The restoration of the cathedral at Kirkjubøúr in the Faroe Islands

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Abstract
For centuries the ruins of the Cathedral at Kirkjubøur in the Faroe Islands was exposed to the very humid and saline north Atlantic environment. Traditional maintenance of the mortar joints was needed to ensure mechanical stability of the structure. The original lime mortar, locally referred to as 'skílp', was quite hard and had excellent adhesion to the basalt blocks. The lime for the mortar was possibly made of seashells, and the aggregate was a mixture of black, volcanic sand and shell fragments. Hydraulic components were identified in samples taken from the areas with high structural load. Different mixtures of lime mortars were tested in the laboratory and on site to determine the resistance against weathering. This work is not yet terminated, but it appears that only a hydraulic lime will be durable in this environment.

1 History

The cathedral in Kirkjubøur is located on the south side of the island Streymoy, 10 km from the main town Tórshavn. The construction began in the beginning of the 12th century, but it is not known when the building was completed [1]. Today only the walls are left, but structural details and stone fragments found around the monument indicate that the church may have had vaults. By the end of the 20th century the ruin was in a poor condition, so a temporary shelter was erected to protect against further environmental degradation. The shelter was designed also to stabilise the walls, in case the inside of the wall structure was already severely damaged by frost. A study of the microclimate concluded that episodes of frost were rare, but there was a risk of accelerated salt decay on the sheltered surfaces

[2]. The monument would be best preserved by maintaining the joints of the walls with an appropriate restoration mortar.

2 Construction

The walls of the monument are approximately 9 m high and 1.6 m wide at ground level. The arches for the windows and porches are constructed of regular blocks with even joints. In contrast, the walls in between consist of basalt boulders in various sizes and shapes, collected from the hillside next to the site (fig. 1). The cavities between the boulders are filled with smaller pieces of rock and mortar. Two core drillings in the south wall confirmed that the inside has solid mortar infill too. The mortar inside the wall is rather hard and good adhesion to the basalt. It is a substantial part of the construction and serves a structural purpose. Once hardened the mortar infill transfer the vertical load from one block to the next, so the stress is evenly distributed over the cross section. But even more important is the ability to transfer the horizontal load from the vaults, which were supported by the walls 5 m above ground.

Fig. 1 The ruin of the cathedral in Kirkjuböúr is located at the foot of the hill facing south to the Atlantic Ocean. The temporary shelter protects against the very humid and saline environment.

3 Original mortar

The islands do not have any geological limestone deposits, so seashells are the only natural source of lime to use for mortar. The shells mainly occur as fragments mixed with particles of eroded basalt, as it is washed up on the beach. It is reasonable to assume that lime was a limited resource, which was difficult to procure in sufficient quantities for such a project. As a rough estimation a total of 50 m^3 of lime was needed to construct the walls in their present appearance. It must have been a huge effort to collect enough shells or to separate shell fragments from the gravel. But the main problem was probably to prepare the lime. The forest, which may have covered the islands in prehistoric times, was already exterminated prior to the medieval period, so it was difficult to provide fuel for firing the lime.

Fig. 2 The walls of the cathedral is made of irregular basalt boulders. The cavities in between are filled with smaller pieces of rock held in place by the mortar. Test area for restoration on the north side of the north wall

A total of ten mortar samples were taken from different positions at the monument for analysis [3]. The sampling may not be entirely representative, because there was not access behind the shelter. Samples were taken from the drilled cores of the south wall, from the mortar joints in the arches and the wall, and from fragments of plaster found a few places in protected areas. Thin sections were prepared from each sample to study the microstructure of the mortar and determine the composition. Chemical analysis was made on the lime fraction to calculate the hydraulic index of the lime. The results of 5 samples are displayed in table 1.

All samples have rather similar volumetric composition and structure (fig. 3). The pores are mainly round and separate, sometimes connected by fissures, in average 15% by volume. In some samples the pore volume is partly filled with crystals of precipitated lime, an evidence of the extreme humid environment. The silicate aggregate makes up 27% of the total volume. It is a mixture of white, rectangular quarz grains and black, round grains of basalt. The aggregate is similar to the natural sand deposits at the beach nearby the monument.

