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A lime based mortar for thermal insulation of medieval church vaults

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Abstract There are 1700 medieval churches in Denmark, and many of these have brick vaults. The thickness is only 12 – 15 cm, and the heat loss through this building component is large. Thermal insulation has not been permitted until now in respect for the antiquarian values and doubts about the effect on water vapour transport through the vault, and the risk of condensation inside the insulation. A new mortar was developed for thermal insulation of bricks vaults, consisting mainly of expanded perlite, mixed with slaked lime. These materials are compatible with the fired clay bricks and the lime mortar joints. The insulation mortar is applied to the top side of the vault in a thickness of 10 cm, and covered by 10 mm lime plaster, reinforced with cattle hair. This assembly is resistant to the weight of a person, working with maintenance of the roof. The thermal conductivity of the insulation mortar was measured to 0.08 W/mK, which is twice the value for mineral wool. It has 1/3 of the resistance to water vapour diffusion as brick, and a high capacity for liquid water absorption. This is a benefit in the case of rain leaking from the roof, because the water does not penetrate further down into the bricks.

1 Introduction

Of the more than 1700 medieval churches of brick in Denmark, many contain vaults of half-brick thickness (approximately 12-15 cm) under an uninsulated roof. The geometry of these vaults, and thickness, cause a large heat loss through this construction part. Due to the old and preservation worthy churches that are very valuable to Danish cultural heritage, insulation of the vaults has not previously been permitted – despite the potential energy savings to be achieved. The pessimistic attitude towards vault insulation is well-founded, and based on risks associated with added insulation: moisture, especially risk of condensation and blocked vapour transport, which could have vital consequences for the church, and cause deterioration or other harm to the construction or interior, including frescoes. Traditional materials and methods are preferred for church insulation,

which was why the lime based perlite mortar was developed and tested for this intended use. Lime is compatible with the existing clay fired bricks and lime mortar joints, and perlite is a naturally occurring volcanic rock type, expanded under heat loads. The insulation mortar is able to lie directly on the existing vault, following the rounded geometry. For increased load bearing capacity, a thin layer of lime mortar reinforced with cattle hair is applied on top of the insulating mortar. A model of the insulated vault is seen in Figure 1.



Figure 1: Model of vault construction with insulation mortar; ½ brick thick vault, 100 mm insulation mortar and 10 mm cattle hair reinforced mortar

The present paper reports studies for determination of hygrothermal material properties of the lime based mortar, one dimensional hygrothermal dynamic simulations of water loads presented in summer and winter periods on vaults insulated with the lime mortar, as well as in situ measurements performed on insulated vault in Annisse church.

2 Methods

2.1 Materials

In Denmark, lime has been used in the building industry since the beginning of the Middle Ages. Lime has good properties with regard to building materials; it is workable, durable, flexible and other relevant qualities. For the insulation mortar, the air lime, Rødvig slaked lime, with grains <0.01 mm has been used. Perlite, when expanded, contains clusters of microscopic bubbles, is inorganic and chemically inactive. Grain size of perlite used in the insulation mortar, was 1-6 mm. The mix proportion of lime to perlite for the insulation mortar is presented in Table 1, as being nearly 1:2. For mixing, the slaked lime was watered down; thereafter perlite was added, and the mortar mixed well.

Table 1: Composition of insulation mortar

Lime [g]	Water [g]	Binding Agent [l]	Perlite [l]	Binding agent : Perlite
1000	1000	1.8	3.53	1:1.96

Cement plaster with aggregate of expanded perlite rather than sand, is not uncommon in the industry, and has advantages such as a reduced weight, higher fire safety and insulation value [7].

2.2 Laboratory experiments

A variety of laboratory experiments were carried out for determination of hygrothermal properties and material characterization. The determined values are later used as input for hygrothermal simulations. All laboratory experiments were carried out on specimens that have completed carbonation process and after standard procedures. Laboratory experiments performed include capillary suction, drying, water vapour permeability, and thermal conductivity.

