers' specifications [14], [15] (see Table 2). All thermochromic colors used are black and have a negative thermochromic effect, meaning that they become transparent when their color change temperature (CCT) is exceeded. We use white base coatings to maximize contrast when the color change occurs. The TCC is applied both to the macroencapsulation of the PCM itself and to plastic sheets used to make the macroencapsulations for further testing (see Figure 6).

Table 2: Selected thermochromic colors.

No.	Short Name	Manufacturer	Color Change Temperature (CCT) [°C]	Color
1	K28	Dipon	28	black
2	SC10_15	Stardust Colors	10-15	black
3	SC26_31	Stardust Colors	26-31	black
4	SC40_45	Stardust Colors	40-45	black
5	SC57_62	Stardust Colors	57-62	black

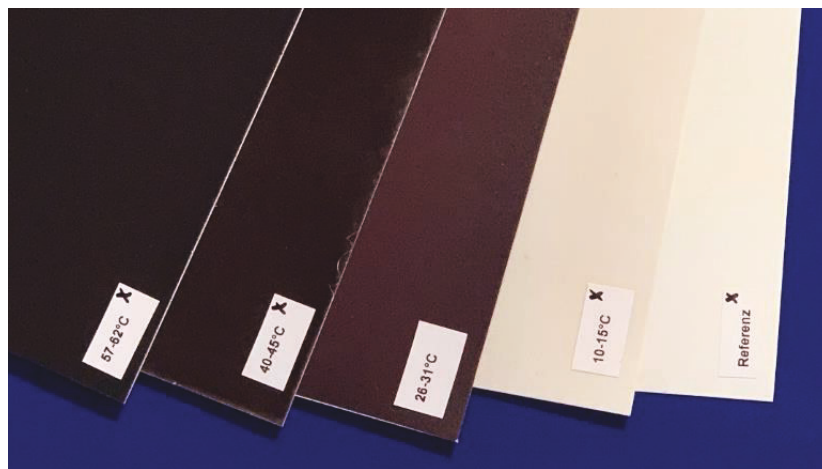


Figure 6: Produced plastic sheets with TCC for general purpose testing.

2.2.1 Activation System

An activation system described in [16] is used to initialize the crystallization process. The activation system is shown in Figure 7. It can be used to reversibly insert a needle filled with nucleating gel into the supercooled PCM through a septum. The activation system was 3D printed using a Formlabs Form 3+ 3D printer.

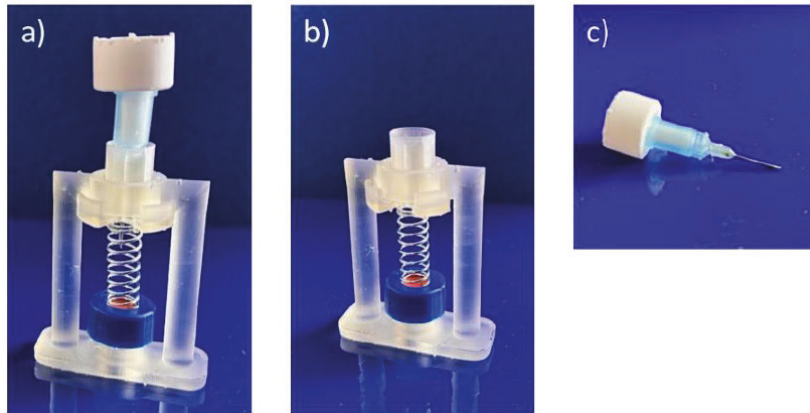


Figure 7: Assembled actuator (left) consisting of the base body with septum and spring (middle) and the cannula unit with seed gel (right).

2.3 Macroencapsulation

Since sPCM cannot be realized with microencapsulated PCM and due to the advantage of higher volumetric heat storage densities, macroencapsulated PCM are used. For this purpose, macrocapsules with two different shapes are produced using a laboratory thermoforming machine (DT2, Vaquform). The two shapes have the following dimensions 180 x 180 x 10 mm (shape A) and 180 x 80 x 10 mm³ (shape B).

The macrocapsules are then filled with storage gel, thermally sealed, and equipped with an actuator. For shape A macrocapsules, the TCC is applied directly, while for shape B macrocapsules, the TCC is cut from the coated plastic sheets and then glued to the surface. Different combinations of sPCM and TCC are realized, and the samples are named according to the shape of the macrocapsule, the PCM used, and the TCC applied. Figure 8 and Figure 9 show examples of constructed BiTs laboratory samples.

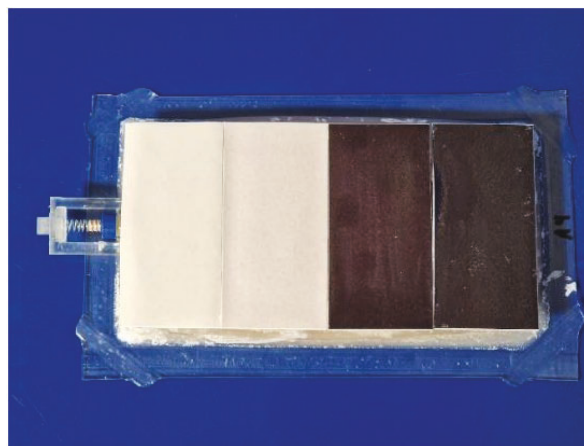


Figure 8: Laboratory sample B_SAT_SC10_SC26_SC40_SC57 (shape: B, used PCM: Sodium acetate trihydrate, applied thermochromic coating from left to right: SC10, SC26, SC40 and SC57).

