Application of mineral grouts. Case study and impact on structural behaviour: Church of St. Catharina at Duisburg (B)

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**ABSTRACT:** Design of grouting as a repair and strengthening technique for masonry structures must be based on knowledge about the grouts, about the masonry and about grouting technology. Although mechanical strength is required for the grout, good rheological properties are of prime importance because they enhance a homogeneous filling of the cracks and voids in the masonry to provide a monolithic unit after hardening of the grout. The paper includes an overview of tests that can be helpful to obtain a well performing composition of the grout. Together with a good composition also the right mixing procedure is of great importance to obtain an adequate injection grout. This paper discusses a church restoration project in Belgium where mineral grouts were used for structural consolidation.

1 **INTRODUCTION**

The efforts for the conservation of ancient valuable monuments are driven by the desire to keep on using these buildings, as well as the desire to preserve cultural heritage as a testimony from the past for the next generations. The conservation of monuments is of great economical and cultural value. Masonry, just as most other physical entities, is not ever-lasting. Physical and mechanical actions lead to the decay of building materials. In course of time, masonry buildings get physically deteriorated, either by inadequate design, human intervention or natural causes. Frequently occurring natural causes for damage are weathering, freeze-thaw action, erosion of the mortar by rain water flow, overload by earthquake actions. A frequent harmful human intervention is inappropriate loading. This is a direct action, but also the lowering of the groundwater table may cause soil settlement and damage to the surrounding buildings. When these damage processes continue, repair or restoration and consolidation are required.

Grout injection is, amongst other techniques, a powerful consolidation method to overcome structural decay. The introduction of a binding agent in liquid form into the masonry fills the holes, voids and cracks. When a good filling and bonding of the cracks is achieved, the load bearing capacity of the building will significantly improve after hardening of the binding agent. The masonry will regain its monolithic behaviour and the overall mechanical resistance will improve. Important for the consolidation of the monuments is that the injections are almost invisible, although not reversible.

2 **FREQUENTLY USED BINDING AGENTS AND THEIR PROPERTIES**

Consolidation injections are mainly carried out using or cementitious grouts or polymers. Injection of polymers, especially epoxy resins, has certain disadvantages. They are expensive, their adhesion on wet surfaces is poor, there is a possibility of problems with moisture permeability and thermal behaviour and only in special cases their use is justified regarding the preservation of the authenticity of the monument. Despite these disadvantages epoxy resins have good penetration in the masonry due to their low viscosity, show excellent mechanical properties and very good adhesion to dry surfaces.

The group of cementitious grouts counts cement and lime based blended grouts. Depending on the granularity of the cement, distinction can be made between normal cement grouts, ultra fine cement grouts (cement with ultra fines added) and micro-cement grouts. The addition of superplasticizers and stabilizers allows the production of a stable and very
fluid grout. The injectability of these grouts can be comparable to the injectability of epoxy resins. Lime grout is probably the material which is the most compatible with the historic substance. However, since the walls of historical buildings are often very thick, the carbonation process of the lime for which CO₂ has to penetrate to the inside of the wall, will be very slow, and most probably too slow for practical and safety reasons. Addition of pozzolanes could solve the problem of final strength, but not of initial strength. The needed amount of water to produce an injectable lime grout is too high and provides a very weak grout. In addition, the injected water decreases the initial friction of the existing masonry, which could seriously endanger the structure and could lead to local or global collapse. The addition of a superplasticizer adapted for lime or hydraulic lime would improve the lime grout application. Recent experimental research at the Reyntjens Laboratory concerning lime-pozzolan-cement grouts reveals that the presence of a cement phase is necessary to obtain a grout capable of repairing and strengthening an existing masonry structure. Lime is a viscosifying agent as far as fluidity is concerned. However, the presence of lime is very important for stability of the grout.

The injectability of the grout, its mechanical characteristics and the properties of the masonry determine the process parameters of the injection work. The design of the injection work has to be based on appropriate data about grouts, about the masonry and about their interaction. The next two chapters describe how grout properties can be quantified.