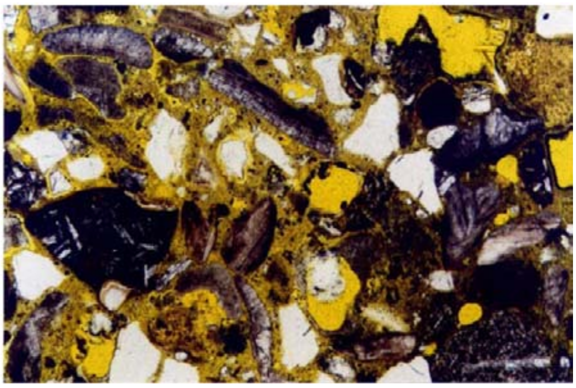

Fig. 3 Thin section of the original mortar in sample 12. The black grains are basalt, the white grains are quarz, the light brown matrix is lime and the grey particles are shell fragments. Yellow areas are pores. The total area is approximately 7 mm^2 . Photo by Thorborg von Konow.

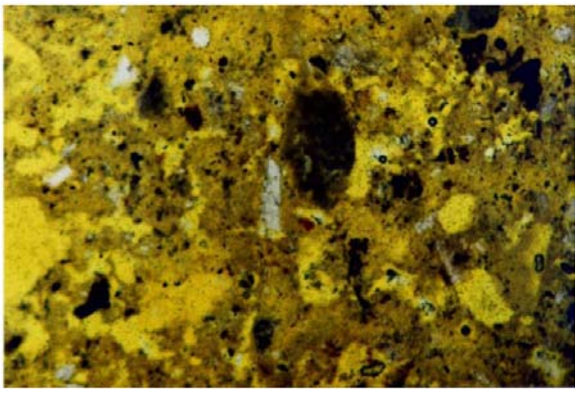

Fig. 4 Thin section of the original mortar. Detail of the lime matrix. The dark brown areas are possibly hydraulic minerals. The total area is approximately 1,2 mm^2 Photo by Thorborg von Konow.

The average lime content is 41%, and there is an additional 18% fraction of unfired seashell and lime inclusions. The presence of shell fragments indicates that the shells were also used for the lime binder. The dark brown areas within the lime matrix might be unfired fragments of the shells, or a hydraulic silicate component (fig. 4). Such minerals do not come from the shells themselves, but may derive from silicate particles mixed with the shells, or deliberately added prior to firing. The hydraulic minerals would evolve during the firing process as in a natural hydraulic lime. The silicate particles may also have been mixed into the lime before slaking or even after slaking to act as a pozzolan.

Table 1 Composition of mortar samples in % volume, and hydraulic index calculated from the chemical composition.

Sample no	4	7	8	10	12
Location	plaster	joint	window	infill	core
Pores	13	15	19	16	12
Silicate aggregate	18	27	33	20	29
Lime aggregate	29	18	9	26	21
Lime binder	39	41	39	38	38
Hydraulic index	0.14	0.11	0.23	0.27	0.75

The hydraulic nature of the lime is confirmed by the chemical analysis. The sample taken from the drilled core of the wall has moderate hydraulic index at 0.75. Two samples taken from a window niche have hydraulic indices at 0.23 and 0.27. Two samples taken from pointing mortar and plaster at the surface have hydraulic index below 0.15, which is considered to be pure lime. The difference in hydraulic content relates to the position of the mortar. The moderate hydraulic lime is needed to resist the compressive stress inside the wall. Furthermore, the diffusion of carbon dioxide deep into the structure is very slow, so it may take years for a pure lime to harden by carbonation. A hydraulic lime will harden much faster and allow the construction work to continue. Similar to this, the mortar joints in the window arches are exposed to compressive stress, and need therefore to gain strength by hydraulic minerals. A pure lime mortar was used at the surface, because the mortar needs little compressive strength for structural reasons.

4 Restoration mortar

The local tradition of firing and slaking lime from sea shells have not survived to modern times, so it is not straight forward to develop a restoration mortar based on local resources. Some initial observations and investigations indicate the performance of imported materials. When the relief on the east wall was put back in place, a lime mortar was used for the joints. After some time the lime started to leak out after rainfall, and after a few years there was a thick crust of lime deposit below the relief (fig. 5). It is not acceptable to have such an effect all over the wall surface. The areas under restoration must be protected against driving rain until the lime has carbonated, but this may take years if the repairs extend deep below the surface.