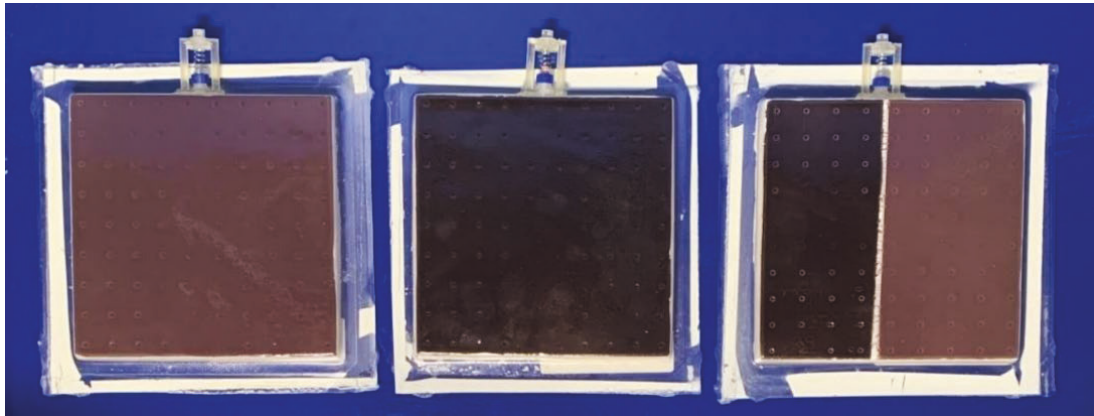


Figure 9: Laboratory samples (from left to right): A_SAT_SC26, A_SAT_SC26_SC40 and A_SAT_SC40.

3.0 EXPERIMENTAL RESULTS

This section presents the experimental results of the basic and functional tests of the PCM and TCC, as well as the laboratory samples produced.

3.1 Switchable Phase Change Materials (PCM)

The modified PCM are cycled up to 100 times and then examined in a 3-layer calorimeter to check for changes in thermal properties. As a result of the 3-layer calorimetry, time-temperature curves are obtained from which the supercooling behavior can be recognized directly (see Figure 10 and Figure 11). In a second step, these curves are used to calculate the enthalpy curves of the materials, which show the amount of heat stored as a function of temperature relative to the chosen reference temperature.

3.1.1 Calcium Chloride Based PCM Gels

The recorded T-t curves of the nucleation gel after 1, 50, and 100 heating and cooling cycles (see Figure 10) are nearly identical, except that the liquefaction plateau loses some contour. The nucleation temperature fluctuates in a range of 3 K during cycling. However, the minimum nucleation temperature of 23 °C is sufficiently high above the proven supercooling limit of the storage gel of about 6 °C. The storage gel is supercooling over the entire measurement range. No latent region can be identified as a plateau.

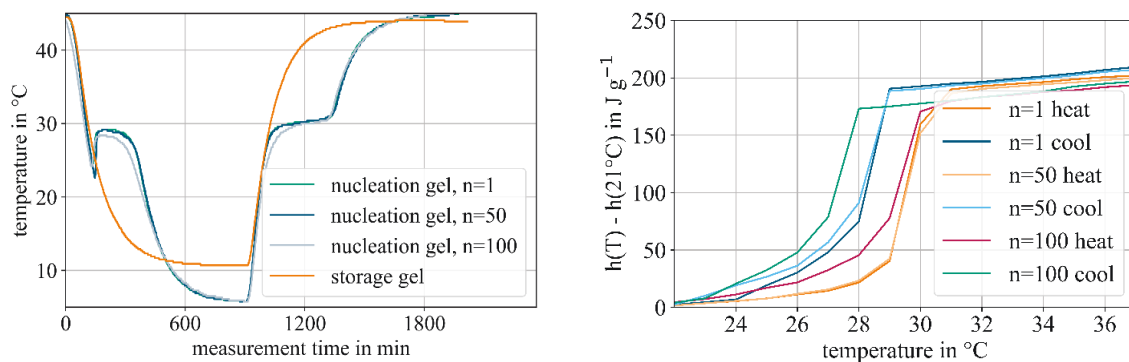


Figure 10: Plot of the temperature-time curve of CCH storage gel and CCH nucleation gel after 1 cycle, 50 cycles, and 100 cycles (left) and plot of the mass-specific enthalpy of CCH nucleation gel in J/g in the temperature range from 22°C to 37°C (right).

The slope of the enthalpy curve in Figure 10 in the liquid region corresponds to the specific heat capacity of the liquid phase, which is the same for all measurements and equal to about 2.5 J/(g*K). The results are summarized in Table 3 and evaluated according to the PCM-RAL criteria [17]. The material properties CCH gels prepared can be assumed constant over 100 cycles.

Table 3: Results of the material characterization of the CCH gel.

	Heat Storage Capacity Heating / Cooling	Phase Change Temperature/ Nucleation Temperature
Cycle	J/g	°C
1	198 / 209	28 / 25
50	200 / 207	28 / 23
100	194 / 197	28 / 24
max. deviation	2% / 5%	0 / -2

3.1.2 Sodium Acetate Based PCM Gels

The recorded T-t curves of the nucleation gel after 1, 50 and 100 heating and cooling cycles (see Figure 11) are also very similar. After 100 cycles, the latent plateau loses some of its sharpness during liquefaction and solidification. The nucleation temperature of the cyclized nucleation gel is initially 54 °C and finally 53 °C after 50 and 100 cycles, respectively. The storage gel supercools over the entire measurement temperature range.

