Desalination of a painted brick vault in Kirkerup Church

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Abstract

A sudden disruption of a wall painting on a vault in Kirkerup Church was caused by the crystallisation of sodium chloride. An attempt was made to desalinate the surface and to extract some of the salt from the upper side of the vault. Various ways of applying moisture to the vault were tried. Both lime mortar and a specially designed salt-extraction mortar were tested as a sacrificial plaster. The major problem was that the salt redistributed within the vault because of the water supplied by the mortar. The main benefit of a thick mortar on top of the vault is probably to protect against moisture from above.

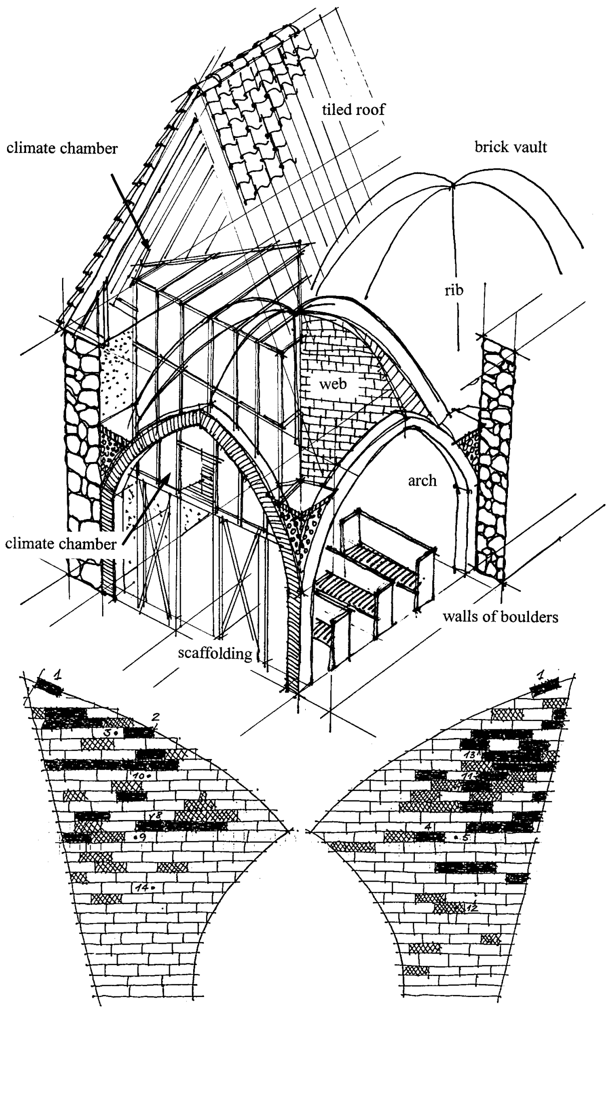

Figure 1. An isometric sketch of Kirkerup Church showing the construction of the cross vault inside the older walls of the nave. The nave and chancel have walls of limestone and granite boulders from the 12th. century, whereas the bricks vaults date to the 14th. century. Notice the climate chambers on each side of the damaged web. Below this is a sketch of the two halves of the web with the damaged bricks. The black bricks are pulverised in depth whereas the shaded bricks have surface damage only. The numbered bricks were chosen for monitoring the salt movements.

Introduction

The crystallisation of salt is a common cause of deterioration of wall paintings. The salt found in Danish medieval churches is usually sodium chloride, sometimes in combination with nitrate or sulphate salts. A particular problem is frequently found on the vaults where the salt has accumulated in some bricks, whereas the other bricks are almost salt free. When the wall paintings are restored, a lime mortar is often applied on top of the vaults to prevent salt damage. This is a traditional way to treat salt contaminated church vaults, called the sacrificial layer method. The question is, does it really work, and if it does, can the method be improved?

The method was tested in Kirkerup Church, situated in a small village near Roskilde. During the winter of 1995 a small pile of snow formed on top of one of the vaults. The nave was heated permanently to 10 °C, so the snow slowly melted and penetrated the bricks (se figure 2). Sodium chloride in the structure was mobilised by the moisture and transported to the under side of the vault. The moisture evaporated in the dry climate leaving the salt to crystallise at the surface and disrupt the painting. The salt efflorescence was removed from the surface, but large amounts of salt was still deposited in the few outer millimetres of the surface, so it was not safe to restore the painting. We therefore tried to remove some of the salt from the structure using the sacrificial layer method.

