Weathering and Conservation of Soapstone and Greenschist Used at Nidaros Cathedral (Norway)

Preliminary summary of results - a work document

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February 2001(PDF-version August 2002)

Introduction

The following is a preliminary summary of the most important results from research on weathering and conservation of soapstone and greenschist used at Nidaros cathedral (1999-2001). *The summary must be regarded as a work document, which will later be used as a starting point for developing a scientific paper about the theme.*

Objectives and methodologies in the work have been:

1. Weathering experiments and investigation of petrophysical and petrographical properties in order to be able to interpret observed weathering phenomena more accurately, and thereby aid the development and use of adapted conservation products.
2. Testing of various conservation products in the laboratory and *in-situ* in order to find a "safe" and useful palette of products to be used in future conservation work.

Stones were selected for investigation mainly on the basis of the problems the Restoration Workshop of Nidaros Cathedral has with their weathering and use:

- Øye greenschist
- Klungen soapstone
- Bjørnå soapstone
- Bubakk soapstone
- Grunnes soapstone

Likewise, conservation products were developed and tested on the basis of the needs of the Workshop:

1. Consolidation methods on the basis of ethyl silicate, silica sol and lime
2. Methods for removal of lime crusts
3. Desalination methods for masonry

All results from the project are documented on CD-ROM (Storemyr, ed. 2001), which should be referred to for those who want more information. Not documented on the CD is the discovery in 2000 of a medieval conservation mortar used at the choir of the cathedral, but this method is briefly described towards the end of this paper.

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Main questions about weathering

Generally, soft soapstone and greenschist at Nidaros Cathedral and elsewhere are very durable stones. This is mainly because of their extremely dense metamorphic structure, "toughness" and resistant minerals. However, as with all stone types, there are also examples of soapstones that weather rapidly. At Nidaros Cathedral the classical case is the so-called Grytdal soapstone, which was used between 1869 and 1892. It has a very high content of pyrrhotite, which upon oxidation contributes to frequent, nearly complete breakdown of the stone after a couple of decades only. Another example is the foliated and fissured nature of quite a few soapstones; sometimes these planes of weakness may be so pronounced that delamination and spalling inevitably occur. The classical example at Nidaros is Klungen soapstone, used for finer details in the high-gothic period.

Among the cathedral's 20-25 types of soapstone there are also a few other varieties that weather rapidly, but their weathering is significantly more difficult to understand than the behaviour of for instance Grytdal soapstone. Using these difficult stones as a point-of-departure, and relying on the studies of Alnæs (1995) and Storemyr (1997, 1999), in this project we especially wanted to clarify:

1. why Bjørnå and Bubakk soapstone develop much more pronounced weathering (granular disintegration and scaling) when strongly exposed to the weather than most other stones used at Nidaros Cathedral;
2. why Grunnes soapstone apparently is extremely susceptible to salt weathering, but very resistant to weathering when strongly exposed;
3. why Klungen soapstone is resistant to grnular disintegration, but easily spalls along foliation planes, veins and microfissures;
4. why Øye greenschist (chlorite schist) is extremely susceptible to salt weathering, but resistant to weathering when strongly exposed - in spite of being very foliated (which causes strong delamination and spalling of free-standing elements).

Comprehensive information about these five stones can be found in Storemyr (1997, 1999), whereas weathering forms and microscopic features are summarised in Storemyr (2001).

Possible relationships between weathering forms and stone properties

Together with earlier studies (Alnæs 1995, Storemyr 1997, 1999), the new investigations on pore properties and salt weathering (Zehnder 2001), as well as on strength, water vapour diffusion and cation exchange capacity (Wendler & Hestermann 2001), has generated much data about the stones. These data certainly show the *general* properties of soapstone in a way that has never before been achieved in Norway or elsewhere. With regard to *finer details and differences between selected stones*, the data are, however, quite confusing. This is partly because of the material inhomogeneity. The geological and petrographic variations are extreme, not only from one quarry to the other but also within one quarry. And not all of the experiments could be conducted on stones from the same part of the quarry. In addition, some of the samples are microfissured/mechanically disturbed, which modifies the behaviour of such dense stones enormously.

Thus, we have tried to discover some *tendencies* in the relationships between weathering forms/rates and petrographical/petrophysical properties. For this purpose we have made graphic representations comparing typical weathering forms under various exposure conditions with the properties of each stone.

