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INVESTIGATIONS ON MULTIFUNCTIONAL TIMBER ELEMENTS IMPREGNATED WITH PARAFFINIC PHASE CHANGE MATERIALS

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ABSTRACT: In this contribution, investigations on multifunctional timber elements impregnated with phase change materials (PCM) are presented. The purpose of the PCM impregnation is a passive air-conditioning by structural timber elements like beams, walls or ceilings. PCM have the ability to take up substantial thermal energy within a narrow, latent temperature range without increasing their temperature. The high specific heat capacity combined with low additional mass can improve the room climate in timber buildings, which have often especially in the summer unpleasant temperature amplitudes without air-conditioning due to low thermal mass.

In order to produce large size PCM-impregnated timber elements several investigations are performed. Besides fundamental impregnation and leakage tests for several wood species, also construction related investigations are carried out. Glue-lamination is important for producing large size structural elements. Thus, different adhesives like, epoxy resin, polyurethane and phenol-based resins are tested for suitability of gluing PCM-impregnated wood. This is also a key aspect for supressing leakage on the surface of the structural element by arranging there a thin layer of not impregnated wood. Other investigations are related to the experimental determination of the mechanical behaviour of PCM-impregnated wood and the combustion behaviour.

KEYWORDS: phase change materials, glue lamination, mechanical properties, combustion behaviour, reaction to fire

1 INTRODUCTION

The use of fossil energy for thermal conditioning of buildings contributes significantly to the global warming by CO_2 emissions. There are several techniques established to reduce the energy consumption of a building for thermal conditioning like thermal insulation, shading, orientation of the building or positioning of the windows etc.

An aspect, which is often not specifically designed is thermal mass or heat capacity, although it is well known that wood buildings have especially in the summer drawbacks compared to heavy buildings made, e.g., of concrete or brick due to low thermal mass. This often results in the necessity of active air-conditioning.

Heat capacity is defined as the product of mass by specific heat capacity of the material. Thus, in order to increase the heat capacity of a building either the amount of material can be increased or a material with higher specific heat capacity can be used. With regard to limited resources, increasing mass just for the purpose of improving thermal conditions seems not to be desirable as it increases the CO_2 footprint and is usually also associated with decreasing usable space or increasing the volume of the building. On the other hand, modifying the specific thermal mass of a material is not easily possible.

However, wood has a cellular structure, which can be used for impregnation to increase the mass and depending on the specific heat capacity of the impregnation materials also the heat capacity of the building element. A special class of materials, so-called phase change materials (PCM), possess a very high specific heat capacity in a narrow temperature range and might be good candidates for impregnation of wood. Especially paraffinic PCM seem to be suitable as they are inert and do not react with the chemicals of the wood. Thus, a long endurance of the PCM is expected. Literature reviews on the impregnation of wood with PCM are given in [1],[2].

By applying PCM, a low amount of additional mass leads to a high increase of heat capacity of a timber element. Previous investigations [1],[3] showed that it is realistic to deposit about 200 kg of PCM per m³ of wood. Thus, depending on the applied wood species the mass is increased by about 30 to 50 %. At the same time, the storable thermal energy is increased in the phase transition range of the PCM by 400 to 600 % (assuming a sensible enthalpy of wood of about 20 J/g and a latent enthalpy of PCM of about 200 J/g in the range of +/- 5°C around the phase transition temperature). By placing PCM in wood elements, temperature amplitudes are passively reduced inside a room over the day by energy uptake of the PCM. By natural ventilation, the room temperature can be decreased over the night below the phase change temperature of the PCM and the stored thermal energy is released.

Most of the previous investigations from literature concentrate on the application of PCM-impregnated wood for interior elements without structural functions like

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flooring [10], etc. In the current investigations, elements like beams, walls or ceilings, bearing structural loads are intended. For practical applications, several aspects need to be investigated. A selection will be addressed in this contribution and is briefly summarized in the following.