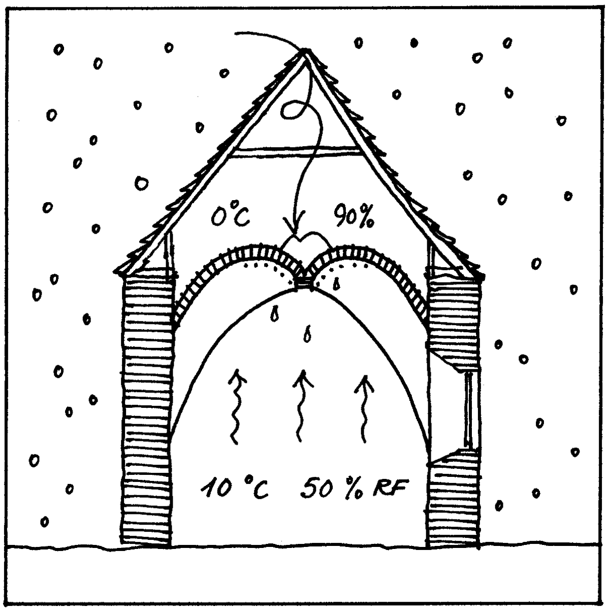

Figure 2. A cross section of Kirkerup Church illustrating the cause of damage. Snow entered through the ridge of the roof and formed a pile on top of the vault. The church was permanently heated to 10°C, so the snow slowly melted and transported salt from the bricks to the under side of the vault. The salt crystallised behind the paint layer as the moisture evaporated, and fragments of the original painting was lifted off the surface.

The principle of the desalination method is shown in figure 3. First a humid climate was established below the vault. The salt would take up moisture at the humid side and move in solution up towards the dry side by capillary force. A mortar was laid out on top of the vault to act as a sacrificial plaster. Both lime mortar and a salt extraction mortar developed in the laboratory were tested in the church. The moisture supplied by the mortar at the moment of application would dissolve the salt, and the solution would move back into the mortar as the moisture evaporated. To facilitate the drying process a dry climate was maintained above the vault. When the salt had precipitated in the mortar, it would be removed and the desalination would be complete. Because the salt movement was worryingly slow, a fine water spray was finally used to speed up the desalination process.

This sequence of procedures is described in this article. At the same time laboratory experiments and computer simulations were used to refine the procedures used in the church (Klenz Larsen, 1998). The feature that distinguishes the church from the laboratory is the inhomogenity of the fourteenth century vault. Some of the bricks were heavily contaminated with salt and eroded half way through their 120 mm thickness, while others were intact and salt free. The long history of decay is attested by early repairs filling in the cavities with bits of tile laid in mortar.

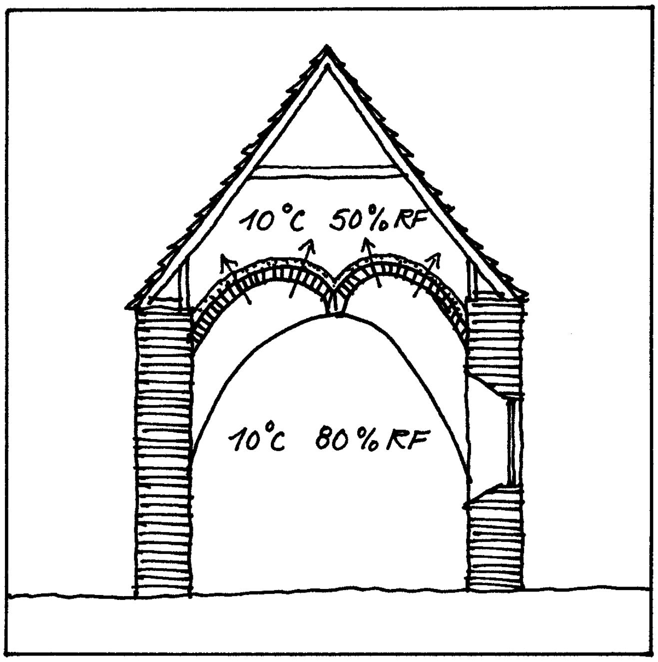

Figure 3. A cross section of Kirkerup Church illustrating the principle of the desalination method. A humid climate was established below the vault and a dry climate was maintained above the vault. The salt would take up moisture at the humid side and move in solution up towards the dry side by capillary force with the RH as driving potential. A mortar was laid out on top of the vault to act as a sacrificial plaster. The moisture supplied by the mortar would dissolve the salt and extract it from the bricks.