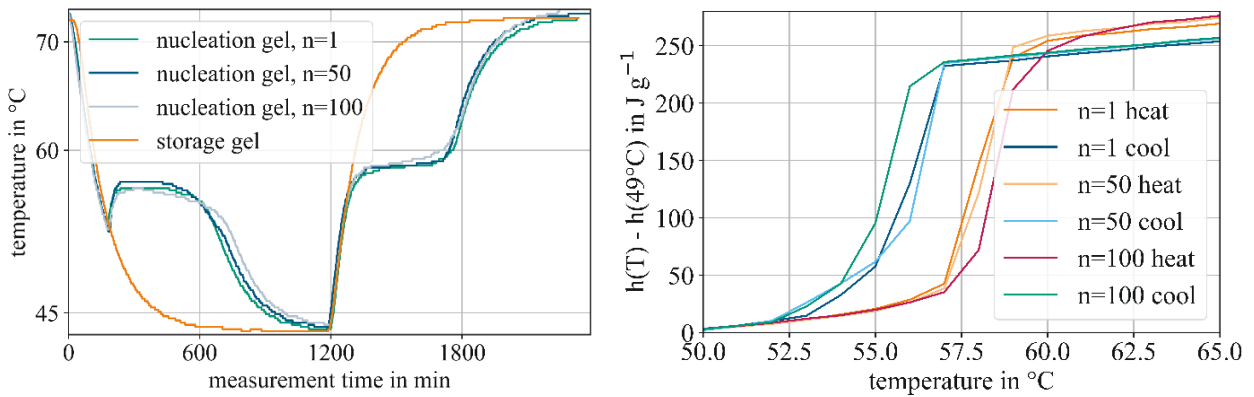


Figure 11: Plot of the temperature-time curve of SAT storage gel and SAT nucleation gel after 1 cycle, 50 cycles, and 100 cycles (left) and plot of the mass-specific enthalpy of SAT nucleation gel in J/g in the temperature range from 50°C to 65°C (right).

Figure 11 shows the specific heat capacities of the gels in both the liquid and solid states, which are approximately 2.5 and 3 J/(g*K) in the liquid and solid states, respectively. The results are summarized in Table 4. The material properties of the SAT gels prepared can also be considered stable over 100 cycles.

Table 4: Results of the material characterization of the SAT gel.

	Heat Storage Capacity Heating / Cooling	Phase Change Temperature/ Nucleation Temperature
Cycle	J/g	°C
1	269 / 254	57 / 54
50	274 / 256	58 / 53
100	276 / 257	58 / 53
max. deviation	3% / 1%	+1 / -1

3.2 Thermochromic Coatings

The thermochromic coatings are tested for their optical and mechanical properties. The TCC samples tested in this section are cut from the coated plastic sheets produced for general purpose testing. The tests are performed approximately 2 weeks after the production of the samples.

3.2.1 Optical properties

The optical properties of the produced TCC are measured by ultraviolet-visible (UV-Vis) diffuse reflectance spectroscopy using a MCS 621 VIS spectrometer (Zeiss). The experimental setup is shown in Figure 12. The sample is placed under insulating material and pressed onto a sample holder, which is temperature controlled by an external thermostat. The measuring probe of the spectrometer is placed at a constant distance above a squared cutout with a side length of about 5 cm. The actual temperature of the sample holder is measured with a PT100 resistance thermometer.

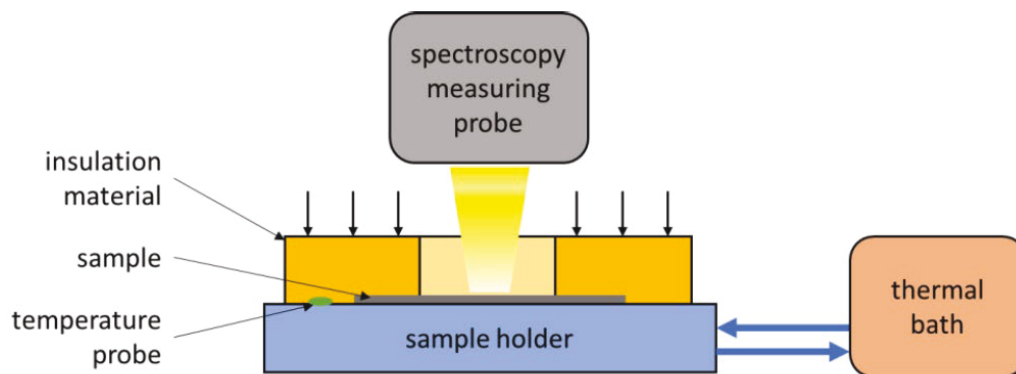


Figure 12: Experimental setup UV-Vis reflectance spectroscopy.

Spectra are then measured over a wide temperature range for each type of TCC produced. The relative change in reflectance is calculated for each temperature measured, using the measurement at the highest temperature of each sample as the reference. The results for K28 and SC26 are shown in Figure 13 and Figure 14. The change in sample color from black to white when the CCT is exceeded can be seen in the results. The reflectance of K28 in the wavelength range from 400 to 650 nm increases by a factor of approximately 9 when the temperature is increased from 19.9 to 34.9 °C. The same is found for the investigated TCC SC26, but with a smaller temperature range of 23 to 31.9 °C, where most of the color change occurs. The experimental results for all TCC are summarized in Table 5, which shows that the CCTs for all TCC are within the manufacturer’s specifications.

