Thermal Insulating Lime Plaster

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ABSTRACT: In this work a thermal insulating lime plaster for interior use in historic and protected building is developed. The mortar matches old masonry constructions based on solid masonry walls prepared using lime mortar in a technical, aesthetics and historic manner. The insulating mortar is a multi-coat system consisting of a lower coat for better adhesion, the thermal insulating rendering mortar based on burned lime and hollow glass spheres as the insulating aggregate and an upper coat to reduce appearance of any shrinkage cracks formed due to larger layer thicknesses of the insulating lime mortar. For a layer thickness of 20-25 mm of the insulating lime mortar the heat loss is reduced with 30-35% for a solid 1½ brick thickness masonry wall.

1 BACKGROUND

In Denmark, the majority of historic buildings and buildings under heritage and protection have solid masonry walls prepared from clay based bricks and lime mortar. These solid masonry walls show great heat loss. The heat loss through a solid masonry wall of 1½ brick thickness is up to 10 times larger than through a 470 mm cavity wall following the Danish 2015 regulations on building energy consumption. For bricks of Danish normal format a thickness of 1½ brick corresponds to 348 mm.

Re-insulation is a possibility to reduce these heat losses. In addition, re-insulation can improve the indoor environment as the temperature of the inner wall is increased. This reduces draught and heat attraction from the room to the cold wall.

1.1 *Material choice*

For restoration of buildings, a general requirement is that the materials chosen for restoration should technically be compatible with the original materials. Regarding re-insulation, application of inappropriate materials can result in moisture build-up and mould formation causing bad indoor environment.

Concerning preservation of historic and protected buildings, it is further advised that materials and techniques of workmanship respect the historic context.

For anonymous apartment buildings, heat loss through the outer walls is often reduced by exterior re-insulation applying a coating of rendering mortar or a facing masonry wall. As this approach changes the architectural expression of the building it is not considered an option for historic buildings. Instead, interior re-insulation can be used. Often, this includes the use of materials like mineral wool, expanded polystyrene, cellular glass, porous potassium silicate boards, gypsum boards etc. From a historical and aesthetic point of view all these materials are regarded as foreign objects. Thus, material like these are not desirable for the aim.

The thermal insulating lime plaster developed in this work is regarded as an alternative interior insulation approach suitable for historic and protected buildings in Denmark. The insulating lime plaster matches the original materials in a technical, aesthetic and historic manner.

1.2 *Moisture and salt distribution in masonry*

Masonry walls are porous structures absorbing moisture from the surrounding environment.

Absorption of water containing salt results in uptake of salt in the masonry construction. High salt levels in masonry are unwanted as salt can lead to discoloration and disintegration of the brick and mortar. The sources of salt can be external like uptake of rising damp, salt strewed at streets and pavements in freezing weather or from salt in the air in coastal areas. The sources of salt can also be internal from salt present in the clay used for brick making. Absorption of moisture will dissolve salts present in the materials and as moisture is transported to the front of the material for evaporation, salt as well is transported towards the front of the material. Evaporation of the moisture in which the salt is dissolved will then lead to precipitation of salt at the evaporation front.

The type of mortar in use, i.e. mortar with lime as the only binder or mortar containing cement or hydraulic lime, is decisive for the moisture level and distribution of both moisture and salt in the construction [1].

In masonry, made with lime mortar, moisture and possible salts are spread over a rather large area and the moisture and salt are most often concentrated in the clay brick. In masonry with mortar containing cement or hydraulic lime, i.e. lime-cement or lime-hydraulic lime mortar, the moisture and salt are primarily concentrated in the mortar joints. And the moisture and salt will not spread much in the construction [1].

This tendency of a material to hold moisture is important in relation to renovation and re-insulation. The use of cement based rendering mortar for interior re-insulation of an old masonry wall prepared with lime mortar will affect the moisture and salt equilibria build up in the materials over several of years. Moisture and salt will accumulate in the new rendering mortar containing cement. This can result in several issues like weakened indoor environment, reduced insulating capacity or peeling of the rendering mortar if dissolved salts precipitates in the rendering.

