REDUCING THE RISK OF THERMAL CRACKING IN CEMENTITIOUS MATERIALS BY MEANS OF ENCAPSULATED PHASE-CHANGE MATERIALS

Didier Snoeck[1], Nele De Belie[2]

[1] Ghent University, Faculty of Civil Engineering and Architecture, Magnel Laboratory for Concrete Research, Tech Lane Ghent Science Park, Campus A, Technologiepark-Zwijnaarde 904, 9052 Ghent, Belgium,
email: didier.snoeck@ugent.be, nele.debelie@ugent.be

SUMMARY: Nowadays, when building new sustainable constructions with cementitious materials, energy efficiency becomes of larger significance especially in terms of global warming. The thermal insulation is hereby of utmost importance and the end-user wants a high and efficient thermal comfort. Concrete, having a high thermal mass, should and can be optimized in terms of heat capacity. Encapsulated Phase-Change Materials (PCMs) could be used for this purpose. PCM-mortars expand the thermal comfort in buildings. They store the heat during hot periods and release their stored heat during colder periods. This leads to a more gradual temperature feeling in buildings, increasing the experienced thermal comfort. PCMs can reduce energy consumption in buildings due to their thermal energy storage capability. In this paper, the effects of PCMs on the fresh properties, strength and thermal properties of mortar were studied. PCMs do not impair workability but they delay setting and reduce the strength, especially when high amounts (more than three mass percentage of cement weight) are added to the mortar. But the strength suffices for most concrete applications. Furthermore – as a proof of concept – the influences on the thermal properties and thermal cracking of insulated concrete sandwich panels were studied. Different PCMs with varying melting points of paraffin were hereby studied. PCMs reduce thermal strains due to their heat storage and thus counteract thermal cracking. They are innovative and promising materials to be used in future applications of civil constructions to promote thermal comfort and to reduce the risk of thermal cracking.

SMANJENJE RIZIKA TOPLINSKOG RASPUCAVANJA CEMENTNIH MATERIJALA S POMOĆU FAZNO PROMJENJIVIH MATERIJALA

SAŽETAK: Danas, kad se grade nove održive građevine, energetska učinkovitost postaje sve važnija, posebno u svjetlu globalnog zagrijavanja. Toplinska izolacija ima najveću važnost, a krajnji korisnik želi visok i učinkovit toplinski komfor. Beton koji ima veliku toplinsku masu treba se i može se optimirati na toplinski kapacitet. U tu svrhu mogu se upotrijebiti fazno promjenjivi materijali (engl. phase-change materials, PCM). Mortovi s PCM-om povećavaju toplinski komfor u zgradama. Oni zadržavaju toplinu u toplim razdobljima, a otpuštaju ju u hladnijim razdobljima. To rezultira u stupnjevitom osjećaju temperature u zgradama povećavajući doživljeni toplinski komfor. PCM-i mogu smanjiti potrošnju energije u zgradama zbog svoje sposobnosti zadržavanja (“skladištenja”) toplinske energije. U radu su istraženi učinci PCM-a na svojstva svježeg i očvrsnulog morta i njegova toplinska svojstva. PCM-i ne utječu na obradivost, ali usporavaju vezivanje i smanjuju čvrstoću, posebno ako se mortu dodaju veće količine (više od tri masena postotka na težinu cementa). No čvrstoća zadovoljava za većinu primjena u betonu. Nadalje, radi dokazivanja ove ideje proučavan je utjecaj na toplinska svojstva i toplinsko raspucavanje izoliranih betonskih sendvič panela. Proučeni su različiti PCM-i s različitim talištima parafina. PCM-i smanjuju toplinske deformacije zbog zadržane topline i stoga smanjuju toplinsko raspucavanje. To su inovativni i obećavajući materijali za buduće primjene u građevinarstvu, jer nude poboljšani toplinski komfor i smanjenje rizika od toplinskog raspucavanja.