2 MATERIAL AND METHODS

2.1 IMPREGNATION OF TIMBER

Results on the impregnation of solid wood were already presented in [1]. Pressure impregnation processes in an autoclave with a maximum pressure of 0.8 MPa were carried out. In this contribution, an update is given. The used PCM is the commercially available paraffin-based PCM RT35HC produced by the company Rubitherm, Germany. Four wood species (spruce, beech, poplar and oak) were applied for the investigations. The effectiveness of the impregnation is described by the PCM uptake, which is the mass of PCM within a certain volume of wood.

2.2 LEAKAGE AND ITS SUPPRESSION

Significant leakage was observed for some wood species, which can be substantially suppressed with increasing the viscosity of the PCM [1]. As a new development, the addition of mineral particles (cement Mikrodur R-X by the company Dyckerhoff, Germany) was tested to reduce leakage with promising results. However, for improving serviceability of timber elements, leakage on the surface needs to be securely suppressed. Therefore, a not impregnated timber layer on the surface is applied, which is able to seal the surface.

2.3 HEAT CAPACITY

The specific heat capacity of the impregnated wood is measured with dynamic differential scanning calorimetry (DSC) using a device Netzsch DSC 204 F1 Phoenix. For calibration, the sapphire standard was used. By integration of the specific heat capacity over a temperature range, the enthalpy can be determined, which is a measure for the storable heat of the material in the temperature range. A detailed description of the test procedure is given in [1].

2.4 MECHANICAL BEHAVIOUR

For structural purposes, the mechanical behaviour of the impregnated timber is important. As the PCM might be available in the solid and the liquid state, the mechanical behaviour is determined for both states. As a first indicator of structural performance, three point bending tests (span 420 mm) were carried out according to DIN 52186 [4]. The dimensions of the samples were 450 mm by 20 mm by 25 mm (length by width by height). Both, clear and impregnated samples of beech, spruce and poplar were tested. The impregnated samples of beech and spruce had a PCM uptake of about 200 kg/m³. Poplar had with about 250 kg/m³ a higher PCM uptake. The tests were performed at room temperature with the PCM either in the solid state or after a conditioning of the respective samples at 50°C (60% r. h.) in the liquid state. For each parametric combination 10 samples, thus, in total 120 samples, were tested.

2.5 GLUE-LAMINATION

For producing large size structural elements of timber, glue-lamination is important. Moreover, smaller dimensions of timber pieces support impregnation and reduce the treatment time. As gluing of paraffin impregnated wood is not standardised, investigations are performed to determine effective lamination techniques. Besides the option of producing large timber elements, a high-quality glue-line also supports the sealing of the impregnated timber parts and the suppression of leakage as pointed out previously.

In order to produce engineered timber elements, the gluability of PCM-impregnated wood was investigated. As a first indicator, the shear strength of the glue line was tested corresponding to EN 205 [5], which is a lap joint tension shear test, with different commercial adhesives: an epoxy resin (Vosschemie Epoxy-BK), a phenol resol resin (Bakelite PF 0283 HL) and a one-component polyurethane adhesive (Collano Semparoc I 12 NV). Impregnated and not impregnated reference samples of beech, spruce, poplar and oak were tested. Each four impregnated and two reference samples were tested. The tests were performed at room temperature, when the PCM was in its solid state. The small sized specimens had a glued area of 10 by 20 mm² (length by width).

2.6 COMBUSTION BEHAVIOUR

The combustion behaviour of materials can be tested with a so-called cone calorimeter according to ISO 5660-1 [6]. In this test, a quadratic board shaped sample is heated at the top side. The sample is wrapped with aluminium foil to avoid the loss of leached PCM during the test, while the top side remains open. Afterwards, the sample is placed on the sample holder, which is attached to a weighing cell continuously measuring the mass of the sample during the test. Above the sample an electrical radiant heater is placed, which heats the sample continuously with 50 kW/m².

For the ignition, a spark plug is additionally placed on top of the sample. It is removed as soon as the samples starts burning. The time for ignition t_{ig} is documented for later evaluation. After ignition, the radiant heater is heating the sample for 30 minutes. Besides the continuous measuring of the weight of the sample, the oxygen content of the air, which is collected via the conical head above the sample, is determined. Based on the oxygen content of the air, the heat release by the sample is calculated. Moreover, the smoke production is determined with a photocell.