Capillary suction was determined by both prEN ISO 15148:2002 [4] and Karsten tube measurements according to Roel Hendrickx [1]. ISO 15148 includes drying out specimens, and placing them bottom's up, on spacers in a water filled tray, with water covering approximately 5 mm of specimen height. The weight of each specimen was registered at certain time intervals, until a break in Q^2 relative to time, was found. Q represents absorbed mass pr. area [kg/m^2] and the capillary number, k , can be calculated. The Karsten tube (also referred to as RILEM tube) was of plastic and fixed to the specimen surface vertically. The tube was filled with water to the 5 ml mark, and every 5 minutes the absorbed volume of water, and the diameter of the wetted area was registered. By means of calculations presented by Roel Hendrickx [1] the capillary number is found.

For the drying experiment, each specimen was sealed on all sides except one for determined drying area. The specimens were saturated by capillary suction, hereafter they were placed in a climate chamber at approximately 22-25°C and 64-70% relative humidity, for daily monitoring of the drying process by weighing. In the experiment, half of the specimens were subjected to 3 m/s air velocity, and the rest 0 m/s air velocity.

Water vapour permeability and water vapour diffusion resistance factor were determined by standardized cup-test (wet-cup) [6]. Specimens were placed on a sealed cup, obtaining 94 % relative humidity by KNO_3 saline solution. Cups were placed in a climate chamber of approximately 23°C and 53 % relative humidity. The air velocity above cups was 2.2 m/s on average. The cups were weighed inside the chamber every other day for 16 days, and determination of vapour permeability was based on formulas provided in EN ISO 12572:2001 [6].

Two methods were used for determination of thermal conductivity. An ISOMET Heat Transfer Analyzer is an apparatus able to determine thermophysical properties of materials. The probe was placed on the material surface, and based on thermal responses to added heat flow, thermal conductivity and heat capacity inter alia were retrieved. The guarded hot plate (GHP) method for determination of thermal conductivity was also implemented and performed according to standard test method [5]. The specimen was placed in an insulating frame, between a heating and cooling plate. Thermocouples were placed on both

specimen surfaces, and voltage from both hot plate and over thermopile is registered. By means of these outputs, the thermal conductivity is calculated.

2.3 Theoretical calculations

Theoretical calculations of the heat loss with and without thermal insulation on the vault were made. Initially calculations of the U-values, are made; $U = 1/\sum R$. Heat loss calculations are based on assumptions of Heating Degree Days in Denmark, and the geometry of a classic medieval Danish church, and constant heating is assumed. The assumptions are summarized in Table 2. The heat loss calculations are based on the following equation: $\dot{\Phi} = U \cdot A \cdot \frac{HDD}{1000} \left[\frac{KWh}{year} \right]$. The ventilation heat loss is calculated by: $\dot{\Phi}_{ventilation} = V \cdot AER \cdot \frac{HDD}{1000} \left[\frac{KWh}{year} \right]$.

Table 2: Assumptions for theoretical heat loss calculations

	Area [m ²]	U-value [W/m ² K]	HDD [days]
External walls	360	0.50	3000
Insulated vault	201	0.72	2000
Uninsulated vault	201	2.63	2000
Windows	11.5	4.40	3000
Floor	144	1.00	1000
	Volume [m ³]	Air exchange rate (AER) [h ⁻¹]	HDD [days]
Ventilation	988	0.5	3000

The Glaser method was implemented for assurance of hygrothermal conditions in the insulated vault. The Glaser method is finished with interior conditions assumed to be 20°C and 50% RH, and exterior conditions are set to -10°C and RH 80%. Various alternative interior and exterior conditions were calculated by the Glaser method.