1. INTRODUCTION

Energy-efficient building technologies are becoming more and more important and focus on increasing the energy efficiency and optimizing the thermal comfort. Construction materials with a large thermal mass, such as concrete, can and should be optimized to increase the energy efficiency and the overall thermal comfort. Outdoor heat can be used and its ingress can be delayed in time by using so-called Phase-Change Materials (PCMs) [1-6]. In this paper, we studied encapsulated PCMs, spherical in form and size. By using these PCMs, the thermal comfort can be increased.

Encapsulated PCMs are made by stirring an emulsion of hot water and paraffin. In next step, monomers and a possible reaction initiator are added. In this way, particles with a paraffin core and polymer shell from polymethylmethacrylate (PMMA) or melamine formaldehyde (MF) are made. By spray-drying these particles, a dry powder is produced. The paraffin plays an important role in the thermal behavior of the PCM. It is able to absorb and release a high amount of thermal energy upon solid-liquid and liquid-solid phase change, respectively. It thus may delay and flatten the increase in temperature during hot periods and may release its stored heat upon cooling during colder periods of time. The general principle is to use a PCM with a phase-change temperature of 1 - 3 °C above the average room temperature, which should be ideal to obtain optimal thermal comfort with possible direct energy savings of 5 - 20% [7].

Aside from this very interesting and positive feature of PCMs, they also possess a negative influence. They may decrease the overall mechanical properties of cementitious materials [8, 9]. In the latter research [9], two different techniques of PCM addition are studied. One is by replacing part of the small aggregates by the same mass of PCMs and the second by addition of PCMs on top. Replacing part of the sand led to less influence on the mechanical properties, as could be expected. They found reductions of 9, 15, 17 and 26% in compressive strength with respectively 5, 10, 15 and 20 % by volume (v%) of encapsulated PCM when using the replacement method. In case of the addition method 24, 40, 38 and 42% reductions in compressive strength were obtained, respectively. The higher decrease is due to the higher amount of small particles and partially due to the decrease in relative amount of cement per cubic meter of concrete. Hunger et al. [8] found a decrease of 29.5 % for 1 weight percentage of total weight (w%) of encapsulated PCM added and an additional 13% for each additional w% of encapsulated PCM added on top.

In this paper, commercially available encapsulated PCMs are studied on their influences on the mechanical properties. The effects on the fresh properties are studied as well as they are interesting from practical point of view. The PCMs were also applied in a practical case with insulated concrete sandwich wall panels. Here, due to differences in temperature, the wall elements tend to bend which causes high tensile stresses and thus also possible cracks in the outer panels. This is not desired and should be overcome as potentially harmful substances may start to deteriorate the concrete [10-12]. PCMs could be used to limit the thermal strains due to temperature variations as they may store part of the heat in their phase-change system.

2. MATERIALS AND METHODS

2.1. TYPES OF PHASE-CHANGE MATERIALS (PCMS)

Five commercial types of encapsulated PCMs were studied. These included Micronal DS 5039 X, Micronal DS 5040 X, Mikrathermic D18, Mikrathermic D24 and Mikrathermic D28. The Micronal PCMs were received from BASF (Germany) and had a PMMA shell and the Mikrathermic PCMs with a MF shell from Devan Chemicals NV (Portugal). All encapsulated PCMs are micro-encapsulated paraffin: 85 - 90 w% PCM and 10 - 15 w% polymer shell. The Micronal DS 5039 X microcapsules were dispersed in water and the other PCMs were powders. Their size, melting point and heat of fusion as found by means of Differential Scanning Calorimetry (DSC) are shown in Table 1. Differential Scanning Calorimetry (DSC) with a DSC Q2000 was used to verify the melting points and to determine the latent heat storage capacity within the encapsulated PCMs around the melting point.