1.3 *Aim*

The aim of this work is to develop a lime based insulating mortar. The success criteria are a functional system proven to be applicable to massive masonry constructions. The requirement to insulating capacity is a system that for reasonable thickness of the rendering mortar can ensure an interior surface temperature of at least 16°C at an outdoor temperature of 0°C and an indoor temperature of 20°C.

2 EXPERIMENTAL

The following materialers are used for the experimental work; sand 0-4 mm Dansand, Braedstrup, Denmark; burned lime (CaO) Faxe Limework, Faxe, Denmark; Hollow glass spheres, 3M Performance Materials, Bracknell, United Kingdom; EPS balls, Sundolit, Billund, Denmark; Perlite particles, Nordisk Perlite, Hillerød, Denmark; Polypropylene fibres, WL Create, Fibervisions, Varde, Denmark, Plastizicer, Sikanol M, Sika, Farum, Denmark.
The compressive strength are measured according to EN 1015-11 however, using prism dimensions of (20x20x120) cm, thermal conductivity is measured as the λ-value using a Isomet 2114 Thermal Properties Analyzer. Measurement are performed at 10°C using a surface probe. Properties of the fresh rendering mortar i.e. consistency, opening time and workability are evaluated based on the experience of a highly qualified bricklayer. Strength and adhesion of the rendering mortar to the clay bricks and masonry wall are evaluated similarly to the fresh mortar properties including susceptibility of the mortar to peel from the support and the susceptibility to the scratched.

3 RESULTS AND DISCUSSION

The insulating lime plaster is prepared as a multi coat system. The multi coat system consists of a lower coat for better adhesion and the thermal insulating lime rendering mortar.

3.1 *Insulating aggregates*

To obtain the insulting properties of the lime mortar, the sand aggregate is replaced by a thermal insulating material. The following materials are tested:

- Expanded perlite particles
- Expanded polystyrene (EPS) spheres
- Glass spheres

Perlite is a naturally occuring amorphous volcanic glass. The chemical composition is that of an alkali aluminosilicate. Perlite expands greatly when heated. This expansion is responsible for the heat insulating properties.
The EPS balls are rounded but irregularly shaped. EPS is an expanded organic polymeric material. It is a rigid and tough closed-cell foam e.g. used to prepare plates or panels.
The glass spheres are hollow microspheres synthetically produced. The spheres are inorganic and nonmetallic. Generally, the spheres are used as alternative to conventional filler and additives as silicas, calcium carbonates, talc etc.
Diameter and bulk density of the materials are seen in Table 1. The perlite and EPS particles are of about the same size and are both rounded but irregularly shaped. Contrary, the glass spheres are spherically and significantly smaller. All three materials are hollow and lightweight causing the insulating properties.

Table 1. Properties of the tested insulating aggregates

Material	Diameter (mm)	Bulk density (kg/m3)
Perlite particles[a]	0,5-6,0	50-90
EPS balls[b]	2-6	≈25-50
Glass spheres[a]	0,002-0,130	100-150

[a] From products sheets, [b] From tests

All three insulating aggregates are tested for preparation of the heat insulating rendering mortar. The materials are tested alone and in combinations of two. For the combinations, glass spheres are mixed with perlite or EPS.

The main components of the thermal insulating rendering mortar is lime and insulating aggregates. In hot lime mortar, the source of lime is burned lime (CaO). As the burned lime is mixed with sand and water, CaO reacts with water forming $Ca(OH)_2$, i.e. the mortar is slaked during mixing. The reaction of water with CaO is an exothermic reaction and heat is released as the mortar is slaked.

Previous investigations [2] have shown, that the use of hot lime mortar contrary to mixing already slaked lime ($Ca(OH)_2$), sand and water generally allows higher lime contents to be used without formation of cracks in the render as it hardens. In addition hot lime mortars generally show larger strength, improved elasticity and better adhesion to masonry compared to mortar prepared from slaked lime [2].