2.4 Simulations

One dimensional simulations were performed in Delphin (version 5.6.8) for planar vertical moisture and heat transfer. The construction in Delphin was built up as homogenous layers of lime plaster, brick, insulating lime mortar and a standard lime mortar reinforced with cattle hair. The simulations were made with constant interior conditions of 23°C and 60% relative humidity, resembling conditions in a church with constant heating. The exterior conditions were based on measured yearly climate data measured in a church attic in the vicinity, of a similar construction. Additional water loads in the form of 4 rain periods in January/February and July/August, with increasing duration (2, 3, 4, 5 hours) of 1 l/(m²·h) were implemented in order to track the moisture conditions. Output locations for simulated results – temperature and relative humidity – are placed at

the top surface, the cattle hair mortar/insulation mortar interface, the middle of the insulation mortar, the middle of the brick layer and at the bottom of the vault.

2.5 *In situ measurements*

In Annisse Church – a classical medieval Danish church with ~140mm thick vault under an uninsulated roof – ¼ of a vault was insulated with the insulation mortar in September 2014. Measurements of temperature and relative humidity were performed, for 1 year (Sep. 2014 – Sep. 2015). The measuring locations are the church attic, the church nave, the middle of the insulation mortar, the middle of the insulated vault, and the middle of an uninsulated vault. The type of loggers used, were Tinytag plus 2, TGP 4505 logging hourly data.

3 Results

Results from laboratory experiments are presented in Table 3 and Figure 2.

Table 3: Results from laboratory experiments

		ISO 15148	Karsten
Capillary suction	k [$\text{kg}/(\text{m}^2 \cdot \sqrt{\text{s}})$]	0.86 ± 0.03	0.68 ± 0.15
Vapour permeability	δ [$10^{-12} \text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})$]	34.58 ± 0.817	
Vapour resistance factor	μ , [-]	5.57 ± 0.135	
		ISOMET	GHP
Thermal conductivity	λ [$\text{W}/(\text{m} \cdot \text{K})$]	0.08	0.09

*material property with cattle hair mortar

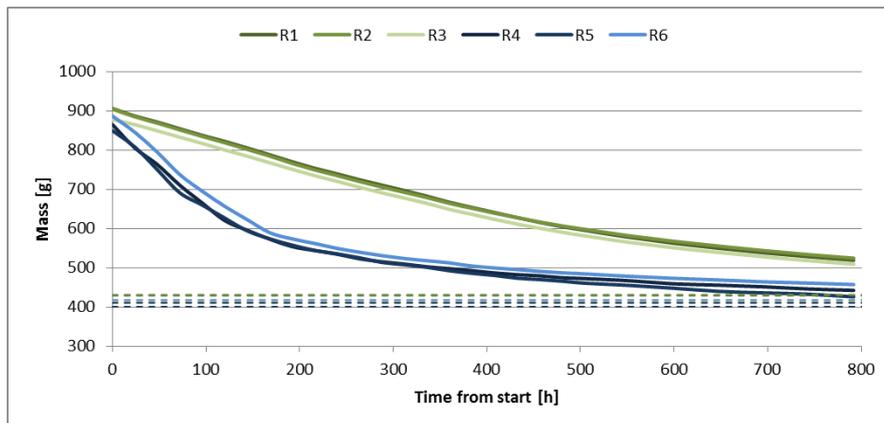


Figure 2: Mass whilst drying of specimens. Specimens numbered 1-3 have been subjected to an air velocity of 0 m/s, specimens numbered 4-6 have been subjected to an air velocity of 3 m/s. The dotted lines represent dry-weight of specimens

The U-values for uninsulated vaults and vault insulated with insulation mortar were found to be 2.63 and 0.72 respectively. The results of heat losses calculated for churches with insulated, and uninsulated vaults as well as heat loss reduction, are shown in Table 4.

Table 4: Heat losses through church components and reductions gained by insulation

	Heat loss [kWh/year]		
	Without insulation	With insulation mortar	With mineral wool insulation
External walls	12960	12960	12960
Vault	25398	6897	3694
Windows	3650	3650	3650
Floor	3456	3456	3456
Ventilation	504	504	504
Total heat loss	45968	27467	24624
Reduction [%]		40	47

Simulation results of relative humidity through the construction are expressed in Figure 3.