Table 1: Different encapsulated PCMs with their size, melting point and heat of fusion

PCM	Size [µm]	Melting point [°C]	Heat of fusion [J/g]
Micronal® DS 5039 X	50-300	23.3	88.1
Micronal® DS 5040 X	50-300	23.3	88.1
Mikrathermic D18	17-22	18.1	177.2
Mikrathermic D24	17-22	23.3	134.3
Mikrathermic D28	17-22	28.3	161.3

2.2. MIXING PROCEDURE, CASTING AND MECHANICAL PROPERTIES

A mortar with a water-to-cement ratio of 0.50 by mass was used and composed of Portland cement (CEM I 52.5 N) (510 kg/m³), silica sand 0/2 (1530 kg/m³) and water (255 kg/m³). The ingredients were mixed according to the EN 196-1 Standard. A varying mass percentage (m%), in terms of the cement mass, of encapsulated PCM was added on top to the composition at the end of the mixing process, in order not to damage the capsules too much. After mixing, the flow value was determined following the EN 12350-5 Standard. After casting, the specimens were stored at 20 ± 2°C and a relative humidity of 95 ± 5%. At an age of 28 days, the mechanical characteristics were determined by means of a three-point-bending test and a compressive strength test following the Standard EN 196-1 on three specimens (40 × 40 × 160 mm³).

2.3. PRACTICAL APPLICATION: INSULATED SANDWICH PANELS

The temperature profiles in small insulated mortar sandwich panels were studied. They had an interior cladding of 90 mm, PU insulation of 50 mm and an external cladding of 60 mm. The width and the length of the tested samples were approximately 200 and 300 mm. Reinforcements were placed in the inner and outer panel (Ø 8 mm and mesh size 150 mm), as can be seen in Figure 1. Encapsulated PCMs were added in an amount of 3 kg per square meter encapsulated PCM. This amount is typically used in thermal applications [1]. This corresponds to approximately 5 m% encapsulated PCM. Thermocouples were put at the outer surfaces and the boundaries with the insulation. The strains in horizontal and vertical direction were also monitored in time at the interior and exterior surface. The specimen was put in an oven as replacement of the oven door and insulation was put around the specimen to ensure a uniform heat transfer through the specimen. The oven was put at 50°C. The dimensions and setup are shown in Figure 1.

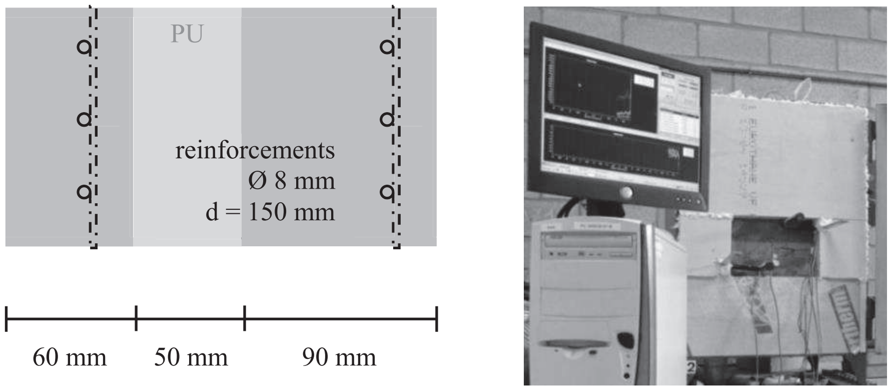


Figure 23: Dimensions (left) and test setup (right) of the insulated sandwich panel test

3. RESULTS

3.1. FRESH PROPERTIES

When investigating the workability upon casting (Figure 2), it is obvious that the addition of encapsulated PCMs reduces the flow values. The reduction, however, is acceptable up to 5 m% of encapsulated PCM addition. From practical point of view, one should limit the amount of PCMs to this value. Additional mixing water could be added to maintain the workability of mortar with PCM addition. However, by doing so, one would change the water-to-cement ratio, which is unwanted in consideration of the strength tests and microstructural properties. Another solution would be to use a superplasticizer, but this would influence the setting properties. Therefore, in this study, no alteration was made in the amount of used mixing water.