In the summer 2007 three test areas were established on the north side of the north wall (fig. 2). Each area is approximately 2.0 x 2.0 m, located 1 m above ground level. The facade is little exposed to wind and sun, so this part of the monument is protected against the natural drying and wetting cycles. Two types of premixed lime mortar were used for the joints, one with lime putty matured for 3 years and one with lime and aggregate slaked together. A premixed hydraulic lime mortar NHL3,5 was also tested. During the first winter lime was leaking from the joints made with the two pure lime mortars, whereas the hydraulic lime mortar remained unaltered. After two years the leaking of lime has stopped, possibly due to full carbonisation.

Fig. 5 The lime deposit below the relief on the east wall has leaked from the lime mortar used for the joints.

The results of the first test encouraged the use of a hydraulic lime for the restoration mortar. Four different types were tested in the laboratory [4]. Type A is a NHL3.5 also used for the site test. Type B is a NHL5-Z, mixed from a natural hydraulic lime and a natural volcanic puzzolan. Type C is a mixture of lime putty and white Portland cement in 2:1 by volume. Type D is a 10:1 mixture of lime putty and an artificial puzzolan produced from kaolin clay. All binders were mixed 1:3 by volume with sand aggregate, grain size 0,1- 1,4 mm. Test specimens by the size 40 x 40 x 160 mm were manufactured in steel forms and stored at 85 % RH.

Some results are displayed in table 2. The compression strength was measured after two and four weeks and after one year. Type C reached a maximum at 7 MPa already after four weeks, whereas it took 6 months for type A and B to reach maximum at 8-9 MPa. The fast hydration is a characteristic of C_3S, which is the dominant mineral in Portland cement. The slow hydration is typical for natural hydraulic lime, which mainly contain the mineral C_2S due to the lower firing temperature. It is often claimed that the late hardening makes the mortar more flexible, but the modulus of elasticity for the natural hydraulic lime and the Portland cement mixture are equal. The compression strength of type D was below 1.0 MPa, which is similar to a pure lime mortar, so the amount of puzzolan was probably too little to have any effect.

Table 2 Compression strength, modulus of elasticity and capillary water uptake for mortars under test.

Mortar type	Time	Unit	A	B	C	D
Lime type			NHL3,5	NHL5-Z	Lime/cem	Lime/puzz
Compression strength	14 d	[Mpa]	2.0	2.0	5.3	0.7
Compression strength	28 d	[Mpa]	2.4	2.5	6.8	0.7
Compression strength	153 d	[Mpa]	8.3	8.7	6.2	0.4
Elastic modulus	28 d	[Gpa]	13	14	11	2
Capillary uptake	28 d	[$Kg/m^2s^{½}$]	0.10	0.23	0.18	0.51

The mortars had different capillary water uptake. Type D took up water 5 times faster than type C, whereas type A and B were twice as fast as type D. When exposed to natural conditions of drying ad wetting, type D would probably take up more rain water than the other types. However, it is not clear if this is good or bad for the durability of the mortar. Specimens were mounted at the south wall 6 m above ground to test the performance in the local environment. The position was not sheltered in any way, and the specimens did not enjoy the thermal stability of the solid wall. After one year the type D mortar had suffered severe degradation and would probably fall apart during another season. The hydraulic mortars were not much affected, so it seems to be the right choice for a restoration mortar.

5 Conclusions

The conservation of the monument involves restoration of the mortar joints to ensure structural stability of the walls. The original mortar is probably mixed of lime from seashells and local sand from the beach nearby. Some samples contain hydraulic components, which may originate from volcanic particles mixed with the lime. The hydraulic effect is needed to ensure sufficient mechanical strength of the mortar in the areas with high compression stress. It is difficult to use a pure lime mortar for the restoration, because the lime tends to leak out before it is entirely carbonised. A natural hydraulic lime will probably resist the natural environment better. Further work is needed to develop a restoration mortar based on local resources.

6 Acknowlegdments

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7 List of suppliers

- Lime putty and premixed lime mortars: Skandinavisk Jurakalk A/S. www.kalk.dk.
- Natural hydraulic lime NHL3.5 for type A mortar: Nordisk NHL Aps. www.nordisknhl.dk.
- Natural hydraulic lime NHL5-Z for type B mortar: Skandinavisk Jurakalk A/S. www.kalk.dk.
- White Portland cement for type C mortar: Aalborg Portland A/S, www.aalborgportland.dk
- Pozzolan Metastar 501 for type D mortar: Imerys Performance Minerals. www.imerys-permins.com.

8 References

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