Each two samples were prepared for the wood species beech, spruce, poplar and oak, which were either impregnated with clear PCM or a PCM-cement mixture. As a reference, also clear wood samples were tested. The samples had dimensions of 100 mm by 100 mm by 30 mm (length by width by thickness). While the longitudinal material orientation was parallel to the length

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direction, there was no special alignment of radial and tangential direction.

The PCM uptake of the samples was different depending on the wood species: the beech samples possessed an uptake of about 130-180 kg/m³, the spruce samples of about 140-180 kg/m³, the poplar samples of about 260-280 kg/m³ and the oak samples of 120-150 kg/m³. The samples were conditioned before the testing at 23°C and 50 % relative humidity.

In a second test, the combustion behaviour of a construction element was tested in a setup according to EN ISO 9239-1 [7]. The element was a three-layer wood flooring with a PCM-impregnated middle layer of 8 mm thickness. The PCM uptake was about 200 kg of PCM per m³ of wood. The PCM contained cement particles. The top layer as well as the counteracting lower layer were not impregnated and had a thickness of 3 mm and 2 mm, respectively. The middle layer and the lower layer were made of spruce. The top layer, which was coated with a commercial lacquer, was made of oak. As a reference, elements without PCM were tested. The reference elements are commercially available.

The specimens had a length of 1050 mm and a width of 230 mm. Since the flooring elements are connected mechanically in practice, these joints have to be considered also in the tests. Thus, for the PCM-impregnated and the reference elements one test with a connection in longitudinal direction and one test with joints in transverse direction were performed. During the tests, the samples were placed on a fibre cement board of 8 mm thickness.

The detailed testing procedure is given in EN ISO 9239-1 [7]. Essentially, the sample is heated for the first 10 minutes with a gas burner at one end of the sample over the entire width. After 10 minutes, the burner is turned off. The flame propagation is observed for another 20 minutes. The flame propagation at the sample is recorded over the entire testing time (1800 s).

Moreover, the smoke development is recorded. For achieving a certain fire class according to EN 13501-1 [8], a certain limit of the critical heat flux *CHF* as well as the smoke density integral $\int R$ needs to be complied. The limits for the fire classes according to EN 13501-1 [8] are summarized in Table 1.

Table 1: *Limits for fire classes according to EN 13501-1*

	Fire class			
	B_{fl}	C_{fl}	D_{fl}	E_{fl}
CHF [kW/m²]	≥ 8.0	≥ 4.5	≥ 3.0	Test acc. to EN ISO 11925-2 [9] necessary
	Smoke development			
	s_1	s_2		
$\int R$ [min·%]	≤ 750	> 750		s1, s2 only for B_{fl}, C_{fl}, D_{fl},

3 RESULTS AND DISCUSSION

3.1 IMPREGNATION AND LEAKAGE

Investigations on the impregnation of wood with PCM RT35HC and leakage of PCM out of the wood were already presented in [1],[3]. Thus, these results are only summarised here briefly. It was shown that a high PCM uptake of up to 400 kg of PCM per m³ of wood, which is close to the theoretical maximum corresponding to the available lumen, could be achieved for poplar with pressure processes. For beech, the achieved uptake is with about 250 kg of PCM per m³ of wood less, which is associated with the smaller lumen. The impregnation of beech can be carried out, in principle, by soaking. Pressure processes only decrease the necessary treatment time. Although the impregnability of spruce is worse, a PCM uptake of about 200 kg of PCM per m³ of wood was achieved with pressure processes. However, there is considerable variation in the results of spruce. Oak is very hard to impregnate and even with the applied pressure of 0.8 MPa only an uptake of about 100 kg of PCM per m³ of wood was achieved. It shall be noted that in the respective investigations, the end grain of the samples was sealed in order to simulate the behaviour for big timber elements in the industry. For smaller elements and with open end grain, higher PCM uptake can be achieved.