3 EVALUATION OF MASONRY FOR GROUTING PURPOSES

Permeability, crack size distribution and moisture content are the most important properties of the masonry with regard to injectability. The overall condition of the masonry used to be determined by coring and analyzing the cores with regard to mechanical properties, cracks, condition of the bricks and the mortar. Less destructive is the combination of non-destructive testing, i.e. (ultra) sonic measurements or electric resistivity measurements, that are calibrated by, again, coring. This combination enables to quantify the qualitative data obtained from the non-destructive testing. These data help to make the diagnosis: does the building need consolidation and can grouting be a part of this consolidation? For the grouting two questions are important: first, what strength improvement is required and what grout can provide it; secondly, how will the grout progress in the masonry?

The required strength improvement is easy to derive from the structural analysis. Fact is that filling the cracks and the voids will cause the masonry to behave monolithically. Research indicated (Tomazevic 1992, Toubakari 2002) that the intrinsic mechanical properties of the grout do not or hardly influence the final strength of a deteriorated masonry wall in case of comparable rheological properties of the grout. This actually reduces the first question to the second one, provided the mechanical properties of the grout are not too low. The flow of the grout through the masonry depends on the permeability of the masonry and even more on the crack size distribution (Van Rickstal 2001).

4 GROUT PROPERTIES

The intrinsic mechanical properties of the grout are not important. Tensile strength and especially adhesion strength to the crack and void surfaces in the masonry are largely more important than compressive strength. Uniform filling of the cracks and voids is also much more important (Schueremans et al 2001). For that reason focus is put on the rheological parameters of the grout rather than on the mechanical properties. However, when a grout is composed meeting the required rheological properties, it is recommended to check the mechanical properties, such as compressive strength, tensile or bending strength, adhesion to the bricks used in the brickwork, and the shrinkage.

These mechanical properties are easy to quantify according to international standards. The most important rheological parameters are the fluidity, characterized by the dynamic viscosity, the yield strength and the flow time for on site control of the composition (Toubakari et al 1997). The stability, the injectability, the granularity of the cement before mixing, the flocculation after mixing and the water retention are other important properties of the grout (Ignoul et al 2003).

5 INJECTION OF THE GROUT IN THE MASONRY WALL

In the two previous chapters the relevant masonry parameters and grout parameters are described. Both groups of parameters were combined into a physical model that simulates how the grout will flow inside the brickwork, what resistance the grout undergoes during the flow and how the grout finally will stop flowing (Van Rickstal 2000). The most important findings of the simulations are discussed in this chapter. Additionally, a composition and a mixing procedure for a cementitious grout are proposed.

5.1 Experiments and findings

To improve the knowledge about the physical mechanisms that take place during injection and that
determine the penetration of the grout in the masonry,plexiglass cylinders filled with a fraction of crushed bricks were injected unidirectionally from bottom to top. The cylinders were filled with different fractions providing different permeability and crack width of the porous medium. The injections are taped on video and analyzed with regard to the rate of rising of the grout. This way the height was plotted against the time, the same was done with the mass. These data are confronted with the laws governing the flow through porous materials.

Findings of the observation are (Van Rickstal 1996):

- When an injection blocks, it is not possible to restart the flow by increasing the pressure.
- There are two different blocking mechanisms: a sudden obstruction of the flow and a gradual obstruction. The physical mechanism of both will be discussed later in this chapter.
- When a permeable zone is in parallel with a less permeable zone, the latter will not be injected, although this zone is, on itself, perfectly injectable. No pressure is built up.
- When injecting with an unstable grout, it can be noticed that cement is sinking to the bottom of the cylinder.

5.2 Composition and mixing procedure

As described above the mixing procedure is also very important for the flow and injection behaviour of the grout. A lot of research has been done to obtain a compatible mixture for a cementitious grout (Van Rickstal 2000).

A composition that gives good results for structural consolidation of historical buildings is described below (Chandra et al 1993):

- 100 kg blast-furnace cement, type CEM III/A
- 2 kg Bentonite (Bentonil CV15)
- 67.5 l water
- 1.5 kg superplasticizer Rheobuild 716, sulphonated naphthalene with poly-hydroxylated polymer

Optimisation of the mixing procedure includes preliminary mixing of bentonite and water, mixing cement with water and plasticizer in successive amounts, and adopting longtime mixing. The optimum mixing procedure gives best fluidity for the same stability. The same fluidity can be achieved using other mixing procedures, but then stability will be less.