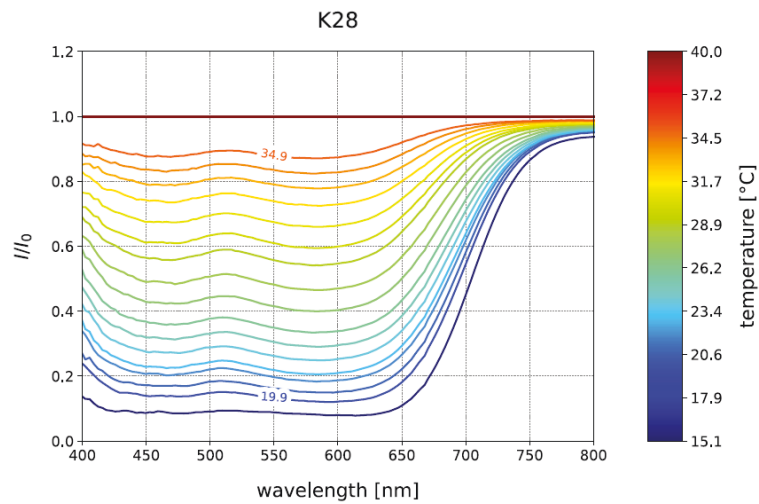


Figure 13: Thermochromic coating K28 – UV-Vis reflectance spectroscopy.

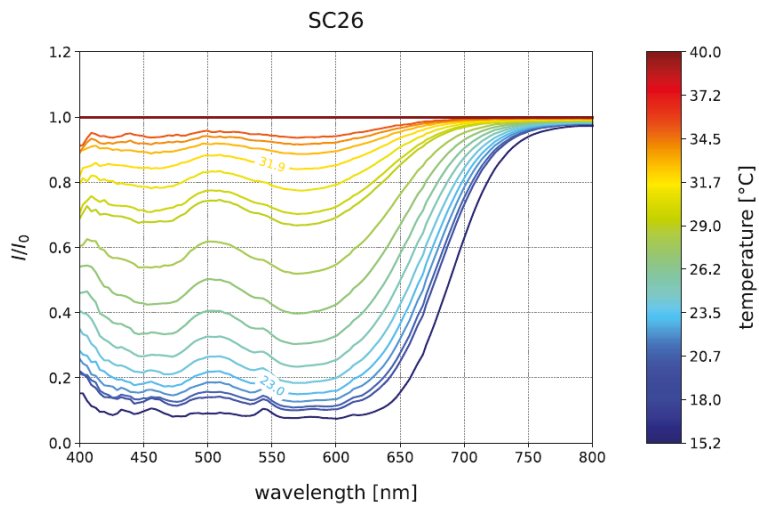


Figure 14: Thermochromic coating K28 – UV-Vis reflectance spectroscopy.

Table 5: CCT ranges for different TCC measured using UV-Vis reflectance spectroscopy.

TCC	CCT Range	
	Manufacturer's Specification	Experimental Result
Cycle	10 – 15 °C	9.1 – 16 °C
1	26 – 31 °C	23 – 31.9 °C
50	40 – 45 °C	38.9 – 44.9 °C
100	57 – 62 °C	59.9 – 64.9 °C
max. deviation	28 °C	19.1 – 34.9 °C

3.2.2 Mechanical Properties

During the phase change of PCM, the specific volume can change by up to 15%. Accordingly, the macroencapsulation used is deformed. To ensure that this does not damage the TCC, its mechanical properties are investigated. The test method is chosen according to DIN EN ISO 1519 [18], which describes a bending test. For this purpose, a self-constructed bending apparatus is used to bend strips of each TCC around cylinders of different radii. For each sample, the cylinder radius is reduced until the TCC is damaged. Two different types of damage were observed (see Figure 15 and Figure 16): some specimens showed numerous small cracks, while other specimens cracked in a single location.

The results of the bending tests are summarized in Table 6 and show that all TCC are compatible with the expected deformations of the flat macrocapsules.

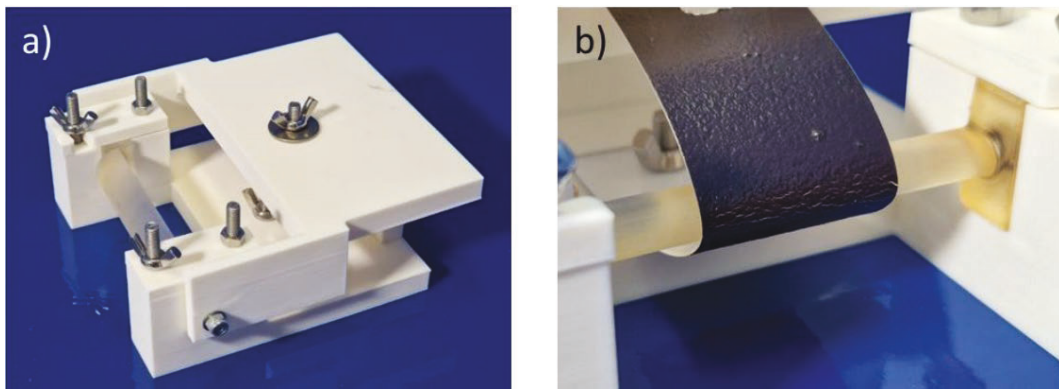


Figure 15: TCC bend test: (a) Bending apparatus, (b) TCC during testing process.