Graphic representations

The graphic representation we have used is a table that looks like this:

Weathering in relation to exposure			Structure and petrography							Petrophysics					
Stone	Grade		Folia-tion	Carb vein	Carb aggr	Carb mtrx	Mg-carb	Mica	S oxi.	Amp re.	D/W flex	Hygr dil.	Por	Por incr	Diff wet	Sym abs/ des.
Øye																
Bjørnå																
Klungen																
Bubakk																
Grunnes																

On the basis of observations over many years, as well as laboratory weathering experiments, it is possible to group the different weathering forms in relation of exposure conditions. according to the following simplified scheme (see also a simple overview in Storemyr 2001):

1. Delamination and spalling at strongly exposed locations (without salts)
2. Weathering (mainly granular disintegration and scaling) at strongly exposed locations (without salts)
3. Salt weathering in sheltered and partly sheltered locations (very often sodium sulphate)

The reason why we have distinguished between delamination/spalling and granular disintegration/scaling, *both at exposed locations*, is that these weathering forms are very distinctive: Delamination/spalling gives "clean-cut" surfaces and is only very rarely followed by granular disintegration.

Thus, we have made three tables, one for each typical exposure/weathering form category. In the first row, the stone types are set in the sequence of their specific sensitivity according to the concerned exposure/weathering form category. In the other rows we have filled in important average results from the studies on structure, petrography and petrophysics for each stone type.

The following legend and scales have been used:

For weathering "grade"	For structure/mineralogy	For petrophysical properties	Colour
Not or rarely present	No or very little/few	No or very low	
Sometimes present	Little-medium	Low-medium	
Often present	Medium-much	Medium-high	
Very often present	Much	High	

This is primarily a relative scale to point out the differences between the selected stone types. But it is actually more than that, as it characterizes the specific properties and behaviours of the stone types.

The following petrographical and petrophysical characteristics have been considered:

Abbreviation	Explanation
Grade	Grade of the actual weathering phenomena
Structure and mineralogy	
From observations and laboratory experiments (Storemyr 1997, Zehnder 2000)	
Foliation	Distinct mineral orientation ("schistosity")
Carb vein	Content of carbonate veins (mostly dolomite)
Carb aggr	Content of larger carbonate aggregates (mm-cm size)
Carb. mtrx	Content of smaller carbonates in the matrix
Mg-carb	Content of magnesite (in the matrix or as aggregates)
Mica	Content of mica (biotite)
S oxi.	Content of sulphides that are easily oxidised (pyrrhotite, small-sized pyrite etc.)
Amp re.	Content of amphiboles distributed as possible "reinforcement" of the matrix
Petrophysical properties	
Mostly from Wendler & Hestermann (2001) and Zehnder (2001), some from Storemyr (1997)	
D/W flex	Dry to wet ratio biaxial flexural strength (1,3-c. 2)
Hygr dil.	Hygric dilatation (100-1000 µm/m)
Por	Water accessible porosity (under vacuum) after 2 days (0,62-1,10 vol. %)
Por incr	Increase of water accessible porosity between 2 and 12 days (0,03-0,13 vol. %)
Diff wet	Water vapour diffusion resistance coefficient (wet cup)
Sym abs/des.	Degree of symmetry in water absorption/desorption

Numbers after the petrophysical properties indicate the range of measured values. For mineral content, see updated information in Storemyr (2001).

Other comments to the diagrams:

(1) Rather homogeneous varieties, but still foliated and with cracks
(2) With talc along the veins
(3) Not measured, but known from experience
(4) Much higher perpendicular than parallel to foliation
(5) Measurements show values higher parallel than perpendicular to foliation, but this seems very peculiar and should be checked once more.
(6) Very dependent on foliation
(7) Symmetrical only parallel to foliation

Delamination and spalling at exposed locations

| Delamination and spalling - exposed | | Structure and petrography | | | | | | | | Petrophysics | | | | | |
Stone	Grade	Folia-tion	Carb vein	Carb aggr	Carb mtrx	Mg-carb	Mica	S oxi.	Amp re.	D/W flex	Hygr dil.	Por	Por incr	Diff wet	Sym abs/des.
Øye										(3)	(4)	(6)			(7)
Bjørnå															
Klungen(1)			(2)						?		(5)				
Bubakk															
Grunnes															

The most obvious and well-known relationship is that delamination and spalling is completely dependent on the foliation of the stones in question. Bubakk and Grunnes are massive stones; they cannot delaminate, and they spall only very rarely. At a few occasions pieces of Bubakk has fallen from the cathedral - this has been because of spalling along thin fissures, either natural or developed due to blasting in the quarry.