Hence, burned lime is chosen as the lime source for development of the thermal insulating lime mortar. As mentioned above, three types of insulating aggregates are tested.

For initial testing, mortar prisms are prepared and the mortar formulation is evaluated in relation to strength and thermal conductivity, i.e. insulating capacity. Generelly, lime rendering mortar for interior use contains 12-14% $Ca(OH)_2$. As the aggregates are all lightweight, the normal weight-weight mixing ratios cannot be used. Instead, for the initial testing formulations are prepared according to volume. Lime and aggregates are mixed as 1 part $Ca(OH)_2$ to 4 parts aggregate. This corresponds to weight ratios of $Ca(OH)_2$: aggregate equal to 0,9-2,0 dependent on the aggregate type and mixing proportions.

The conclusions from the testing of the various insulating aggregates is, that the best insulating properties are obtained using either glass spheres as the only aggregate or a 50/50 mixture of glass spheres and EPS balls. Thermal conductivities and compressive strengths of the mixtures are shown in Table 2.

Table 2. Properties of the two mortar showing best thermal conductivity.

Aggregate	Thermal conductivity (W/(m·K))	Compressive strength (MPa)
100% Glass spheres	0,048	0,88
50% Glass spheres 50% EPS balls	0,048	0,49

From the table it is seen that similar thermal conductivities are obtained for both formulations. Both formulations results in thermal conductivities of 0,048 W/(m·K). For comparison a commonly stated value of the thermal conductivity of stone wool is 0,045 W/(m·K). The compressive strength of the mortars containing glass spheres is almost twice as high as the strength of the mortar containing a mixture of glass spheres and EPS balls. The compressive strength of the mortars containing glass spheres as the sole insulating component is 0,88 MPa. For comparison the strength of a category CSI rendering mortar is 0,4-2,5 N/mm^2. This constitutes the lowest strength class according to EN 998-1.

Based on the testing of strength and thermal conductivity it is decided to use glass spheres as the insulating aggregate.

From the first application tests of the rendering mortar it is evident that the rendering shows severe cracking upon hardering. To reduce the risk of crack formation, polypropylene fibres are added to the formulation. The fibers in use have a diameter of 15-30 μm and a length of 6 mm. The intension of the fibers is to act as a fiber reinforcement reducing this tendency of crack formation and improving the strength. The fibers are added in doses up to 0,7% of the solid material.

3.2 *Lower coat*

The aim of the lower coat is to improve the adhesion of the insulating mortar to the masonry. It is important that the lower coat show good adhesion to a range of clay bricks of different porosity and water adsorption.

The lower coat is applied by throw-out technique. For this, the mortar must be of appropriate consistency and show a sufficient opening time before setting. No crack formation must occur during setting and hardening of the lime mortar.

The development of the lower coat mortar is done in an iterative process, and the performance in relation to its application is evaluated during practical testing by a highly experienced bricklayer.

The composition of the lower coat mortar is optimized in relation to consistency, opening time, workability in throw-out test, adhesion to masonry wall and durability after mixing. The formulation is optimized varying the following parameters: water/lime ratio, sand/lime ratio, initial use of lime water and addition of polypropylene fibers and plasticizer.

As a starting point for the optimization of the lower coat composition a CaO to sand ratio of 0,5 is used. This correspond to the $Ca(OH)_2$ content of 40% in the mortar.

To improve the consistency of the mortar water/solid ratios in the range 0,67-1,17 are tested. A water/solid ratio of 0,73 is chosen as this results in the best consistency and opening time of the mortar. At lower water contents the mortar is too dry and do not obtain the right consistency for rendering. Whereas water contents above w/s = 0,73 yields too liquid mortars and initial phase separation of the sand and lime.

During mixing of the mortar the temperature increases to above 60°C. Due to this, the mortar is prepared a least one day prior to the use. Tests show that if the mortar is stored in a closed plastic container it can be used at least one month after mixing.

Application of the high lime mortar on bricks results in severe crack formation and poor adhesion. To improve these parameters, the lime content of the mortar is reduced. Reduction of the lime content from 40% $Ca(OH)_2$ to 20% significantly reduces the tendency to cracking and improves the adhesion to bricks with both high and low water absorption.