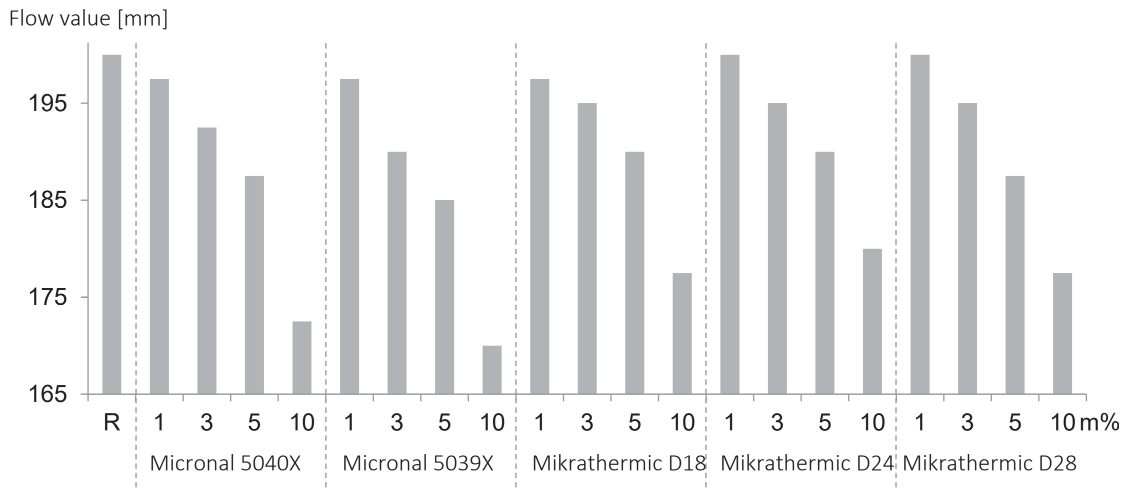


Figure 24: Workability (flow values) of samples with and without encapsulated PCMs

If one used a dispersed PCM, i.e. the Micronal DS 5039X, the workability was lower. As the amount of mixing water was reduced to counteract the fact that the dispersed solution also had water included, the overall workability was lower. This is due to the clogging of PCMs upon mixing due to the high viscosity of the Micronal DS 5039X. Part of the dispersion water is therefore trapped in between different PCM particles. In practical point of view, one should always use dry PCMs for their good dispersion in the cementitious matrix. This dispersion was also verified by breaking open the samples. Single PCMs were found and in case of the dispersed PCMs, some cluster formation of the PCMs was seen. This is unwanted as the interior PCMs will not be exposed to the heat as efficiently as the exterior PCMs. This may lead to a less positive influence of the PCMs in terms of absorbing the heat and thus the overall thermal comfort.

3.2. MECHANICAL PROPERTIES

The mechanical properties, especially flexural and compressive strength were studied, as can be seen in Figure 3. The overall trend in flexural strength is a reduction upon addition of PCMs. As the effective cross-sectional area of the samples is reduced, the flexural strength is lower. But, overall, it was found that the results were not significantly different from one another. In case of the compressive strength, the decrease is significant and larger when higher amounts of encapsulated PCMs are added. Again, the dispersed PCM proved to be less practical as a high reduction in strength was found. Furthermore, compared to the larger Micronal DS 5040X, the smaller Mikrathermic D PCMs behaved better considering the compressive strength of the mortar. The smaller PCMs are less influencing the strength due to their size. Furthermore, the reduction in compressive strength is in accordance with the results found in literature [8, 9]. For example, Hunger et al. [8] found a decrease of 29.5 % for 1 w% versus total weight (7.8 m% versus cement mass) of encapsulated PCM added and an additional 13 % for each w% of encapsulated PCM added on top. This value (29.5 % for 7.8 m%) seems to be of the same order of magnitude as the result found in this research (27 % for 5 m%).