Klungen has in addition to foliation and cracks also numerous carbonate veins, frequently associated with thin talc/chlorite veins (talc/chlorite is often developed along the veins, or between the veins and the matrix). These very weak planes explain why this stone has a tendency to spall.

Interestingly, the stones that delaminate most easily are also the only ones containing mica (10-30 vol %, biotite). Whether this increases the possibility of delamination of these chlorite-rich rocks is uncertain.

Apart from the relationship between foliation and delamination, the "puzzle" of stone properties in the above table is not yet clear.Another possible relationship is between delamination and a high ratio between dry and wet flexural strength. With regard to Øye greenschist, we know by experience that it becomes very soft and easy to break when wet - it seems obvious that this also increases the possibility of delamination. It may be suggested that this is also the case with Bjørnå and Klungen.

Apart from the relationship between foliation and delamination, the "puzzle" of stone properties in the above table is not yet clear. Hygric dilatation, for instance, shows a confusing picture. It may seem that the massive stones have lower values than the foliated ones, but the reason why Klungen has such a high dilatation, and that Bjørnå on the other hand shows low values, cannot be explained.

It should be strongly underlined that the above discussion is restricted to the relationship between weathering form and texture/foliation, and does not consider the climatic impacts of the exposure, nor the processes governing weathering. Other features of the above table will have be correlated in a further step of evaluation.

Granular disintegration and scaling at exposed locations

Weathering at exposed loc.		Structure and petrography								Petrophysics					
Stone	Grade	Folia-tion	Carb vein	Carb aggr	Carb mtrx	Mg-carb	Mica	S oxi.	Amp re.	D/W flex	Hygr dil.	Por	Por incr	Diff wet	Sym abs/des.
Bjørnå															
Bubakk															
Klungen(1)			(2)						?		(5)				
Øye										(3)	(4)	(6)			(7)
Grunnes															

This table considers granular disintegration and scaling taking place at strongly exposed locations. Obviously no salts accumulate at such locations because of excessive water-runoff. This is a rare weathering phenomenon on soapstone, which normally exhibits extremely well preserved surfaces (except for clean-cut delamination, spalling and slight dissolution of carbonates), even after thousands of years of exposure in nature.

The only stones at Nidaros cathedral showing this type of weathering is Bjørnå, Bubakk, Gullfjellet and Grytdal stones. The two latter ones have not been included in our investigations. Among all of these four stones, Bjørnå is by far the most problematic one with regard to surface weathering - also because it delaminates at exposed locations, making the situation even worse.

As can be seen from the table, there are few clear relationships between the weathering phenomena and petrography. One possible relationship is that carbonates in Bjørnå and Bubakk stones are distributed as smaller grains and in the matrix, rather than as larger aggregates and as veins. This might indicate that dissolution of the carbonates perhaps contributes to "undermining" the structure and gives water easier access to the interior of the stones. Moreover, Bubakk has much magnesite, which is more soluble than calcite and dolomite (0,6 g/l against 0,01 and 0,3 g/l at 20ºC, respectively. For comparison; gypsum has a solubility of 2 g/l at 20ºC)

With regard to petrophysics, it may seem that there is a relationship between weathering and absorption/desorption: Bjørnå and Bubakk have a tendency to keep water for a longer time; the desorption is slower than for the other stones. Moreover, Bubakk tend to increase the water uptake significantly more than the other stones when wetted for longer periods of time. Bjørnå, on the other hand, shows a high water vapour diffusion resistance. If it were not for the fact that in all these cases Klungen stone complicates the picture, we could have concluded that Bjørnå and Bubakk tend to keep water in the structure for longer periods of time, thus perhaps being more sensitive to frost.

Interestingly, it seems rather easy to explain why Grunnes stone behaves so well under severe exposure conditions: It has no foliation, few carbonates in the matrix, little sulphide, an amphibole network perhaps acting as reinforcement, low ratio between dry and wet flexural strength, low hygric dilatation, very low porosity, low water uptake increase over longer periods of time, a low water vapour diffusion coefficient and a symmetrical absorption/desorption behaviour. All this means that the stone cannot take up much water, and when it takes up some water, this water is not staying for a

long time; thus the stone is (relatively seen) resistant to frost. Furthermore, the advantageous petrography adds to the picture of a very resistant stone.