To further improve the strength and reduce the risk of crack formation during hardening of the mortar, polypropylene fibers are added to the lower coat. The fibres in use are the same as used for the heat insulating rendering. Fibre contents of 0,05-0,5% in relation to the content of solid material is tested. From the testing it is clear that the fibres must be mixed with water prior to mixing with the solid material. This procedure improves the distribution of the fibres by reducing the entangling. The highest content of fibres shows the greatest positive effect on both strength and reduction of crack formation when tested on bricks.

After this the lower coat is tested on a masonry mock-up of 1,5 m x 1,5 m. Mortar is applied to the mock-up by throw-out technology. The mock-up is divided into quadrants and individual tests are performed in the four areas.

For the first test, lower coat mortar corresponding to the mixing proportions developed above is applied to the mock-up. The masonry is wetted prior to throw-out of the mortar. Differences in the shade of grey appear between top and bottom of the test area and between rendering covering bricks and mortar joints. In the second quadrant, the variation in grey shade is avoided by application of lime water to the masonry prior to throw-out of the rendering mortar.

To further improve the strength development and adhesion of the mortar to the masonry, a plasticizer is added to the mortar. The aim of the plasticizer is to increase the cohesion of the mortar thereby slowing down the evaporation of water, thus improving the conditions for hardening of the lime. The content of plastizicer is 0,1% in relation to the CaO content. When applied to the mock-up the rendering show good adhesion and strength.

The characteristics of lower coat optimized in relation to consistency, strength and adhesion are given in table 3.

Table 3. Characteristics of the composition of the lower coat mortar.

Water/solid ratio	0,73 w/w
CaO/solid ratio	0,17 w/w
$Ca(OH)_2$ content	20%
Fibre content rel. to solid material	0,5%
Plasticizer content rel. to CaO	0,1%

3.3 *Insulating lime mortar*

For the thermal insulating mortar the aggregate accounts for the insulating properties. Thus, a high aggregate content will result in good insulating properties. On the other hand, lime is the binder, and a high lime content will promote high strength and good adhesion to the lower coat. High lime content will however also increase the rate of hardening hence increasing the risk of crack formation. Thus, the final composition of the insulating mortar is a balance between strength, risk of crack formation and insulating properties.

During preparation of mortar prisms (paragraph 3.1) the mixing proportions between CaO and glass spheres are 60 % (w/w) CaO relative to the total content of solids. This content is used as the starting point for testing the application of the insulating mortar in combination with the lower coat at the mock-up. During preparation of the mortar, the temperature increased to above 50°C. The bricklayer considered the consistency of the fresh mortar to be fine for rendering, and the mortar is applied while still warm. The mortar is applied to the masonry wall using a plastering board. Severe crack formation is observed soon after application of the mortar.

To reduce the risk of crack formation the water content of the mortar is reduced and cooling of the mortar is allowed prior to application to the mock-up. Test of water/solid ratios from 1,9 to 5,3 results in the use of a water/solid ratio of 2,3. At higher water contents the mortar is too liquid and extensive phase separation of the solid components occur. Similarly, to the lower coat, tests show that the insulating mortar beneficially can be stored in closed containers for up to at least one month. This allows the mortar to be applied at room temperature. The aim of both initiatives, i.e. increased water content and reduced temperature at application of the mortar, is to reduce the rate of hardening thus extending the hardening period potentially reducing the risk of crack formation. Mock-up tests show that cracking still occur however, the period after application until cracks occur is prolonged.

To further reduce the risk of crack formation, the content of lime is reduced and plasticizer is added. Again the aim is to reduce the rate of the hardening process. Tests show that the reduction in lime content requires that the mortar is continuously stirred during the application of the mortar. The consistency of the mortar is comparable to gypsum based render. The mortar is easily applied in a layer thickness up to about 20 mm. For the large layer thicknesses shrinkage cracks however still occur during hardening of the mortar. To reduce the appearance of these cracks a thin top coat of the insulating mortar is applied 2 hours after application of the thick insulating layer. Figure 1 and 2 show how this significantly reduced the appereance of the cracks.