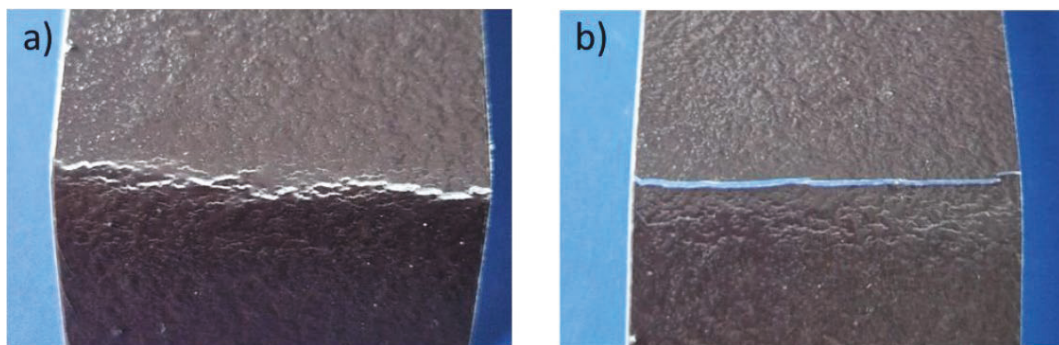


Figure 16: TCC damaged with many small cracks (a) and TCC damaged by a single crack (b).

Table 6: Critical bend radius of different TCC.

TCC	Critical Bend Radius
SC10	4 mm
SC26	4 mm
SC40	2.5 mm
SC57	4 mm
K28	5 mm

3.3 Functional Test of Laboratory Samples

All laboratory samples are tested under laboratory conditions. For this purpose, the sample to be tested is first heated in an oven to a temperature approximately 15 K above the melting temperature of the PCM, and then placed on a table to cool down. After the sample has reached ambient temperature, the crystallization of the PCM is triggered by the activation mechanism. The crystallization of the PCM is then recorded using an ordinary video camera (TG-5, Olympus) and a thermal imaging camera (A655sc, FLIR). The results are shown in Figure 17 and Figure 18.

a) $t = 0$ s



c) $t = 10$ s



a) $t = 25$ s

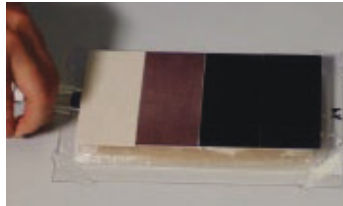


a) $t = 60$ s

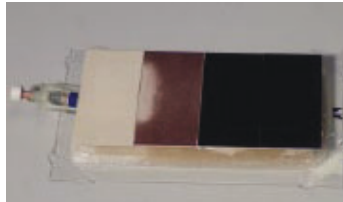


Figure 17: Test of laboratory sample A_SAT_SC26_SC40.

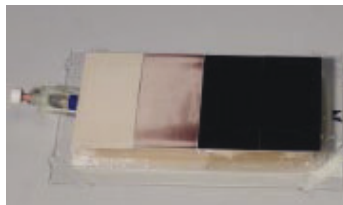
a) $t = 0$ s



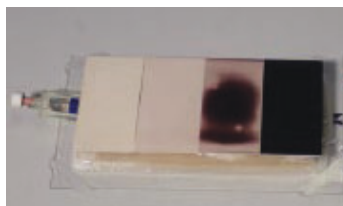
c) $t = 20$ s



a) $t = 30$ s



a) $t = 90$ s



e) $t = 210$ s



Figure 18: Test of laboratory sample B_SAT_SC_10_26_40_57.

The crystallization of the PCM takes about 1 minute. For the directly coated macrocapsules (Form A), the surface temperature changes faster than for the other sample because of the additional thermal resistance of the glued TCC. With the A_SAT_SC26_SC40 sample, both TCC change color from dark to white. While the SC40 coating has a black color at ambient temperature, the SC26 coating appears slightly brighter. Using the B_SAT_SC_10_26_40_57 sample, the SC10 TCC is already white at ambient temperature, while the SC57 TCC remains completely black even after activation of the sPCM, which has a solidification temperature of approximately 58°C.

The laboratory samples produced are also examined in another experimental setup shown in Figure 19. This setup consists of a sun simulation lamp (BF Sun, BFE) using a mercury vapor lamp (HMI 2500 W/DXS, OSRAM) placed 150 cm above the surface of the sample holder cube. The lamp is calibrated with a pyranometer (CM4, Kipp&Zonen) and operated at 1000 W/m². The BiTs sample B_CCH_SC10_26_40_57 is placed on the inner test surface of the sample holder cube, which is colored white for the experiments. The ambient temperature and the temperature next to and under the sample are measured using PT100 resistance thermometers. The experiment is started with an ambient temperature of about 20 °C and the maximum temperature in the measuring room is limited to 28 °C by an air conditioning system. The experiment is monitored in the visible and IR wavelengths using the same camera setup as in the first bispectral tests.