If it seems easy to explain why Grunnes behaves so well, it is again difficult to say why Klungen (and also Øye) behaves as it does. As with Grunnes, surfaces of Klungen stone tend to be very resistant towards granular disintegration when strongly exposed, even though almost all petrophysical properties deviate from those for Grunnes.

The tendencies interpreted above do not take into consideration real situations where also biology might play a significant role. For instance, Bjørnå, and to a lesser extent Bubakk, seem susceptible to growth of lichen and moss. We are not yet able to explain why.

Salt weathering at sheltered locations

Salt weathering		Structure and petrography								Petrophysics					
Stone	Grade	Folia-tion	Carb vein	Carb aggr	Carb mtrx	Mg-carb	Mica	S oxi.	Amp re.	D/W flex	Hygr dil.	Por	Por incr	Diff wet	Sym abs/des.
Øye										(3)	(4)	(6)			(7)
Grunnes															
Bjørnå											(5)				
Klungen(1)			(2)						?						
Bubakk															

In salt weathering experiments with sodium sulphate (Zehnder 2000) it is evident that Øye, and to a lesser extent Grunnes, behave completely different than the other stones. Øye and Grunnes appear to be extremely sensitive to sodium sulphate - a feature also observed at the cathedral. Observations show that also the other stones may weather under the influence of soluble salts, but usually not in an extreme manner.

One apparently important relationship in the above table is that the stones most susceptible to salt action are those with a symmetrical absorption/desorption behaviour. Compared to the other stones, which generally tend to keep water in the structure for longer periods of time, Øye (parallel to foliation) and Grunnes quickly release water that has been taken up. These two stones also have a low water vapour resistance, implying a relatively seen more effective drying behaviour. However, Bubakk, which is little affected by salt action, has the lowest water vapour resistance of all the stones, and at the same time it does *not* show a symmetrical absorption/desorption behaviour.

Although we certainly have to compare these results with what has been reported in the rich literature on salt weathering, it may seem tempting to try to interpret the behaviour of Øye and Grunnes with more "powerful" cycles of crystallisation/dissolution/recrystallisation as when compared to the other stones.

Attempts at interpreting the behaviour should also consider the actual pore structure. However, at the moment we cannot see a clear picture. From the microporosity measurements (mercury porometry),

Øye and Grunnes are for instance not significantly deviating from the other stones. In fact, Bubakk, which is little affected by salt weathering, has the largest content of micropores - and in addition it is the only stone with a clear bimodal pore distribution.

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Other petrophysical results - cation exchange capacity

In order to try to understand the hygric dilatation of soapstone, and the behaviour when subjected to soluble salts, the cation exchange capacities (CEC) were determined. Our hypothesis was that large cations in chlorite (and talc/biotite) might be exchanged by foreign ions such as sodium. The CEC is apparently very high, much higher than in most sandstones, but since the cations *released* mostly are Mg and Ca in a c. 1:1 ratio, it seems that they represent ions *mobilised* from dolomite (in an ammounium acetate solution, which was used for dermining the CEC). Thus, this probably means that there is no significant real cation exchange in the actual stones. In the figure below it can be seen that Øye greenschist behaves differently from Klungen and Grunnes. This is probably because the samples were peculiar: OY-D-1.S.R.1 was taken from a dump close to the quarry and had been buried in the earth for hundreds of years, whereas VS-3S.R.1 had been used closed to lime mortar joints at Værnes church, thereby being enriched in Ca.
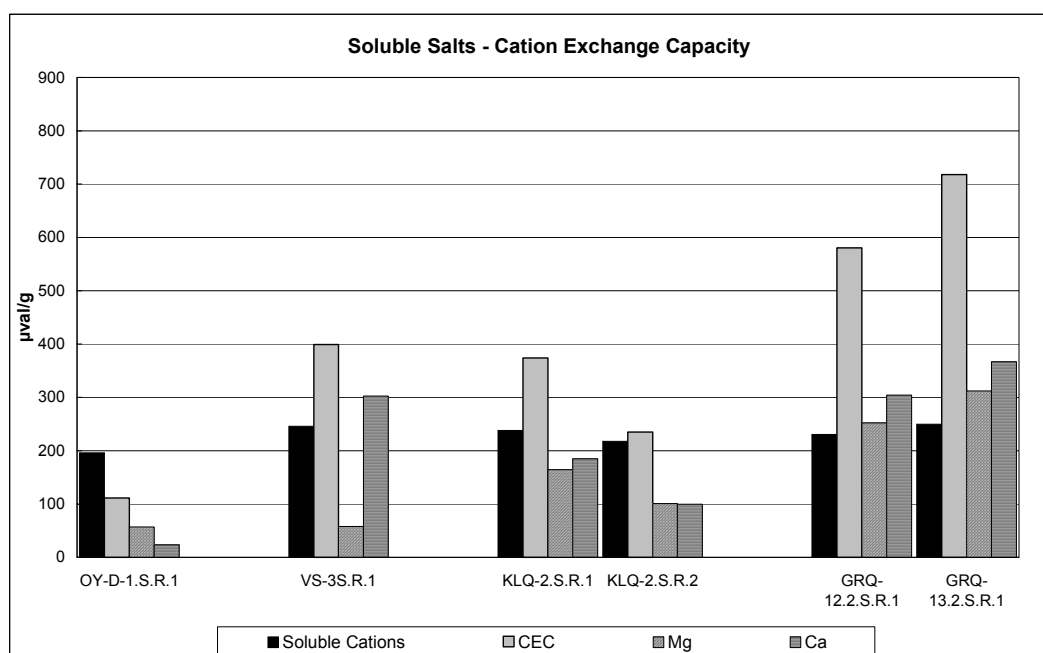