Concerning the lime-pozzolan-cement grouts (or ternary grouts) a lot of research has been done concerning new mixing procedures. Tests where done with a high-turbulence mixer (with and without superplasticizer) and with an UltraSonic mixer (Toumbakari 2002). Using an US-mixer allows to reduce water and superplasticizer contents to achieve the same penetrability. This result is attributable to the better dispersion and wetting of the particles. However, better dispersion could induce an increase of internal microcracking.

The mixing procedure with the ultrasonic-mixer consists in an ultrasonic dispersion at 28 kHz and a simultaneous simple mechanical stirring (at 300 rpm). First the water and the superplasticizer are mixed and then silica fume is introduced and mixed. Subsequently, lime and pozzolan are introduced and stirred. Then without stopping the mixing procedure, the cement is added. Disadvantage of this mixing procedure is that the equipment is not commercially available.

6 CASE STUDY: CHURCH OF ST. CATHARINA AT DUISBURG (B)

6.1 Introduction

The construction of the church of Saint Catharina at Duisburg probably started in the 13th century. The exact date of construction is not known. The documents containing this information were lost when the vicarage burnt down in 1731. The construction was made possible thanks to a contribution of the duke of Lotharingen (B). Originally, the church was built in a romanesque style. The choir and the transept were replaced by a gothic construction in the 14th century. The nave and the tower are still in their original style. The church is shown in figure 1.

![Figure 1. Church of St. Catharina at Duisburg (b), 1896.](image-url)
During the 15th and 16th century, the church suffered from some severe fire damage and from the religious wars during that period. In 1590, the first repair works were executed.

The spire of the church tower was replaced in the 17th century. In 1758, a second fire damaged the church. The roof vaults of the transept collapsed and were replaced by a flat roof. The 4 horizontal anchors (fig. 2) in the choir were probably also placed in this period to prevent the walls from further cracking and bulging.

At the end of the 19th and the beginning of the 20th century, the first large scale restoration was carried out. The tower, the façade of the church, and the choir required repair works. A lightning conductor was put in place to protect the church tower.

In 1945, valuable wall paintings were discovered in the southern transept. Due to an explosion of an ammunition depot near the church in 1946, new repair works were needed. Especially the roof was seriously damaged. Also the large windows were severely damaged by the explosion.

The restoration works carried out in the 19th and the beginning of the 20th century were inadequate. Therefore a new restoration was planned. The total restoration of the church is divided in several phases. In the 80's the wooden spire of the tower was investigated and repaired. The restoration of the choir and the façade of the church were completed in 2002.

6.2 Consolidation of the choir

The walls of the choir showed severe cracks. An investigation of the foundation was carried out in 1984. This inspection revealed an insufficient foundation of the walls and the buttresses. This caused cracking of the walls due to differential settlements. Furthermore, the walls were leaning outwards. The 4 horizontal anchors of the 18th century in the choir were placed too low to prevent the deformations of the choir walls, caused by the horizontal loads of the cross vaults on the walls. Moreover, they were anchored in the thin wall parts and not in the buttresses. The thin wall parts were punched by the concentrated anchoring force. The anchors and the cross vaults can be seen in figure 2.

A severe deterioration of the masonry of the buttresses could also be observed. The masonry of the buttresses of the choir was deteriorated rapidly due to an inadequate use of iron reinforcements during the repointing of the 19th century.

6.3 Restoration works

The necessary strengthening works in the choir were completed in 2002 together with a total restoration of the façade of the church. A schematic overview of the consolidation works in the choir is shown in figure 3 (Ignoul et al 1998, Ignoul et al 1999).