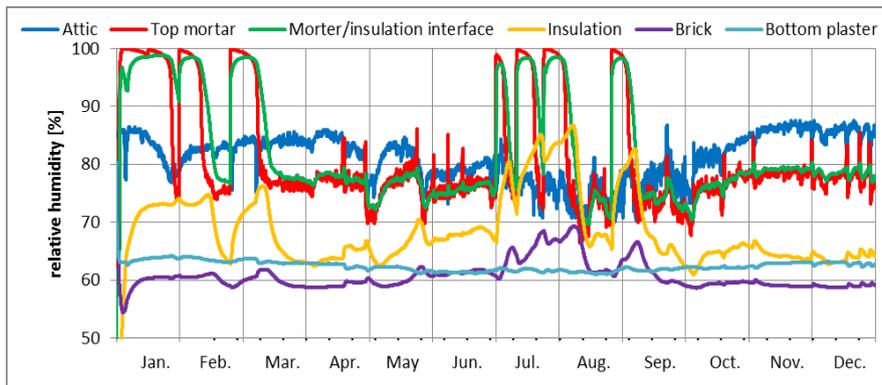


Figure 3: Yearly simulation of church vault with 100mm insulation mortar

Results from in situ measurements of temperature and relative humidity are shown in Figure 4 and Figure 5.