Diagram showing the amount of soluble salts and the cation exchange capacity of various stones (OY=Øye, VS=Øye, KL=Klungen, GR=Grunnes). Soluble cations means cations from salts (mostly Na), CEC means measured cation exchange capacity, and Mg and Ca means ions mobilised from the samples, in an ammounium acetate solution.

Remarks the discussion on relationships between weathering forms and stone properties

As stated earlier, we are not yet able to consistently interpret the quite confusing analyses and measurements. Our efforts will continue; we have, for instance, to better include the dependence of measured values on foliation. Moreover, the thin-section analyses have not been concluded yet. We

perhaps also ought to undertake better reflective-light microscopy in order to determine the opaque minerals (the sulphides) in a more reliable way, as well as chemical analysis of the stones. Although it is difficult, we should also think of ways to undertake microscopical analyses of the pore space in these extremely dense stones.

Stone conservation

Especially at the medieval parts of Nidaros cathedral there are several types of damages to stonework made from soapstone and greenschist that potentially require direct conservation measures like cleaning, desalination, structural consolidation and fixing of scales and delaminated areas. At present there are no "safe" conservation products available to deal with such problems, implying that we need to gather broad experience on possible conseveration products. In this project emphasis have been on developing products for structural consolidation and fixing of scales, as well as desalination and removal of calcite crusts. All methods have been developed by FKD (Wendler & Hestermann 2001).

For structural consolidation and fixing of scales, the point-of-departure before introductory laboratory tests was the philosophy of the *module system*, described in Wendler (2000). These laboratory tests essentially showed that products based on ethyl silicate, silica sol (colloidal silica in water) and dispersed lime had some potential, and were therefore later applied to test areas at the cathedral. Test areas were also made for calcite crust removal and desalination.

A very important feature is that the products for structural consolidation require to "stay in the system". One cannot for instance mix lime or silica sol with ethyl silicate because water from the lime and silica sol will negatively influence the hardening of ethyl silicate.

Ethyl silicate module system

Normal or elastified ethyl silicate (in this case Funcosil 300E) is not able to effectively bind to the minerals in soapstone and greenschist. However, it was found that when adding an adhesive coupling agent (in this case 1-3% propyl amino silane), the ethyl silicate may work perfectly also in real situations. Another problem is that ethyl silicate has a low viscosity and is not able to bridge distances between minerals larger than, say, 50-100 μm, i.e. it is not able to fill most fissures. The problem can be overcome by using a precondensed ethyl silicate and add fume silica - a product which is able to bridge somewhat larger distances.

For larger fissures an injection grout based on ethyl silicate was developed. Moreover, in order to protect *strongly exposed*, weathered surfaces, a "wash" based on ethyl silicate was made. For various purposes, an ethyl silica mortar was developed: it was for instance used to prevent the thinner ethyl silicate products from "escaping" through hollows etc.