In a preliminary project, a system of micro piles was designed for underpinning of the foundation of the buttresses and the walls, thus preventing further cracking due to differential settlements. By that, the longitudinal stability of the choir would be restored. Due to the cemetery next to the choir walls and due to the high cost, this system was abandoned. The new concept is now to create a deep masonry beam in the lower part of the choir, see figures 3 and 4. That U-shaped beam should carry the total load of the choir, and prevent differential settlement and thus prevent cracking. All cracking, if any in the future, will be concentrated at the choir-transept intersection. The flexibility of the transept walls in the longitudinal direction of the church allow the structure to deform, also called 'to breathe', so that cracking is not likely to occur. The choir act as a 'rigid body'.
Horizontal steel anchors (a, fig. 3) are put in drilled holes in the walls. Steel anchors of 32 with a high tensile strength (1030 MPa) and covered with an epoxy coating are used. To roughen the surface and thus to enhance the bonding capacity, sand is sprayed in the epoxy coating. The first layer of 2 anchors is placed at a height of 3 m. The second layer is placed 80 cm above the first layer. The anchors are put in drilled holes with a diameter of 50 mm. To ensure a good bond between the masonry and the anchors, the hole is injected with a cement based grout. To ensure a good filling of the drilled holes special plastic tubes (fig. 9) are put in place at the injection holes so grout can be added after injection of the masonry around the steel bars.

The anchors are placed all along the walls of the choir, so that a kind of reinforced masonry beam is constructed. The placement of the anchors is shown in figure 5. The choir walls with the steel anchors make a ring beam that prevents excessive cracking, due to eventual further differential settlements of the walls and the buttresses. Injection of the foundation masonry (b, fig. 3) was done to enhance the stiffness of the foundation masonry and thus increasing the stiffness and load bearing capacity of the newly created masonry ring wall.

The vault anchors (c, fig. 3) are needed to prevent the walls from leaning outwards, due to the horizontal load of the cross vaults. The 4 original horizontal anchors (fig. 2) were insufficient and inadequate. They were not anchored in the buttresses and were placed too low. New horizontal anchors are put in place.

For a proper design of these steel anchors, the horizontal load of the cross vaults on the walls must be calculated. The horizontal load can be found through the calculation of the funicular polygon of the vaults, assuming different possible positions for its points of application. This iterative calculation is based on an equilibrium of forces. When calculating this equilibrium, no tensile forces are allowed in the masonry structure. With the results of the different calculations the position and the dimensions of the anchors are designed. Inside the buttresses, behind the façade a special concrete anchor block (f, fig. 6) is constructed. When the new vault anchors were put in place, the old horizontal anchors could be removed.
To strengthen the buttresses, a system of vertical steel anchors (d, fig. 3) Ø 25 BE 500 is used to create a reinforced masonry column. The vertical anchors are put in drilled holes filled with a cement grout for good bonding. The steel anchors are anchored in the concrete ring beam (e, fig. 3) on top of the choir wall and in the masonry ‘beam’ (a, fig. 3). Both ‘beams’ act as a fixed point for the reinforced buttresses. This system restores the transversal stability of the choir. The calculation principle is shown in figure 6.

The drilling of the anchors and the injection works are shown in the figures 7 to 9. The composition of the grout and the mixing procedure are the same as described in paragraph 5 for the cementitious grout.

The new vault anchors and the concrete anchor blocks inside the buttresses are shown in figures 10 and 11.

When all the necessary reinforcements were put in placed, the old anchors were cut (fig. 12).

With a monitoring system (strain gauges and convergence measurements), the deformation of the choir wall and the forces in the old and the new anchors are monitored during the restoration works and in the years to come. A schematical overview of the monitoring
system in the choir is shown in figure 13 (Ignoul et al 2002).

In figure 14, the choir can be seen after completion of the restoration works in 2002.

7 CONCLUSIONS

Consolidation by grout injection has been successfully used in many projects. The technique is moving from experimental to scientific. Recent research gave the composition of high performance grouts. The addition of superplasticizers and the use of microcement provide a grout that is as injectable as polymer resins are.

The determination of the most important grout properties is described. A few control measurements suffice to check for important differences between the grout composed in the laboratory and the grout made on the site. The research activities resulted in useful
compositions and mixing procedures for compatible grouts that are appropriate for structural consolidation as described for the recently completed restoration works at the Church of St. Catharina at Duisburg (B).

REFERENCES