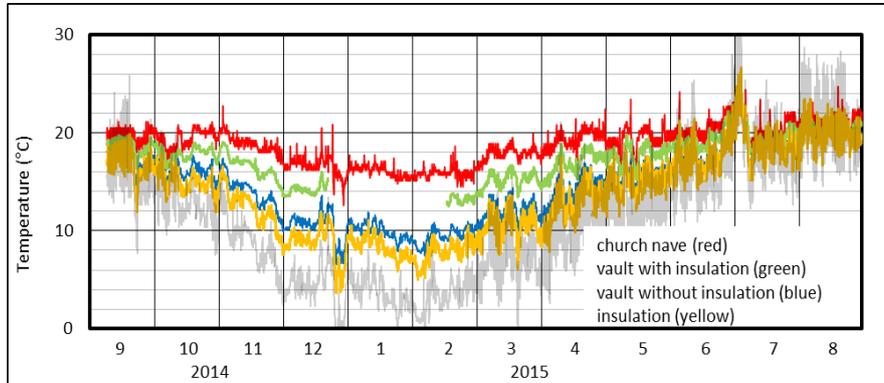


Figure 4: Temperature measurements from Annisse Church

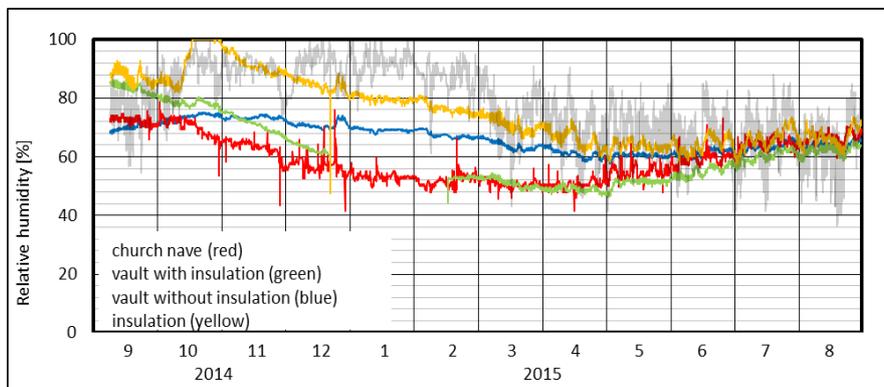


Figure 5: Relative humidity measurements from Annisse Church

4 Discussion

The results of capillary suction showed, that LBM Test Method 1 had more reliable results than the Karsten tube measurements, as more specimens were tested in LBM, and the standard deviation found to be 5 times lower than Karsten tube. On the other hand, the results did not differ outrageously, and it was found that the capillary suction in the insulation mortar is higher than both brick and lime mortar [3]. It is seen in the drying progress depicted in Figure 2 that the air velocity has a big influence on the drying rate, as the mass of these specimens drastically reduced in the first 200 hours. After 200 hours the drying curve levels out. At the end of the experiment, specimens subjected to air movement are closer to initial weight, dry weight, but the difference at this point is not substantial. The value of 3 m/s for air movement is not realistic in the church attic however the air is not still, as there are many leakages in these roofs. The experiment showed that in the course of 1 month, capillary saturated insulation mortar can almost dry completely with air movement from 0-3 m/s. The cup-test revealed a more than 3

times lower water vapour resistance factor in the insulation mortar compared to brick [2]. These results yield no reason for concern in regards to the vapour flow through the vault, verified by Glaser method. The Glaser method also expressed, that there is not a risk of condensation within the construction at assumed external and internal conditions. The thermal conductivity of the insulation mortar was found to be approximately twice the value of mineral wool [3], however still within parameters applicable to insulation materials. Theoretical heat loss calculations based on the found thermal conductivity, yield little difference in the total heat loss for the church compared to the solution with mineral wool, see Table 4.

The simulation results indicated that only the upper three output points were clearly affected by the exterior water loads. The exterior water loads added in winter and summer, seemed to have a significant influence on humidity conditions in layers down to the middle of the insulation layer, but not further, towards the brick layer. It was seen, that the interface area between brick and insulation, as well as the middle of the brick layer, was influenced during summer periods, but to no severe extent. In the summer period the superficial layers dried out quicker than in winter due to increased temperature, which also made the vapour pressure in the attic increase and cause the deeper penetration of moisture during summer. Neither the bottom part of the brick or the bottom layer of plaster was affected by the external water loads at any time.

The temperature measurements, seen in Figure 4, show that the temperature of the insulated vault was 2-3° warmer than the un-insulated vault during winter. The temperature measured in the insulation was slightly colder than the uninsulated vault. In the summer period, the temperature in both vaults and in insulation were very similar. The measured relative humidity is depicted in Figure 5. It is seen that the humidity in the insulated vault is initially a bit higher than the uninsulated vault, but due to drying of building moisture, the insulated vault reaches humidity levels resembling interior conditions within ½ year. The humidity measured in the insulation mortar, is higher for a while, with a peak in October 2014. The peak was likely caused by the carbonization process of lime, which expels water, also explaining the high humidity declining in the insulation layer. In the period where the humidity reaches 100 % in the insulation, it is seen to not affect the underlying brick in any essential way. The relative humidity in the uninsulated vault has less variation.

The risk of frost damage to the outer layers of the insulation- and cattle hair mortar is not considered a problematic issue, as the temperature in the church attic barely reaches the freezing point. Also, any liquid moisture from rain/condensation/carbonization will likely evaporate before potential frost.

5 Conclusion

A new insulation mortar was tested and proved to work as intended for the purpose of church vault insulation. The new insulation system consists of

materials that go well along the materials traditionally used in historic constructions in Denmark. There is great potential for energy savings, and the properties of the mortar seem to ensure moisture safe performance of the insulated historic vault. Both simulations and measurements show, that the brick layer is not significantly affected by moisture loads added externally or moisture loads in the insulation layer. This is likely contributed by the fact that the capillary suction is higher in the insulation mortar compared to brick, and the moisture is transported within this layer, also due to geometry and gravity. The temperature measurements indicate no risk of condensation at interfaces, and the dew point in no measuring points is reached at any time. Despite the fact that the thermal conductivity of the insulation mortar is twice as high as in mineral wool, simplified calculations show that energy consumption can be reduced by 40 % by implementing the insulation mortar on church vaults, in a church with constant heating. Furthermore, the material shows great drying potential and vapour permeability, emphasizing the possibilities for future use.

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