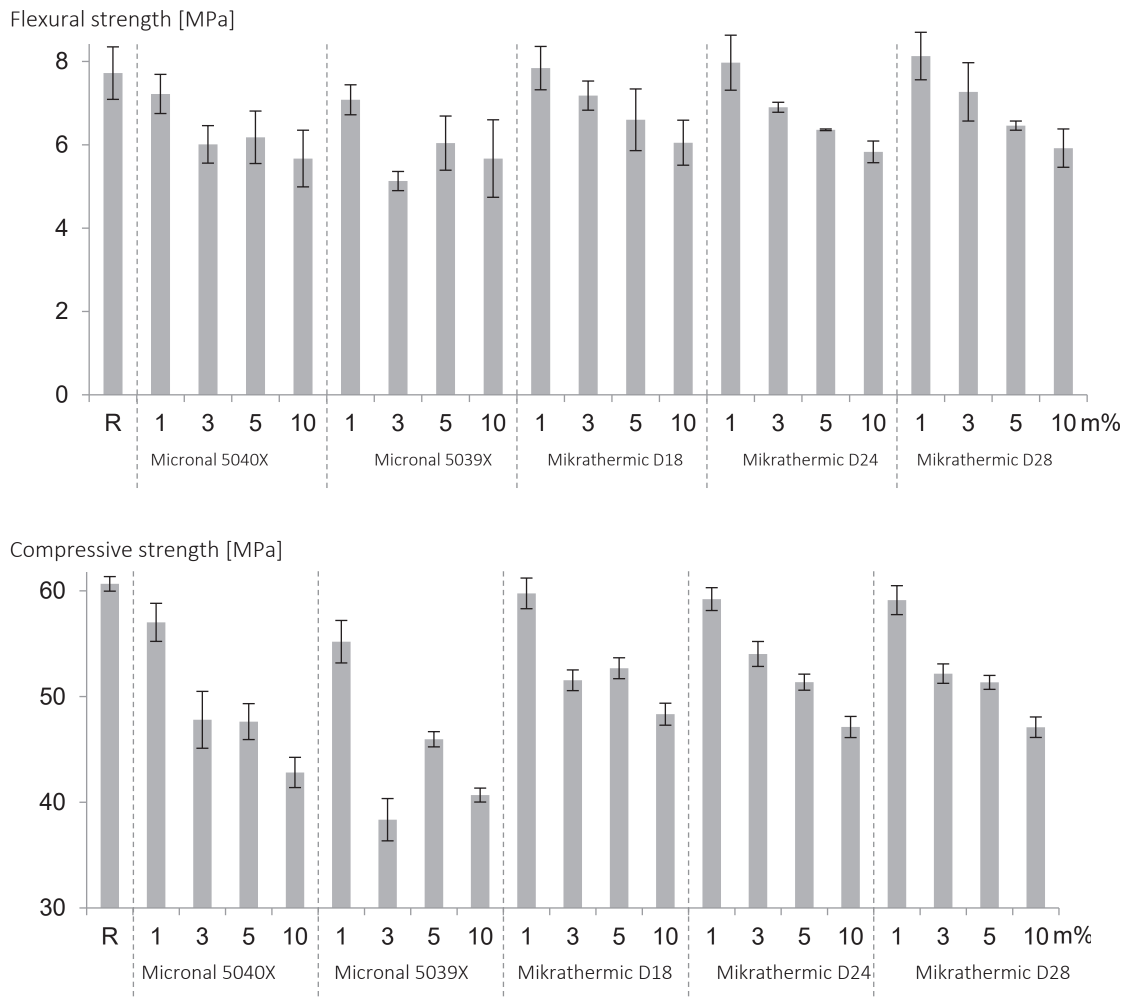
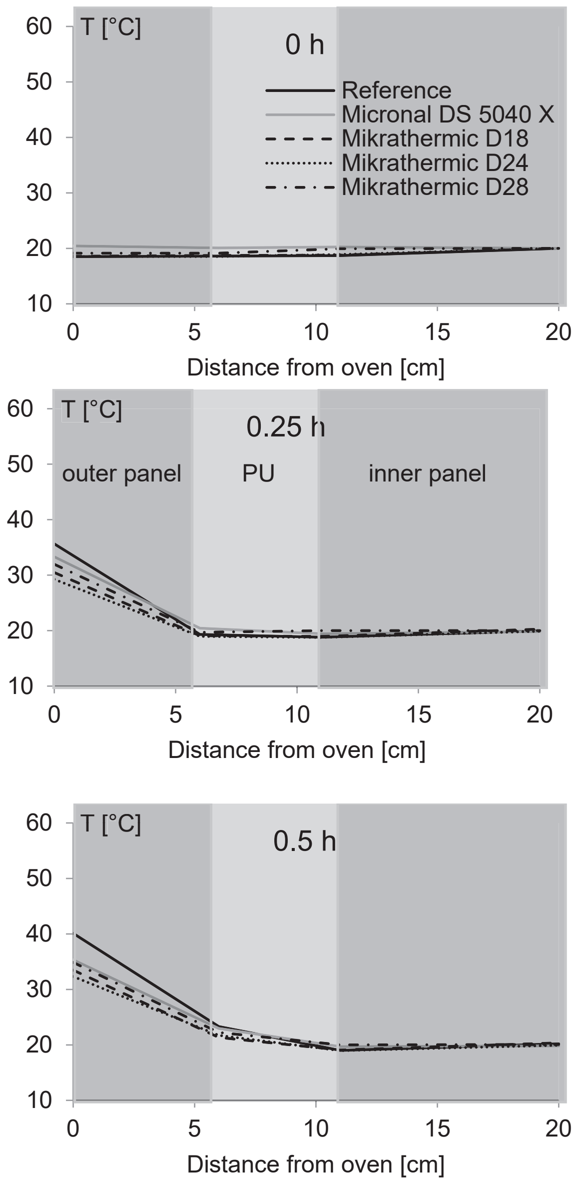