Measuring the salt content

The salt movement in the vault was monitored during the desalination campaign by drilling powder samples from the bricks. Two bricks were chosen in an area where all original painting was lost. One of them was eroded on the upper side and the other had no damage. It was acceptable to drill right through these bricks, so they were used to measure salt profiles. These profiles are given in figure 5 and figure 6. Another 9 bricks were chosen evenly distributed over the web, 6 damaged and 3 without damage. In the neighbouring webs 6 bricks were chosen as a reference, three damaged and three undamaged. All these bricks were only drilled half way through from above. The average results from these samples are given in figure 7.

Figure 4 gives the results of the salt analysis of the first samples taken from the damaged brick. Sodium and chloride were the dominant ions whereas potassium and nitrate where present in smaller concentrations only. The concentration of calcium, magnesium and sulphate was very low, so they are left out of the diagrams. Based on the composition of the ion-mixture it seemed reasonable to use sodium as a tracer-ion for the salt content. The sodium content in aquious solutions of the extracted salt was measured with a flame photometer.

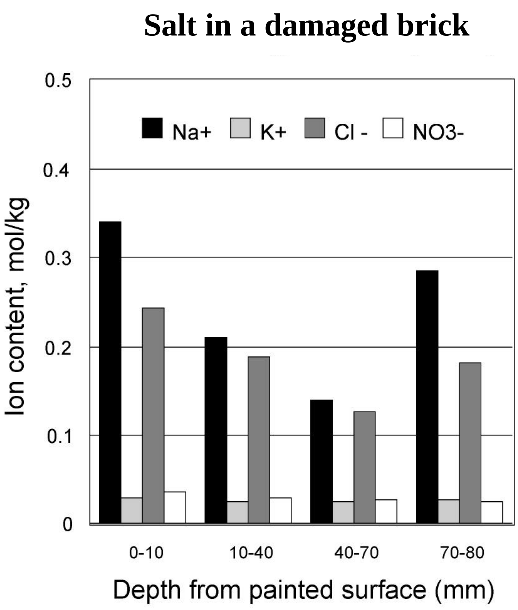

Figure 4. The results of the salt analysis of drilled samples from a damaged brick. The samples were drilled from the under side of the vault. The brick powder was analysed for the content of the following ions: Sodium, potassium, calcium, magnesium, chloride, nitrate and sulphate. The content of calcium, magnesium and sulphate ions was very low, so they are left out of the diagrams.

Test of the lime mortar

The evolution of the desalination campaign will be described in the following along with the results obtained. A diagram summarising the chronology is given in figure 8. In may 1996 a climate chamber was erected below the vault. Here, an average RH at 80-85% was maintained throughout the desalination campaign. The first samples taken in July shows that the undamaged brick initially had a moderate salt content at the painted surface, whereas the rest of the brick was almost salt free. The average salt content of the damaged brick was much higher and the profile was U-shaped with more salt at both surfaces than in the middle of the brick.

In September 1996, a lime mortar was laid out on top of the vault. First, the surface was wetted and a thin layer of pure lime was applied to assure good adhesion. Then, the cavities were filled with lime mortar to even out the surface and finally the entire vault was plastered with two layers of lime mortar. The total thickness of the mortar was 20 mm on average, but on the bricks with the worst deterioration it was up to 60 mm. Roughly estimated, the vault had an average of 5 litre per m^2 of water added, but the damaged bricks had more, because more mortar was used here to fill the cavity.