The addition of thermoplastic additives for increasing the viscosity and, thus, reducing leakage resulted in reduced PCM uptake. For beech and poplar, still high PCM uptake was achieved. As a new development, cement particles with a diameter of less than 5 µm were added to the PCM for reducing leakage by closing the tips of the wood cells. The achieved PCM uptake is comparable with the values when thermoplastic additives are added. Specific values are given related to the description of the other investigations.

Since the wood has a more or less open porous structure, PCM can leach out of the wood volume, which is undesirable for the practical application. The proneness to leakage depends on the wood species. Poplar shows a maximum leakage of about 10 % of the initial amount of PCM. Leakage depends on the PCM uptake, which means that with lower PCM uptake also less leakage occurs, both absolute and relative. For oak, the observed leakage was less than 10 % and, supposedly, limited to PCM in the outermost cell layers. While leakage can be reduced for both wood species by increasing the viscosity of the PCM or by addition of cement particles, a post-treatment at a temperature above the phase transition temperature allowing excessive PCM to leach is advisable and sufficient.

For spruce and beech, leakage of more than 60 % of the initial volume was observed, especially with high amounts of PCM uptake. The addition of thermoplastic or cement particles can reduce leakage significantly to less than 20 % of the initial amount of PCM in the wood. Thus, a post-treatment for leaching excessive PCM is advisable but additionally a careful sealing is necessary to avoid leakage permanently.

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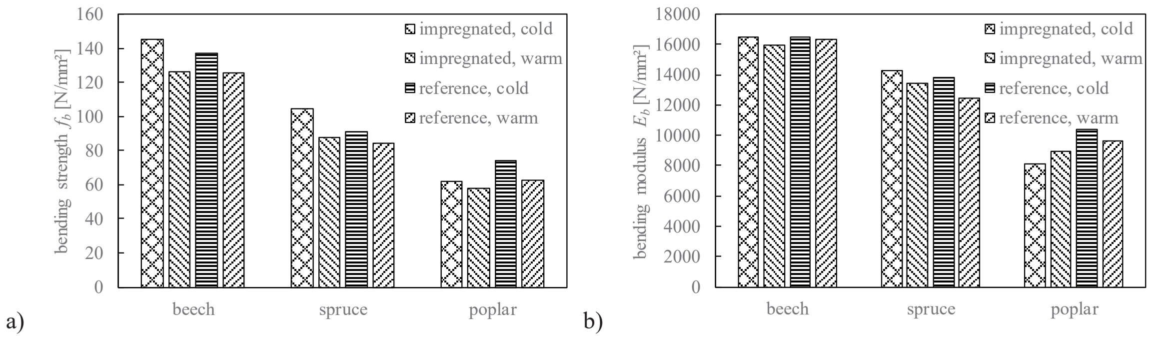

Figure 1: *Results of the bending tests; a) Bending strength, b) Bending modulus*

3.2 HEAT CAPACITY

Results regarding the determination of the heat capacity of the PCM-containing wood were already presented in detail in [1]. Thus, only a summary is given here. The determination of the specific heat capacity of PCM around the phase transition temperature is associated with some challenges due to a dependency on the applied temperature gradient and the amount of the tested material in the DSC. However, the enthalpy, which is the integral of the specific heat capacity over a temperature range, in this case the phase transition range, is independent of the temperature gradient and the amount of material.

Moreover, the enthalpy might be more useful for evaluation of the influence of the PCM on the thermal mass since it gives the total amount of storable heat around the phase transition temperature. In contrast, the specific heat capacity of PCM shows only a peak at the phase transition temperature and has before and after a value in the magnitude of the respective value of wood. Thus, the peak value is not representative for the entire temperature range in service. The results of the investigations presented in [1] show that the phase transition enthalpy of the impregnated wood is proportional to the PCM uptake.

Thus, the enthalpy of fusion or solidification of about 200 J/g of the applied PCM RT35HC and the amount of PCM in the element, i.e. the PCM uptake, can be directly used for estimating the influence on the room temperature e.g. in climatic simulations.