Figure 25: Mechanical properties of samples with and without encapsulated PCMs, with averages and standard deviations on single results

3.3. THERMAL PROPERTIES AND INSULATED SANDWICH PANELS

Generally, when heating and cooling mortar samples with and without PCMs, a typical thermal behavior was obtained. The delay upon cooling due to the encapsulated PCMs was clearly visible and the energy stored in the prisms was released more slowly if cooling is applied. Upon heating, it was the other way around; a delay in increase of temperature as could be expected. The biggest effect was seen with Mikrathermic D18, followed by Micronal DS 5039X, Mikrathermic D24, Micronal DS 5040X and Mikrathermic D28 which showed the smallest effect upon heating. Upon cooling the samples behaved inconsistently. There, in order of decreasing influence can be listed: Mikrathermic D28, Micronal DS 5040X, Mikrathermic D24, D18 and Micronal DS 5039X.

The insulated sandwich panels were heated till 50°C, and the temperature profiles at different times are shown in Figure 4. Again, it was found that encapsulated PCMs delayed the temperature changes. They also increased the heat capacity as they lowered the thermal conductivity. As this is only the case for PCM specimens, the heat in reference panels increased considerably, especially the temperature between the outer panel and the insulation itself. There were no significant temperature differences for the temperatures at the exterior of the inner panel, as was expected. But, as the average temperature gradient in the reference samples was higher compared to the specimens with PCMs, one can expect higher failure probability when using the reference panels. The reference wall elements tend to bend which causes high tensile stresses and thus also possible cracks in the outer panels. This cracking should be counteracted and the use of PCMs seems promising.