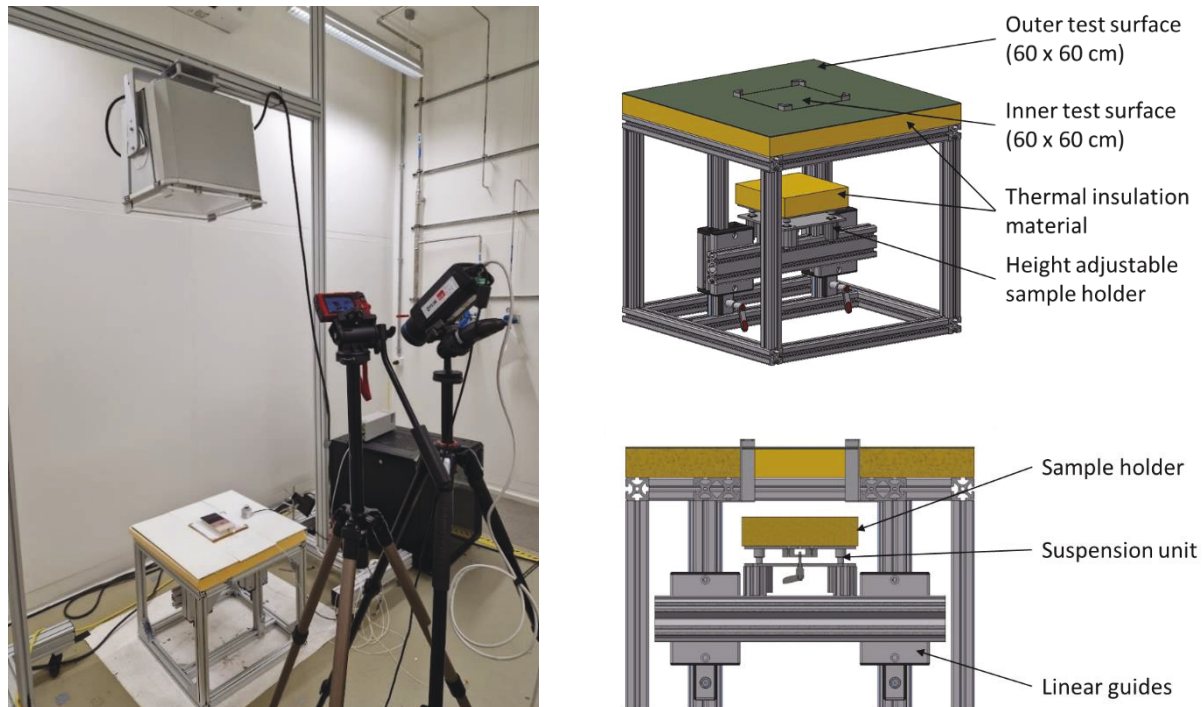


Figure 19: Test of laboratory sample B_CCH_SC10_26_40_57 in a simplified environmental simulation laboratory: experimental setup.

After approximately 1 hour, the temperature under the sample reaches approximately 30 °C, which corresponds to the melting temperature of the PCM (see Figure 20). The subsequent melting process of the PCM can be recognized by the almost constant temperature level, before the temperature begins to rise again after about 4.5 hours. The temperature of the measuring surface next to the sample rises to about 40 °C within 4 hours, while the room temperature also reaches its maximum value of 28 °C after about 4 hours. After that, slight fluctuations in the room temperature occur, which are due to the operation of the air conditioner. The sun simulation lamp is turned off after about 6.5 hours when the temperature under the sample exceeds 40°C. The bispectral images of the melting process are shown in Figure 21. During this process, the SC26 TCC changes color from dark to white and the SC40 TCC becomes brighter and slightly brownish. Small discontinuities in the surface temperature can be seen in the infrared images, which probably indicate air bubbles in the laboratory sample. After melting, the sample was cooled overnight at 19 °C for about 14 hours. The next morning, crystallization was successfully initiated using the actuation system. The bispectral images of the crystallization process are shown in Figure 22.