3.3 MECHANICAL BEHAVIOUR

Figure 1 shows the evaluation of the results of the bending tests in terms of bending strength f_b and bending modulus E_b. It can be seen that, as well known, the three wood species have different strength and elasticity values.

Moreover, the known effect of a reduction of f_b and E_b with increasing temperature is observable. In the solid state, the impregnation with PCM results in increasing f_b compared to clear wood for beech and spruce. To lower extent, this is also observable for spruce for E_b. In the liquid state of the PCM, the increase of f_b and E_b vanishes. For poplar, both f_b and E_b were smaller for the impregnated samples than the clear samples. This was also associated with a significantly more brittle failure behaviour.

For the practical application, it can be assumed that at least for the common species for construction purposes spruce and beech, the mechanical properties are not significantly influenced by the impregnation with PCM. This corresponds also to findings in [11]. For poplar, a reduced PCM uptake might result in more favourable mechanical properties and less brittleness.

3.4 COMBUSTION BEHAVIOUR

The combustion behaviour of PCM-containing wood was investigated with two different tests. Figure 2 shows the results of the cone calorimetry for the different wood species and impregnations. It can be seen that the mass of the samples decreases quasi-linearly during the combustion process. Only short before the end of the combustion an increasing mass loss rate is observable. This can be explained by a bending deformation of the samples, which results in a better access of oxygen to the bottom of the sample and an increasing burning surface.

The mass loss rate during the undisturbed combustion before bulging of the sample is approx. the same for the impregnated and the clear reference samples. Except of beech, the mass loss rate is also similar for all the wood species. Nevertheless, it can be seen that the combustion time is longer for the PCM-containing samples due to the higher total mass and has for some samples not ended at the end of the test after 1800 s. The heat release is larger for the PCM-impregnated samples than for the clear reference samples. While the heat release rate *HRR* during undisturbed combustion is except for beech approx. the same for the clear samples of the different wood species, it depends for the impregnated samples on the PCM uptake. Corresponding to the PCM uptake, *HRR* of the PCM-impregnated samples is the lowest for oak and the highest for poplar. There is no significant difference due to the addition of cement observable. The somewhat higher *HRR* for the cement-containing samples of beech can be explained by a higher PCM uptake compared to impregnated samples without cement.

Based on the measured quantities, indicators characterizing the fire ignition hazard and the provided energy for fire propagation can be calculated [12].