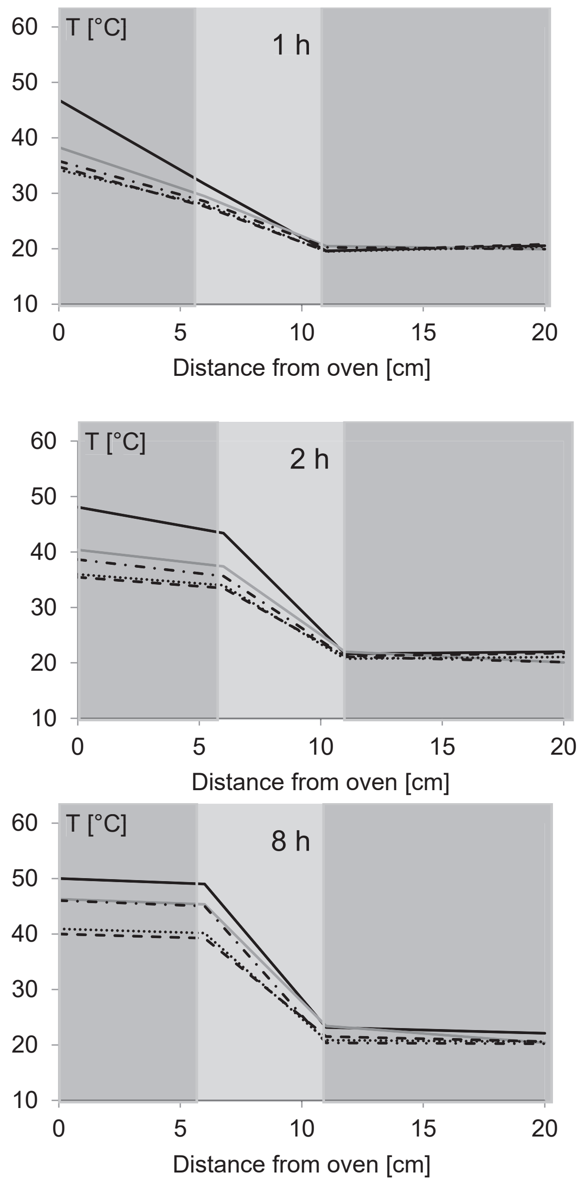


Figure 26: Temperature distribution in insulated sandwich panels with and without encapsulated PCMs

The best performance is found with Mikrathermic D18, followed by Mikrathermic D24 and Mikrathermic D28 and Micronal DS 5040X. As the melting temperature of Mikrathermic D28 particles is higher, they only become active after a certain period, and thus have a limited effect in terms of thermal properties. They can, however, be interesting in other countries or practical applications where the ambient temperature is expected to be higher. The high heat storage of Mikrathermic D18, as shown in Table 1, explains the best behavior. The reason why the Micronal DS 5040X behaves less in a larger specimen could be explained by the difference in particle size. As the particles are bigger compared to the Mikrathermic D type PCM, the heat flow may run in between the less well-distributed encapsulated PCMs, thus not decreasing the thermal conductivity as good as compared to the Mikrathermic types. The latter thus are better distributed in the matrix and can store the heat in an efficient way. Furthermore, when using small encapsulated PCMs, the overall surface area of PCM exposed to the cementitious matrix is higher, explaining the overall better behavior in terms of heat storage transfer and capacity. The heat is stored more quickly in the small PCMs compared to the larger ones.

The same trend as for the thermal behavior is found when simultaneously measuring the strains both in the vertical and horizontal directions at both faces of the sandwich panel. The directions of strain measurement did not show any differences in strains. This was expected as the panels are able to move and deform freely in every direction. The measurement therefore served as proof of concept of the measurement itself. During heating, a reference panel showed 140 µm/m strain, the panel with Micronal DS 5040X 117 µm/m, the panel with Mikrathermic D28 106 µm/m, the panel with Mikrathermic D18 84 µm/m and panel with Mikrathermic D24 only 80 µm/m strain. The accuracy of the strain gauges was approximately 1 µm/m. As expected, this confirms the previous conclusions.