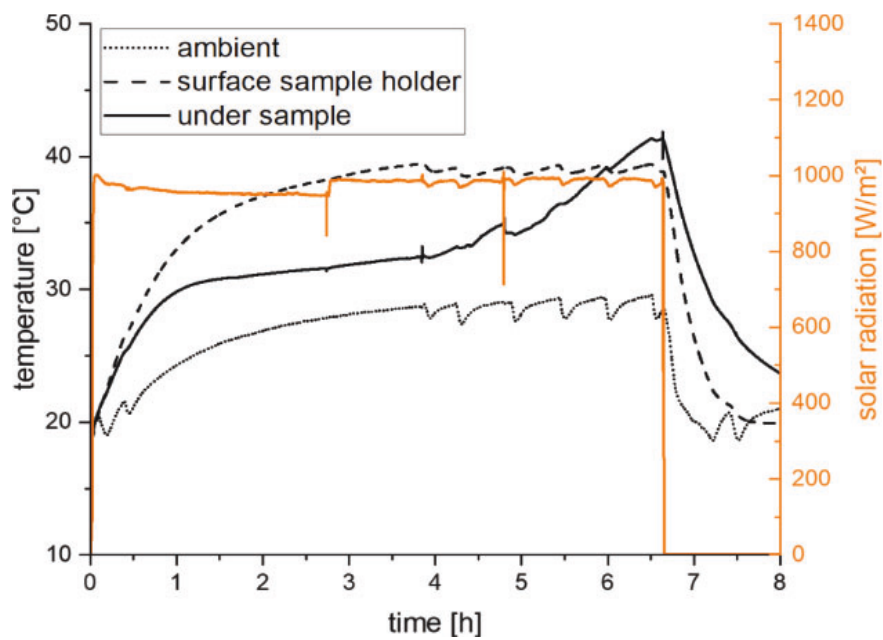
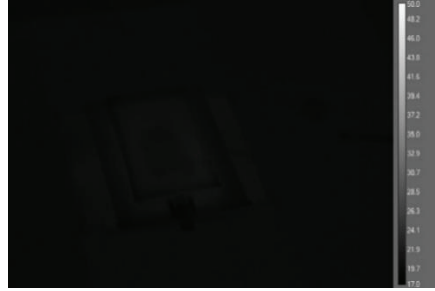
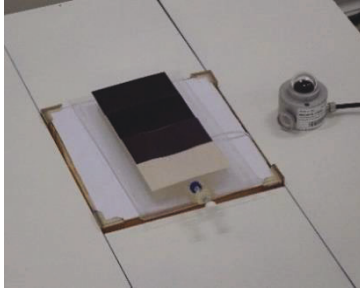
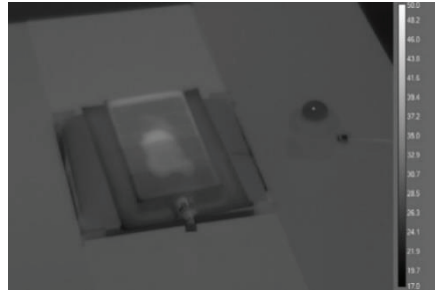
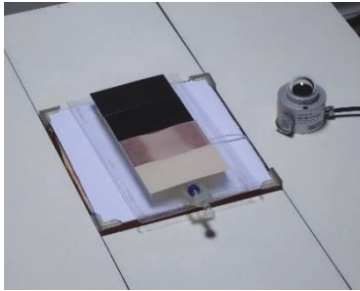


Figure 20: Test of laboratory sample B_CCH_SC_10_26_40_57 in a simplified environmental simulation laboratory: recorded temperatures during the melting process.

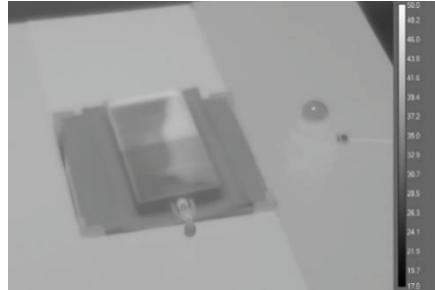
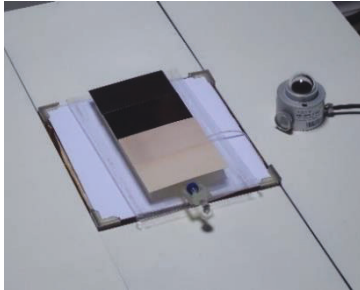
t = 0



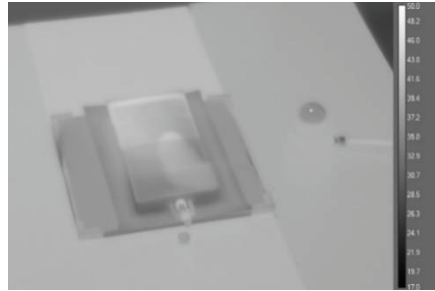
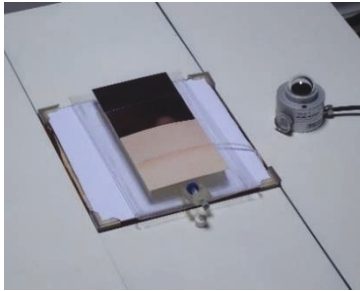
t = 1 h



t = 3,5 h



t = 5,5 h



t = 6,5 h

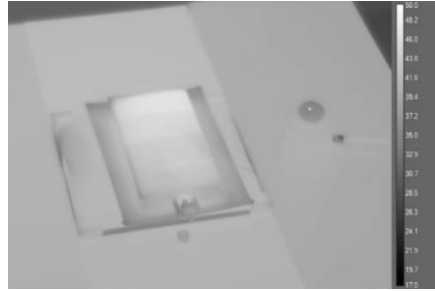
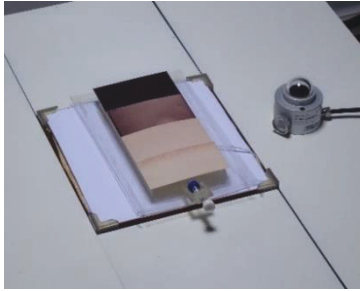
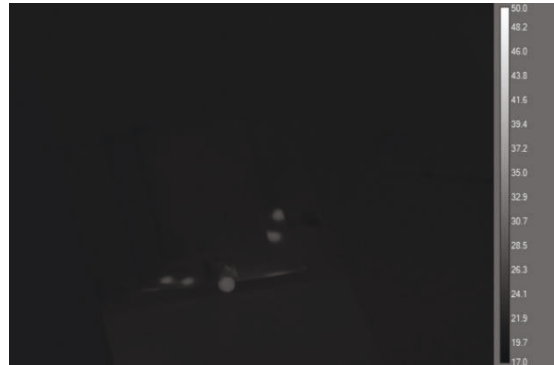
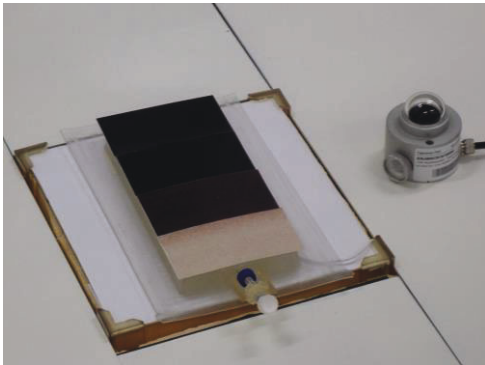