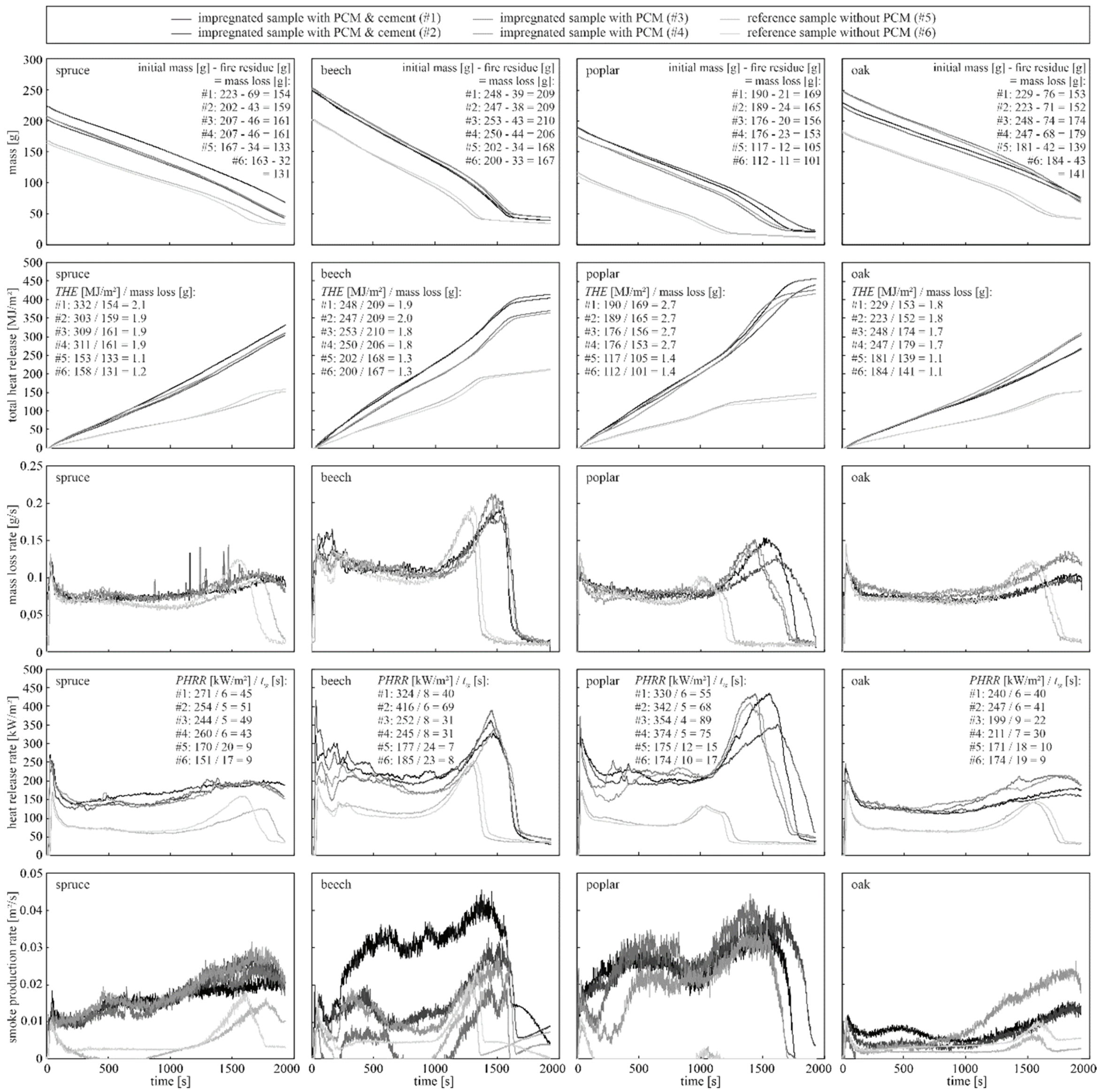

Figure 2: *Results of the cone calorimetry tests*

A first indicator is the ratio of the peak heat release rate *PHRR* and the time to ignition t_{ig}. Both values as well as the ratio are given in Figure 2 in the diagrams of the heat release rate versus time. It can be seen that t_{ig} is substantially smaller for the impregnated samples compared to clear reference samples while the PHRR values are considerably larger. The ratio PHRR / t_{ig} is approx. four to five times larger for the impregnated samples, which means that the PCM acts as fire accelerant.

A second indicator is the ratio of the total heat release at the end of the test *THE* and the mass loss of the sample. This ratio is for the impregnated samples less than twice as large as for the clear reference samples. Thus, for the propagating fire the PCM has a less significant influence than for ignition.

As a conclusion, it can be stated that unprotected PCM-containing wood ignites faster and provides more heat during combustion for fire propagation than clear wood. However, the results of the cone calorimeter tests cannot directly be transferred to real fire events due to a large dependency on length scale [12]. Thus, further tests are necessary.

As described in Section 2.6 also fire tests according to EN ISO 9239-1 [7] on wood flooring containing PCM were performed. Table 2 shows the achieved values of the fire tests with the flooring samples. Besides the *CHF* and $\int R$ values, also the maximum flame spread L_{max} and the

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maximum light absorption R_{max} are given. The flame spread propagated in all samples until the end of the test after 1800 s.