4. CONCLUSIONS

The encapsulated PCMs were homogenously dispersed in mortar and the reduction of workability is acceptable up to 5 m% of PCM addition. Practically, dry PCMs are preferred for adding to mortar.

The mechanical properties and especially the compressive strength decreased significantly. The amount of PCM addition should be limited to 5 m% not to reduce the strength too much.

Encapsulated PCMs are suitable for increasing the thermal comfort in buildings if cooling happens daily, thus giving the encapsulated PCMs the opportunity to release their stored heat. Encapsulated PCMs lead to lower thermal conductivity and increased heat capacity of a concrete structure. They improve the thermal performance of concrete and therefore may save energy.

Encapsulated PCMs are promising materials to use in sandwich panels as they delay the temperature rise and, by doing so, decrease the resulting stresses and strains. They thus may reduce thermal cracking.

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REFERENCES

[1] Baetens, R.; Jelle, B.P.; Gustavsend, A.: Phase change materials for building applications: A state-of-the-art review, *Energy and Buildings*, 42 (2010) 9, pp. 1361-1368, 0378-7788

[2] Bentz, D.P.; Turpin, R.: Potential applications of phase change materials in concrete technology, *Cement and Concrete Composites*, 29 (2007) 7, pp. 527-532, 0958-9465

[3] Delgado, M.; Lázaro, A.;Mazo, J.; Zalba, B.: Review on phase change material emulsions and microencapsulated phase change material slurries: Materials, heat transfer studies and applications, *Renewable and Sustainable Energy Reviews*, 16 (2012) 1, pp. 253-273, 1364-0321

[4] Mehling, H.; Cabeza, L.F.: *Heat and cold storage with PCM: An up to date introduction into basics and applications*, Springer, 978-3-540-68557-9, Berlin, (2008)

[5] Snoeck, D.; Priem, P.; Dubruel, P.; De Belie, N.: Encapsulated Phase-Change Materials as additives in cementitious materials to promote thermal comfort in concrete constructions, *Materials and Structures*, 49 (2015) 1, pp. 225-239, 1359-5997

[6] Zalba, B.; Marín, J.M.; Cabeza, L.F.; Mehling, H.: Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, *Applied Thermal Engineering*, 23 (2003) 3, pp. 251-283, 1359-4311

[7] Peippo, K.; Hauranen, P.; Lund, P.D.: A multicomponent PCM wall optimized for passive solar heating, *Energy and Buildings*, 17 (1991) 4, pp. 259-270, 0378-7788

[8] Hunger, M.; Entrop, A.G.; Mandilaras, I.; Brouwers, H.J.H.; Founti, M.: The behavior of self-compacting concrete containing micro-encapsulated phase change materials, *Cement and Concrete Composites*, 31 (2009) 10, pp. 731-743, 0958-9465

[9] Meshgin, P.; Xi, Y.: Effect of phase change materials on properties of concrete, *ACI Materials Journal*, 109 (2012) 1, pp. 71-80, 0889-325X

[10] Snoeck, D.: *Self-Healing and Microstructure of Cementitious Materials with Microfibres and Superabsorbent Polymers*, Ghent University, 978-90-8578-845-4, Ghent, (2015)

[11] Snoeck, D.; Steuperaert, S.; Van Tittelboom, K.; Dubruel, P.; De Belie, N.: Visualization of water penetration in cementitious materials with superabsorbent polymers by means of neutron radiography, *Cement and Concrete Research*, 42 (2012) 8, pp. 1113-1121, 0008-8846

[12] D. Snoeck, K. Van Tittelboom, S. Steuperaert, P. Dubruel, N. De Belie, Self-healing cementitious materials by the combination of microfibres and superabsorbent polymers, *Journal of Intelligent Material Systems and Structures*, 25 (2014) 1, pp. 13-24, 1045-389X