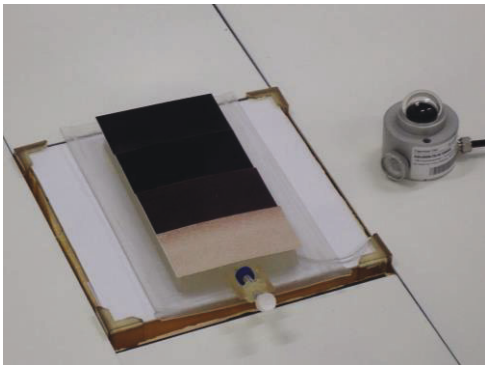
Figure 21: Test of laboratory sample B_CCH_SC_10_26_40_57 in a simplified environmental simulation laboratory: melting process.

BiTs: Bispectral Camouflage System Based on Switchable Phase Change Materials (sPCM) and Thermochromic Coatings

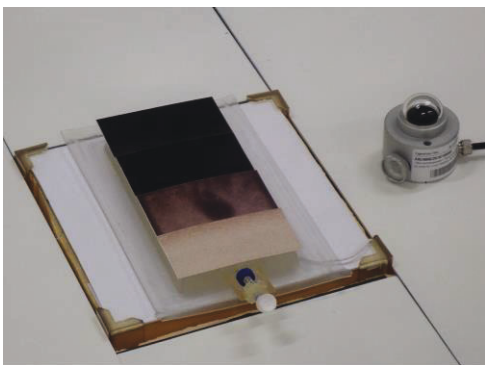
t = 0



t = 30 s



t = 90 s



t = 210 s

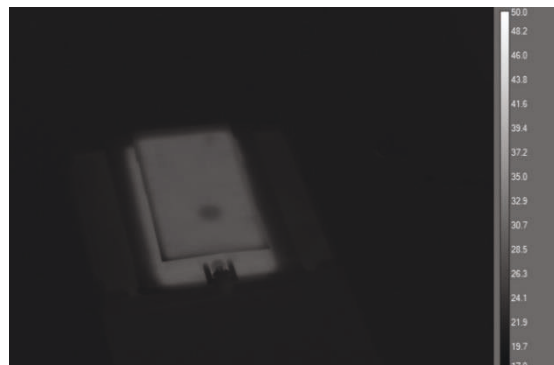
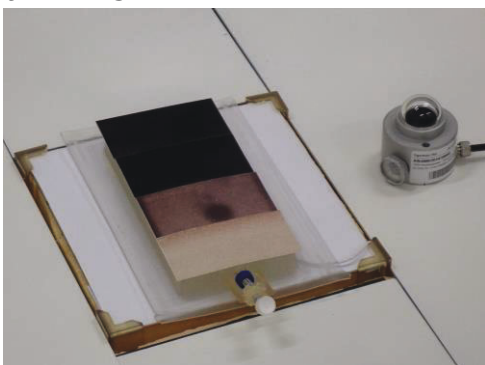


Figure 22: Test of laboratory sample B_CCH_SC_10_26_40_57 in a simplified environmental simulation laboratory: recorded temperatures during the crystallization process.

4.0 CONCLUSIONS

In this work, the principal feasibility of a bispectral camouflage system based on switchable phase change materials (sPCM) and thermochromic coatings (TCC) was investigated.

For this purpose, two PCM based on calcium chloride hexahydrate (CCH) and sodium acetate trihydrate (SAT) were used, whose cycle stability was ensured by modifying them with gelling agents. The thermophysical properties of the PCM storage gels prepared in this way, such as their melting enthalpy, cycle stability, and supercooling behavior, were investigated experimentally after 1, 50 and 100 cycles. Only the storage capacity showed a loss of about 5% after 100 cycles. The storage gels produced could be supercooled down to about 6 °C (CCH gel) and just below 0 °C (SAT gel). In addition to the supercoolable storage gels, non-supercoolable PCM gels, the so-called nucleation gels, were prepared by adding suitable nucleating agents, which can be used in an actuation system for controlled heat release from the supercooled storage system. In this work, an actuation system based on an injection mechanism was designed and used for this purpose.

In parallel to the described work on the PCM, five commercially available thermochromic colors for the temperature range of 10 to 62 °C were identified and procured, and sheet samples were fabricated with the respective TCC. The optical properties of the TCC were investigated by reflectance spectroscopy and the mechanical properties by bending tests. When the color change temperature is exceeded, the thermochromic colors in the TCC reach about 90% transparency, making the underlying base coat visible. In terms of mechanical properties, it can be summarized that the TCC used can withstand slight deformation. They can therefore be applied to the surface of PCM macroencapsulations, which deform slightly due to the phase change of the PCM during use.

The fabricated PCM gels, the developed actuator, and the TCC were finally combined into several functional laboratory samples. The general functionality of the laboratory samples was demonstrated both with laboratory samples that were previously melted in an oven and with laboratory samples that were melted under simulated solar radiation.

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