Figure 3 shows diagrams of the flame spread vs. time and the characteristic relation for determining *CHF*. From Table 2 and Figure 3, it can be seen that *CHF* of the samples containing PCM has a higher value than the reference samples without PCM. Thus, the flooring containing PCM has with C_{fl} a more favourable fire class than the reference flooring, which achieves only D_{fl}. This probably unexpected result can be explained with the higher heat capacity of the PCM-containing elements, which initially absorb the heat and cool the flamed top layer. This is possible because the PCM is not directly flamed but protected by the not impregnated top layer. Thus, the flash point of the PCM at 177°C is not instantaneously reached like in the tests with the cone calorimeter previously described.

It should be considered that the PCM was in its solid state at the beginning of the test and, thus, a significant additional heat uptake was possible. It remains to be tested, how the behaviour is when the PCM is in its liquid state right from the beginning of the test and, thus, the cooling effect is not existing. It can be assumed that in this case also the PCM-containing elements achieve only fire class D_{fl}.

The second characteristic for the definition of the fire class is the smoke development. As Table 2 shows, the PCM-containing elements behave less favourable with stronger smoke development in terms of $\int R$ and R_{max} compared to the reference samples. Still, the values are considerably below the acceptable values as given in Table 1 for classification s_1, which, thus, both the PCM-containing samples and the reference samples reach.

As a conclusion, it can be stated that a protection of the PCM-containing wood improves the fire behaviour significantly and can compensate the fire accelerating properties of the PCM when directly flamed.

Table 2: *Results of the reaction to fire test according to EN ISO 9239-1 on wood flooring with PCM*

Value	Sample without PCM (long. joint)	Sample without PCM (trans. joints)	Sample with PCM (long. joint)	Sample without PCM (trans. joints)
CHF [kW/m²]	3.98 (D_{fl})	3.71 (D_{fl})	4.58 (C_{fl})	4.67 (C_{fl})
$\int R$ [min·%]	42.1 (s_1)	50.4 (s_1)	175.7 (s_1)	110.7 (s_1)
L_{max} [mm]	480	498	440	434
R_{max} [%]	8.7	11.1	20.7	15.8

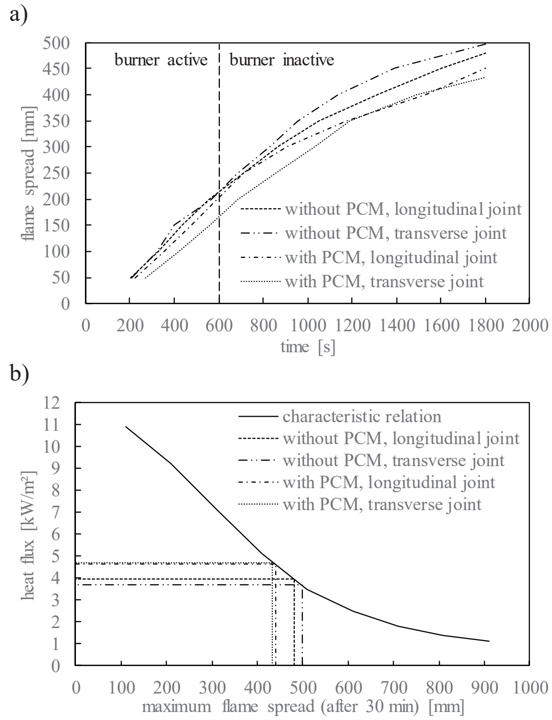


Figure 3: *Results of the fire tests acc. to DIN EN ISO 9239-1 on flooring elements; a) Flame spread vs. time, b) heat flux vs. flame spread (characteristic relation)*

3.5 GLUABILITY

The previously shown results regarding leakage and combustion behaviour indicate that it is advantageous to place the PCM-containing wood not at the surface of the building element. One technique for this purpose is glue lamination.