Thus, the ethyl silicate module system that was tested *in situ* at six different test field looks like this:

Ethyl silicate module system tested at Nidaros cathedral

| Uses/ weathering forms	Method	Product	Product abbreviation
Granular disintegration, microfissures	First consolidation	Funcosil 300E + PAS	300E-PAS1
Fissures, delamination	Second consolidation	Funcosil VM857-500STE	VM857-500STE
Thicker, visible fissures, delamination and scales	Injection grout/ "Third consolidation"	Funcosil VM857-500STE + Funcosil KSE aggregates + Poraver light glass + pigments	HFM.REM. 2.c.1a
Various	Repair mortar	Funcosil VM857-500STE + quartz sand + soapstone/greenschist powder	SES.TRO. 2.1 & 2.2
Granular disintegration, scaling (surface)	Surface wash (for stabilising surface)	Funcosil VM857-500STE +/- quartz sand + soapstone/greenschist powder +/- Funcosil KSE aggregates +/- pigments	SL.TRO. 2.1 & 2.2

Explanations:

Funcosil 300E:	Elastified ethyl silicate (from Remmers, http://www.remmers.de)
PAS:	Adhesive coupling agent - 1-3% propyl amino silane
Funcosil VM857-500STE:	Ethyl silicate with fume silica (from Remmers)
Funcosil KSE aggregates:	A: Schist powder "Plasturit" (< 30-$40\mu m$),
	B: Quartzpowder "Microdorsilit" ($< 40\mu m$) (from Remmers)
Poraver light glass:	Hollow glass particles from Poraver (http://www.poraver.de)
	(0 - 0,25 & 0,25 - 0,5 mm)
Pigments:	Vagone Earth 4175 & 48440
Quartz sand:	40-150 μm
Soapstone/greenschist powder:	Øye greenschist and Grunnes soapstone (0-125μm & 125-250 μm)

It should be noted that these products cannot be used on surfaces on which there is high biological activity. Thus, algae and lichen were first eliminated by using hydrogen peroxide (H_2O_2).

The time passed since the establishment of the test fields (summer 2000) is of course much to short to be able to state anything about the long-term durability of the products. However, some comments on the application experiences can be made:

- Many test field were salt laden, and although visible salts (as well as loose material) were removed mechanically before application, *the use of the ethyl silicate module is risky*.
- The practical application of the products was undertaken without any significant problems (no problems with for instance injection needles becoming packed).
- Washes and especially repair mortars were much too light in order to blend with the rather dark soapstone surfaces; these products will have to be coloured before application in real situations.
- One test with washes on a very exposed stone was made already in the spring of 2000 - this wash has not shown any significant alterations yet (until February 2001)
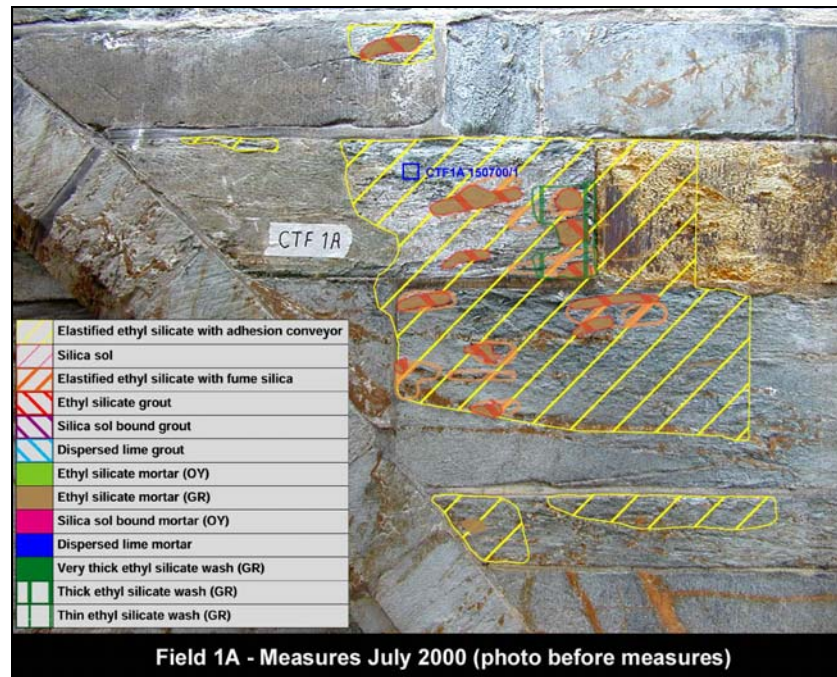
Example of documentation of test fields (field 1A at the north aisle of the choir). The upper picture shows a map of applied products, whereas the lower one shows the field after application (washes and mortars are visible on the picture)

Silica sol (colloidal silica) module system

Colloidal silica comes as a water based system. Upon drying, hydroxyl groups on the surface of the particles condense by splitting out water to form siloxane bonds (Si-O-Si) resulting in coalescence and interbonding.