The final composition of the insulating lime mortar is given in table 4.

Figure 1. Rendered wall with ≈ 20 mm insulating lime mortar.

Figure 2. Rendered wall with ≈ 20 mm insulating lime mortar and top coat to reduce appearance of shrinkage cracks.

Table 4. Characteristics of the composition of the insulating lime mortar.

Water/solid ratio	2,3 w/w
CaO/solid ratio	0,44 w/w
$Ca(OH)_2$ content	50%
Fibre content rel. to solid material	0,7%
Plasticizer content rel. to CaO	0,25%

3.4 *Insulation capacity*

The thermal conductivity of a slab of the insulating mortar of its final composition is measured. The thermal conductivity is 0,070 W/(m·K). It is noticed that this thermal conductivity is significantly increased thus the insulating capacity is reduced compared to the measurement perform on prisms. The loss in insulating capacity is observed despite an increase in the content of insulating aggregate.

A possible explanation for the reduced insulating properties could be the change of mixing procedure as larger portions are prepared contrary to the smaller portions for preparation of prisms. Investigation of mortar prism thin sections using polarization microscopy show a fraction of the glass spheres to be broken and thus filled with lime. It is speculated that a more harsh mixing conditions could cause a larger fraction of the glass spheres to be broken.

As mention previous, the aim of this work is to develop a system that for a reasonable thickness of the rendering mortar can ensure an interior surface temperature of at least 16°C at an outdoor temperature of 0°C and an indoor temperature of 20°C. For a solid masonry wall of 1½ brick thickness the indoor wall surface temperature is 13,8°C. To fulfill the aim of the project this temperature should be raised by 2,2°C to 16°C by application of the thermal insulating mortar. Calculations show, that this requires a layer thickness of 25-26 mm of mortar. This is slightly larger than the thickness applied during the final testing. Here a layer of 20 mm is applied. This layer thickness results in a temperature increase to 15,7°C.

4 FUTURE WORK

At present the insulating lime mortar developed in this work is tested in a large demonstration project at the Danish Technical University. In this project about 14 systems for interior re-insulation are tested and compared in combination with solid masonry mock-ups under controlled temperature and atmosphere. Sensors for temperature and moisture are positioned within the mock-up and re-insulation materials. The project continues to the beginning of 2017.

Mixing of the lightweight aggregate and burned lime induces dust challenges normally not observed when mortar is mixed. Thus, the next step of the project is to involve a mortar producer in the development of an industrial mixing procedure. At the same time, a field test of the mortar should be performed at an appropriate location.

During this testing, the formulation of the thermal insulating lime mortar can be fine-tuned as to further improve the insulating capacity and reduce the risk of crack formation.

5 CONCLUSION

In the work, a system for interior thermal insulation of historic buildings and buildings under heritage and protection is developed. The system is applicable with constructions of solid masonry walls prepared from clay based bricks and lime mortar. The system matches the original materials in a technical, aesthetic and historic manner.

The system is a multi-coat rendering system consisting of three layers. The lower coat is a lime mortar applied to improve the adhesion to a range of bricks showing varying porosity and water absorption. The thermal insulating mortar is based on burned lime and hollow glass spheres as the insulating component. The insulating mortar is easily applicable in layer thicknesses around 20 mm. This results in a temperature increase of the inner surface of a solid masonry wall of 1½ brick thickness of 1,9°C to 15,7°C at an outdoor temperature of 0°C and an indoor temperature of 20°C. This corresponds to a 30% reduction of the energy loss. A thin upper coat of the insulating rendering mortar is applied to reduce the appearance of shrinkage cracks. In this work, the system is proven to be operable in a practical manner.

As the insulating mortar is based on lime moisture and salt will not concentrate in the mortar. Thus the rendering will not show negative effects on the indoor environment.

6 ACKNOWLEDGEMENT

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7 REFERENCES

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