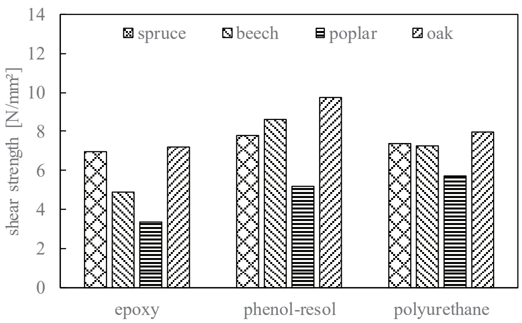
Figure 4 shows the results of the gluing tests as described in Section 2.5 in terms of the shear strength. It can be seen that the results depend on the wood species and the adhesive. The lowest strength of the glue line was observed for the epoxy resin. Except of beech, the PCM impregnated samples showed higher strength of the glue line compared to the reference samples. This somewhat unexpected behaviour might be explained by the cell lumen filled with PCM preventing a deeper intrusion of the resin, which is associated in the reference case with an insufficient amount of adhesive at the glue line.

The strength of the glue line is larger for the phenol-resol adhesive than for the epoxy resin. However, no clear tendency can be seen whether the performance is impaired by the PCM or not. It depends on the wood species. While for poplar and beech, the strength of the glue line is clearly impaired by the PCM, it is improved for spruce and seems to be not influenced for oak. A similar result can be seen for the PUR adhesive.

Although for poplar and beech the highest values of the reference samples are not achieved for the PCM-impregnated samples, a high-quality glue line can be

produced. The gluability of oak, which has a comparatively low PCM uptake, was not significantly changed by the PCM. For spruce, the PCM resulted in an improved performance of the glue line for the tested adhesives.
Besides these promising results, it shall be noted that tests with the PCM in the liquid state need to be performed. Moreover, long term and cyclic loading tests should be performed for a final evaluation.

a)



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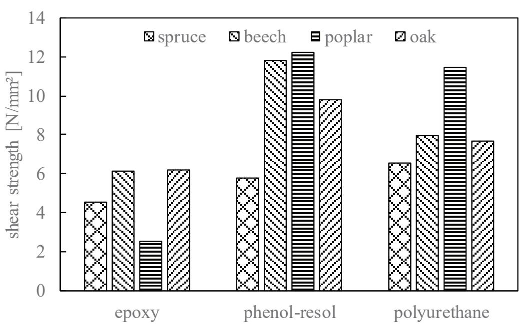

Figure 4: *Results of the gluing tests; a) PCM impregnated samples, b) not impregnated reference samples*

4 SUMMARY AND CONCLUSIONS

In this contribution, different investigations with regard to an application of PCM-containing wood in load-bearing timber elements were presented. A key aspect is the mechanical properties. The results of the bending tests showed that the PCM impregnation does not impair the strength and the modulus for commonly used wood like spruce and beech. In order to produce large sized timber elements from small sized pieces, the gluability is a key aspect. The investigations showed that high-quality glue lines could be achieved for PCM-containing wood. Although further investigations might be necessary, glue lamination is possible for PCM-containing wood. With this regard, using smaller timber pieces also facilitates the impregnation with PCM.
An exemplary glue-laminated timber element is shown in Figure 5. The element takes the aforementioned findings into account. The element consists of a core of clear glue-laminated spruce. The core remains without PCM since the heat penetration over the day is assumed to be limited and the PCM would not be activated at this position. On the side and the bottom faces of the core, PCM-impregnated spruce boards are laminated for locally increased heat capacity. In the case that the side faces are not ventilated in the room, the PCM-containing layer could be also placed only at the bottom face. As top and PCM-free, sealing layer, a thin board, which could be also a veneer, of oak is glue-laminated. Oak is hard to impregnate and serves as a barrier against leakage of the PCM. On the other hand, it has also decorative value. If the latter is not intended or necessary, other wood species, which possess a bad impregnability, like spruce could be used. However, it should be considered that knots and cracks could impair the barrier against leakage.
The PCM-free top layer also improves the fire behaviour. As the respective investigations showed, the direct flaming of the PCM-containing pieces should be prevented. Then, the PCM can even have advantageous properties regarding the fire behaviour by absorbing heat and, thus, cooling the flamed surface of the element, which delay the fire propagation.
The general concept might be applied also to other engineered timber elements like cross-laminated timber.

Figure 5: *Glue-laminated timber element*

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