The second salt profile was measured in January 1997 to study the influence of the humid climate and water introduced by the lime mortar. The salt content of the damaged brick was reduced significantly both at the under side and at the top side and the profile had a gentle slope towards lower salt content at the top side. The concentration of sodium ions in the outermost 10 mm was reduced to half the initial content, probably because the RH was well above the crystallisation humidity of sodium chloride. The salt dissolved in the humid climate and the solution was sucked deeper into the brick. On the upper side of the brick, the salt was washed away by the water supplied by the mortar. However, hardly any salt had found its way into the lime mortar. This means that most of the salt had spread to the neighbouring bricks or mortar joints.

In February 1997 a climate chamber was erected above the vault. Here, the climate was kept dry by heating and some natural ventilation. The temperature was kept constant at 15°C and the RH was maintained at an average of 50%. The third sampling took place in may 1997, and now the salt distribution in the damaged brick had changed again. The profile had an inverted U-shape and the total salt content had increased. The reason for this may be that the salt distribution in the brick was uneven from the start. A preliminary investigation had shown that the initial salt content may vary up to 100 % from one end of the brick to another. Anyway the salt content in the mortar was unchanged, so the drying had no influence on the desalination.

Salt distribution in a damaged brick

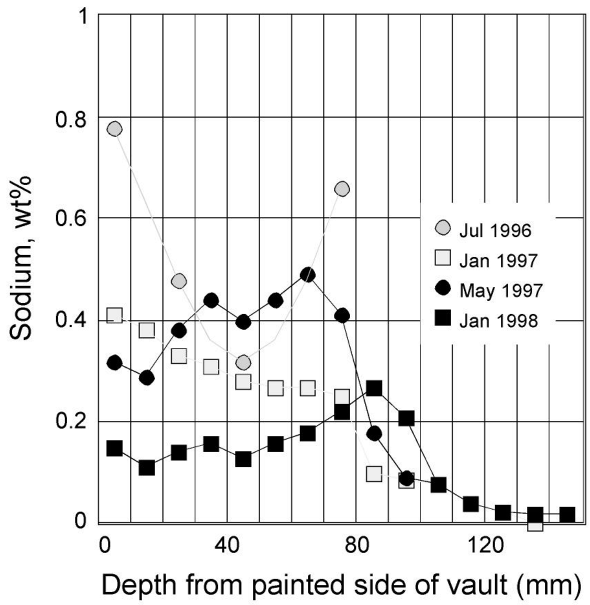

Figure 5. A diagram showing the change of the salt (sodium) distribution in one damaged brick during the desalination campaign in Kirkerup church. The RH was 85% in average below the vault (left in the diagrams) and 55% in average above the vault (right in the diagrams). The first profile (June 1996) shows the initial salt content in the brick. At this stage, samples were not taken for each 10 mm. The next profile (January 1997) shows the influence of the humid climate below the vault and of the moisture supplied by the mortar. The third profile (may 1997) illustrates the influence of a dry climate above the vault. The last profile (January 1998) shows the final salt content after water had been sprayed to the under side of the vault.

In October 1997 we tried to wash the salt away with a boost of liquid water. During a three day period 5 litre per m^2 was sprayed on from the under side. At the same time dehumidification was started above the vault, keeping the RH constantly at 55% for 3 months until January 1998, when the last samples were taken. The moisture supply had a significant influence on the salt profile. The salt was moved upwards and some was moved up into the mortar. But most of the salt disappeared from the damaged brick and may have distributed to the surroundings. It could not have not spread very far, however. The salt profiles of the undamaged brick shows no sign of such contamination. On the contrary, the salt content at the surface decreased during the desalination campaign ending up at 0.1% by weight of sodium.

The results from the desalination campaign showed that it is possible to reduce the salt content at the surface to a low level by keeping a high RH. In May 1998 the paintings were restored and have not yet shown any signs of degradation. However, the investigations also revealed that it is not easy to extract salt from the bricks in a vault. Climate control alone does not move much of the salt into the sacrificial plaster, and if liquid moisture is supplied, there is a large risk of redistributing the salt instead of extracting it. One of the reasons may be that lime mortar is not well suited for the purpose. The pores of the mortar are much too coarse compared to the pores of the brick. Therefore the mortar does not provide the capillary suction necessary to extract salt solution from the brick.