Silica sol module system tested at Nidaros cathedral

Uses/ weathering forms	Method	Product	Product abbreviation
Granular disintegration, small fissures	Consolidation	Syton X30 + fume silica	SyX30-Cb5
Thicker, visible fissures, delamination and scales	Injection grout	Syton W30 + Funcosil KSE aggregates + Poraver light glass + fume silica	HFM.LUS.3f
Various	Repair mortar	Syton X30 + quartz sand + soapstone/greenschist powder	SES.TRO.3.1

Explanations:

Syton X30/W30:	Colloidal silica from Du Pont (http://www.dupont.com/silica/)
Fume silica	General information about fume silica, see http://www.silicafume.org/
Funcosil KSE aggregates:	A: Schist powder "Plasturit" (< 30-40μm) (from Remmers)
	B: Quartzpowder "Microdorsilit" (< 40μm) (http://www.remmers.de)
Poraver light glass:	Hollow glass particles from Poraver (http://www.poraver.de)
	(0 - 0,25 & 0,25 - 0,5 mm)
Quartz sand:	40-150 μm
Soapstone/greenschist powder:	Øye greenschist and Grunnes soapstone (0-125μm & 125-250 μm)

The silica sol system was applied at one test field only (in order to fix a scale). The application experiences were good, although the injection grout and repair mortar was too light-coloured.

Products based on dispersed hydrated lime

Lately, there has been considerable development in the field of using dispersed hydrated lime for conservation purposes (Jägers, ed. 2000). Dispersed lime has a higher reactivity (i.e. more rapid carbonatisation) than "normal" lime, and is thus potentially useful as an injection grout.

We used the dispersed lime only at two test fields as an injection grout in order to fix scales. Our application experiences were relatively good, but the product became quite "hard" after carbonatisation (apparently harder than soapstone and greenschist; whether this is a drawback has to be evaluated). We have made similar experiences during testing of the product as an injection grout on mural paintings (Franz & Storemyr 2001). Moreover, the product is much too light and will have to be coloured if it is decided to use it in real situations.

Dispersed lime module system tested at Nidaros cathedral (explanations on next page)

Uses/ weathering forms	Method	Product	Product abbreviation
Thicker, visible fissures, and scales	Injection grout	CalXnova	HFM.TRO.1
Various	Repair mortar	CalXnova + quartz sand + soapstone/greenschist powder	SES.TRO.5.1 and 5.2

Desalination with two-layered compress (poultice) and lime mortar

Weathering at Nidaros cathedral is very often influenced by soluble salts, especially derived from Portland cement mortars used during restoration campaigns. Because the accumulated salts remain active/damaging and because they tend to spread and therefore may threaten further (valuable and sensitive) portions of the cathedral, it is desirable to remove the salts as much as possible. Thus, it was decided to include tests with large-scale desalination of masonry using two-layered compresses (poultices) based on bentonite, light aggregates and cellulose.

The first layer, which should stick to the salt-laden stonework (after pre-moistening) consists of bentonite mixed with cellulose (Arbocel 200) (http://www.jrs.de/jrs/german/nm/arbocelt.htm) and water, whereas the second layer is a mixture of Arbocel 200 and bentonite, light glass aggregates (Poraver 250-500μm and 500-1000μm, see http://www.poraver.de) and water.

Dry two-layered desalination compress five days after application (test field 4, north turret of the choir)

The idea is that the first layer should ensure maximum contact to the stonework, while the second layer is intended for taking up the crystallising salts. Moreover, such a two-layered compress prevents the salts from re-entering the stonework after crystallising. The functioning of the compress is dependent on a decreasing moisture gradient from the stonework outwards, which means that the compress should not be completely covered by diffusion resistant materials (plastic). We utilised a simple reinforced plastic cover that was slightly open at one side, but otherwise covering the compress very well in order to prevent it from drying out too quickly.

This system has worked well at numerous sandstone buildings in Germany and the compresses have usually stayed slightly moist for 4-6 weeks, which is the minimum time required for effective desalination. In our case (see picture on the previous page), the compresses surprisingly dried out after some four-five days only. The second layer had at that time developed numerous cracks and was beginning to fall from the masonry. Moreover, the first layer had removed quite a lot of superficial stone powder from the masonry, although it had been carefully mechanically cleaned before application.

The main explanation of the rapid drying drying of the compress must be that soapstone is dense and thereby contains very little moisture, as compared to e.g. sandstone. Another reason might be that the cover simply was not good enough, or "promoted" too rapid drying; perhaps it is better to apply tight "Glad Pack" cover, which is said to be diffusion open. A diffusion open covering is og corse a prerequisite in order for the compress to work. These possible explanations will be considered when trying to repeat the experiment. Moreover, perhaps it is better to apply such compresses in the dry Trondheim spring? At this time of year we know by experience that there is strong moisture (and salt) transport from the masonry outwards.

Also lime plaster was tested as a possible desalination agent - or as a sacrificial layer. We used a simple, coarse plaster in order to find out whether it is effective. The mortar mix was 1:2,6 (lime putty:sand), and the aggregate grading 0,25 - 2,0 mm (the finest fraction was removed). Awaiting salt analyses, we don't yet know the results of this experiment.

Removal of calcite crusts with ion exchange paste

White calcite crusts are very widespread at Nidaros cathedral. They originate from uncarbonised parts (calcium hydroxide) in cement based mortars used in masonry cores and joints during restorations. Although doing little or no physical harm, the crusts are quite unsightly, and has proved extremely difficult to remove by mechanical means alone (chisels, scrapers) without damaging the surfaces of the stone.

Before and after removal of calcite crusts (test field 5, south side of the choir).

Our approach was now to take away as much as possible by mechanical means and apply and ion exchange paste to remove the rest. For the paste we used cellulose (Arbocel, see http://www.jrs.de/jrs/german/nm/arbocelt.htm) and bentonite mixed with a weakly acidic cation exchanger (from Merck; see http://www.merck.de/english/services/chemdat/index.htm - 104835 Ion exchanger IV). The idea was to dissolve the crust and remove the Ca-ions without damaging the stone.

As can be seen from the picture above, the paste worked quite well for thin (up to, say 0,5 mm) calcite crusts, but it was not effective for the remaining thicker crusts. Either we will have to remove more of the crust by mechanical means or we will have to develop a "stronger" ion exchange paste (Or we can let the crusts stay!).

Discovery of a medieval conservation mortar

During a mortar sampling campaign at the south aisle of the choir in the spring of 2000 a white, fine grained mortar used for fixing scales and cracks was discovered by Thorborg von Konow. The mortar seemed to have fulfilled its purpose and was very well preserved. von Konow made a thin-section of the mortar, which was found to largely consist of very fine grained marble aggregates and small amounts of an unknown binder (von Konow 2000).

In the summer of 2000 a mapping campaign at the south aisle was undertaken by PS. Surprisingly, the same type of mortar turned up virtually "everywhere", and by careful stratigraphical analyses it could be stated that the mortar was already used in the Middle Ages. At several places it was for instance used for "gluing" together small pieces that were obviously broken during the original building period. Thus, the mortar is highly interesting, not only as a building archaeological feature, but also because it is very well preserved after 800 years of exposure. Thus, we might be able to reproduce the mortar and use it for modern purposes.

Medieval conservation mortar at the choir (south aisle).

Microphoto's width of field c. 4 mm (normal light)

Further analyses are in preparation, but and initial XRD recording shows that the mortar consists of calcite, dolomite and a little chlorite, mica and talc (from the surrounding stone), as well as an unknown mineral (probably a sulphate, but not gypsum or bassanite). The preliminary conclusion is that there is lime in the binder, but we cannot rule out the possibility of organic materials as well.

In addition to further sampling and analytical work (chemical, IR etc.), the aim should be to reproduce the mortar and test it *in-situ*. Perhaps it is possible to include it in the "lime module system" described above?

Concluding remarks

Although the interpretation of comprehensive greenschist and soapstone analyses is still in progress, we can conclude that the programme has given an insight into the "inner life" of these stones never before achieved. The aim is to continue the interpretation work and publish the results in an international journal before undertaking additional analyses.

With regard to the conservation test programme, we have been able to develop realistic module systems based on ethyl silicate, colloidal silica and lime, but much more time is of course needed in order to draw conclusions about the long-term efficiency and durability. A monitoring programme will be developed and colouring of some of the products to blend with actual stonework is high on the priority list. The desalination and calcite crust removal attempts were unfortunately rather disappointing, but may give a starting point for further work.

The medieval conservation mortar is an important discovery from several perspectives. To our knowledge, similar products of this age have not been reported earlier. The discovery shows that the medieval stone builders had a few problems with spalling, cracking and scaling too!

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