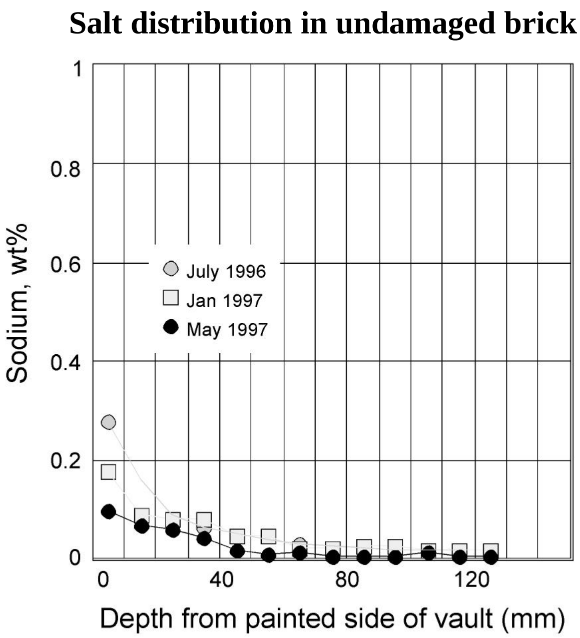

Figure 6. A diagram showing the change of the salt (sodium) distribution in one undamaged brick during the desalination campaign in Kirkerup church. The RH was 85% on average below the vault (left in the diagrams) and 55% on average above the vault (right in the diagrams). The profiles are contemporary to the ones shown in figure 5. The last profile is not shown, because it was identical to the third profile.

Test of a new salt extraction mortar

A new mortar was specially designed to extract the salt solution from the bricks. The recipe for the mortar was a mixture of perlite and kaolin. Perlite is an expanded glass similar to pumice, and kaolin is a pure clay. The perlite forms a rigid structure that prevents drying shrinkage and the kaolin binds to the perlite in a coherent, finely porous structure. The particle size of the kaolin is about 1 micron, so the pores between the particles are in the range 10-100 nm, which is exactly right for establishing a capillary suction. The fine pores have the ability to suck up the salt solution by capillary force, and the large voids allow the moisture to evaporate, leaving the salt to crystallise in the mortar. Table 1 gives some physical properties of the kaolin mortar compared to brick and to lime mortar.

The kaolin mortar was tested in a laboratory experiment and found to work well under these ideal conditions. In a brick specimen contaminated with 2% by weight of sodium chloride the mortar would easily extract half the salt when applied at one end (Klenz Larsen, 1998). It was therefore decided to test the salt extraction mortar in the church by applying it to a neighbouring web. This time only the damaged bricks were treated, to minimise the supply of water to the vault. The RH was not controlled on either side but monitored during a six weeks period to be around 75 %. Samples were taken from five bricks before and after the treatment. The samples were only taken at a depth of 60 mm from the top, but since some bricks were eroded half way through it gives a good impression of the desalination effect.

Figure 7 gives the results of the salt extraction mortar together with the result from the lime mortar. The salt content of some untreated reference bricks in a neighbouring web is shown for comparison. The salt extraction mortar reduced the salt content of the bricks less than the lime mortar. This may come from the fact that much less water was introduced by this mortar. On the other hand, more salt was extracted by the kaolin mortar than by the lime mortar, but in both cases much salt was lost. It seems from this that even if the moisture supply is reduced to a minimum and the capillary uptake of the mortar is improved, it is still not possible to avoid the spreading and redistribution of the salt. The salt content of the damaged bricks was reduced, but it is not known if it is sufficient to avoid damage to the paintings for the future

Maybe the main benefit of a thick mortar on top of the vault is preventive, because it acts as a buffer for the liquid moisture that occasionally enters the loft. It was found during the work that condensation on the roof happens much more frequently than one should expect from a well ventilated loft. We often found pools of water on top of the climate chamber and on one occasion we even saw the condensed water dripping from the ridge of the roof. When the nave is heated the moisture moves downwards and salt is transported along to the painted side. Such a process would be avoided by a thick plaster, because it absorbs the liquid moisture very fast and releases it again to the loft by evaporation.

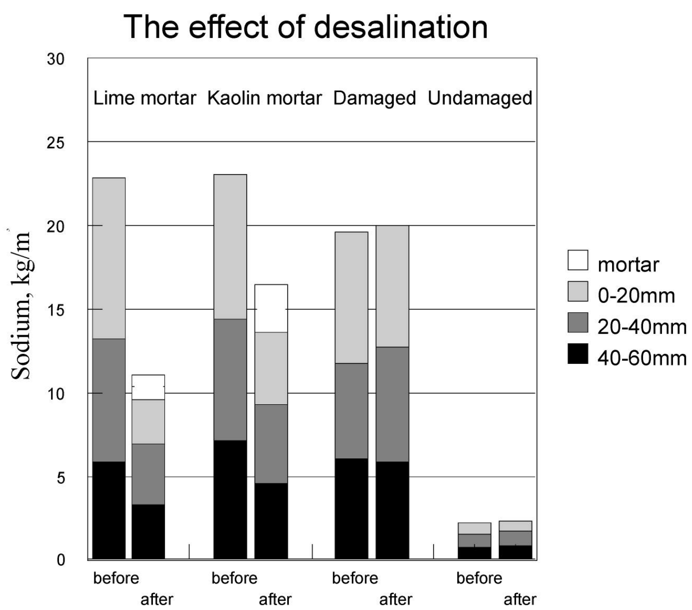

Figure 7. A diagram showing the desalination effect of the two mortars that were used on a vault in Kirkerup Church. The samples were drilled from the top side of the vault. The results of each mortar is an average of five bricks. The salt content of some untreated reference bricks in the neighbour webs is shown for comparison. These results are given as the average of three bricks. The left column for each material is before treatment, and the right column is after treatment.

Conclusion

The desalination campaign gave important information about the salt movements in a vault. It was possible to reduce the salt content of the painted surface to a low level and to remove half the salt from the damaged bricks. However, only a minor part of the salt was extracted by the lime mortar that was laid out on top of the vault. The investigations did not show what hap-pened to the lost salt, but it is likely that it distributed sideways into the mortar joints. The salt was not moved much by the influence of the climate alone. The desalination was many times more efficient when liquid water was applied either from above or from below. The excess of water, however, made it possible for the salt to redistribute within the vault instead of being sucked up by the mortar.

A new mortar better suited for the sacrificial plaster was developed. The mortar, a mixture of perlite and kaolin, was designed to have finer capillary pores than lime mortar, so it was able to suck up the salt solution from the brick by capillary forces. The bricks lost one third of the initial salt content, but only a minor part was taken up by the salt extraction mortar. The main reason for this was probably again that the salt redistributed within the structure. The investigations did not give any information concerning the long-term effect of a sacrificial plaster. It is possible that the main benefit of a thick plaster on top of the vault lies in the ability to absorb condensed water or melting snow and to release it again by evaporation from the upper surface.

Year	1996	1997	1998
Humidifying below	----------------	--------------------	-----------
Lime mortar applied	x		
Heating above		--------	
Dehumidifying above		--------	---
Spraying water below		x	
Salt extraction mortar applied			x
Sampling	x	x x	x x

Figure 8. The diagram summarises the chronology of the various interventions during the desalination campaign in Kirkerup Church.

References

Larsen, Poul Klenz (1999): "Desalination of painted church vaults". Ph.D.-thesis, The Technical University of Denmark, The Department of Structural Engineering and Materials. (in press).

List of suppliers

Bricks: Falkenløve, Løntoft 9, DK- 6400 Sønderborg, (+45) 74 48 54 38
Lime mortar: Skandinavisk Jurakalk, Kronhøjvej 10, DK- 4660 St. Heddinge
Kaolin: Alfred Gad A/S, Karensgade 9, DK-2500 Valby, (+45) 36 16 90 11
Perlite: Nordisk Perlite, Sundkrogskaj 2, DK-2100 København Ø, (+45) 39 20 07 44

Table 1. Some physical properties of the materials used.

Physical property	Density	Porosity	Vapour diffusion	Capillary uptake	Capillary saturation
Unit	kg/m^3	m^3/m^3	kg/Pa·m·s	$kg/m^2 s^{½}$	kg/m^3
Lime mortar	1,820	0.3	$0.15 \cdot 10^{-10}$	0.48	190
Red brick	1,730	0.38	$0.12 \cdot 10^{-10}$	0.23	225
Kaolin mortar	~ 300	~ 0.90	$0.27 \cdot 10^{-10}$	~ 0.1	-