Development of an appropriate grout for the consolidation of the column foundations in Our Lady's Basilica at Tongeren (B).

by

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Synopsis:

Archaeological excavations inside Our Lady's Basilica at Tongeren (Belgium), one of the most beautiful religious monuments in Belgium, are made possible through an adequate consolidation of the columns masonry foundations. The project includes a large archaeological excavation of the central nave up to a depth of more than three meter. To prevent instability of the columns, the foundation masonry is injected with a hydraulic grout. For the preservation of the archaeological remains, possibly available in the soil, the penetration of the grout into the layered soil must be prevented. Specific properties of the grout are thus required. The fluidity of the grout must be sufficient during injection, but has to decrease rapidly after a pre-determined period. Combined with an effective injection procedure, only the foundation masonry will be filled. The archaeological artefacts will thus be preserved. The grout has to be stable and bleeding must be under control. The compressive and bending strength must be sufficient and secured in time. The injectability of the grout in the foundations must be assured. The development of an appropriate grout for the injection of the columns foundation masonry will be described in this paper. The selections of the grout composition, as well as the design of an effective injection procedure are based on laboratory and on site tests. It is demonstrated that a grout containing a mixture of slaked lime and hydraulic cement performed excellently within the preset boundary conditions.

Keywords:

ancient masonry, binary grout, calcium hydrate, consolidation injection, physical compatibility

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INTRODUCTION

Tongeren is an old Roman city, with a history of more than 2000 years. The city centre is an accumulation of remains of successive civilisations and cultures. Archaeological excavations in the 'Vrijthof' market place next to the church indicated that the gothic church was built just on top of a most interesting archaeological site [1]. Archaeological research in the Vrijthof-market at the south side of the church goes back to 1844. At that time J.L. Guioth discovered a series of foundations, which he and his successors in the 19th century interpreted as the remains of a Roman fortress. At the re-arrangement of the Vrijthof site in 1994-1996 extensive excavations revealed that these remains are parts of two different defensive walls of the medieval Minster, one dating from the 10th century and one from the 12th century. At the same time a Roman town house with bathhouse from the 2nd and 3rd century was discovered, as well as a tower and connecting sections of the 4th century town wall. The archaeologists were convinced that the remains of the bathhouse were only the southern exterior walls of a rich urban residence, of which the remaining parts are situated under Our Lady's Basilica.

The idea grew to disclose the remains under the church. However, religious life in the church is very active, and the church is an important monument as well. One had to look for a solution that could combine the desires and needs of all parties involved. The proposed solution was the construction of an archaeological cellar under the church. This cellar will be an underground archaeological field. The cellar will have no solid concrete bottom floor. Visitors will walk on bottom soil surface of the excavations, to keep the archaeological sensation as complete and as realistic as possible.

From the beginning on it was clear that the excavation of an archaeological cellar underneath the existing church structure would cause great structural problems. From existing small cellars it was estimated that foundation depth of walls and columns would be about 2.7 to 3.0 m. The necessary excavation depth for an accessible cellar, taking into account the necessary space for a roof plate and new flooring system for the church, would be 3 m. To give the visitors the real feeling of an archaeological site, and not of a crypt under the church, it was decided to excavate the central nave and the adjacent aisles as well as part of the choir. This presents a surface of about 20 m by 40 m, in which the column footings and the wall foundations would be stand-alone elements. Removing of the soil around the foundations also takes away its constraining action on the foundation masonry. Moreover, the direct foundations at depths of about 3 m than become direct foundations on the soil surface. The load carrying capacity of surface foundations is very limited and uncertain, and unconstrained rubble masonry of foundations has nearly no strength. Both effects significantly endanger the structure, leading to an almost certain collapse.

Therefore the project was preceded by a preliminary investigation to reveal the composition and quality of the foundation masonry, and to study possible injection grouts for consolidation of the masonry, to strengthen it sufficiently to be able to transfer the anchoring forces of the micro piles (see igure 2). The consolidation procedure was adapted according to the findings from the preliminary investigations.

CONSOLIDATION AND STRENGHTHENING: CONCEPT AND EXECUTION

Requirements

The whole project is divided in several phases. Phase I is the excavation and re-arrangement of the west part of the church (1999-2001); phase II concerns the central part of the church (started August 2004). Excavation works and consolidation and strengthening as well as re-arrangement works are going on simultaneously. This means a lot of organisation and compromise between archaeologists, contractor, designers and users. Figure 1 shows a plan of the nave, aisles and chapels of the church. The massive west tower is not shown (more information about the consolidation of the tower can be found in [2]. The first phase of the excavations is shown in the left part of the plan. Figure 2 gives half of the cross-section of the archaeological cellar. The micro pile system under the columns and walls is also presented. The load bearing capacity of the micro piles is 200 kN pro pile.

The underpinning of the columns and uncovered walls is needed because the strength of the foundation soil becomes insufficient after removal of the soil layer of about 3 m, representing a surface load of 50 kN/m². This heavy soil load will be removed over a large area of about 20 x 40 m, and by that the strength of the foundation soil drops drastically under the column footings and under the foundation walls. Also the stress distribution in the soil all over the church surface changes considerably and as a consequence also the deformations of the soil will change. This might lead to excessive differential settlements of structural elements, leading to cracking of walls and vaults. The underpinning of all the columns and walls in and adjacent to the excavation will avoid such differential settlements.

Ground anchors with tension capacity of 200 kN are installed in the north and south wall of the cellar. They secure these walls during the excavation, when exterior horizontal soil pressures are acting on the freestanding walls, not yet supported by the roof plate. Micro piles and ground anchors must be anchored in a stable masonry, able to take up the concentrated forces from piles and anchors. Therefore the masonry walls are injected with mineral grout.

Phase I: (1999-2001), injection with cement-based grout [3]

The injectability of a cement grout depends amongst other on the fineness of the dispersion of the cement particles in the water phase. The addition of stabilizers and superplasticisers prevents the dispersion from coagulation and segregation. The injected cement-based grout was a mixture of cement, additives and water (see also Table 1).

The mixing procedure is of prime importance and determines the physical and mechanical properties of the cement grout. The following routine was adopted:

- dry mixing of cement and bentonite
- addition of 50 % of the water and mixing
- after 2 minutes, addition of 50 % water with 50 % of superplasticizer amount and mixing
- addition of 50 % superplasticizer and mixing

The average final mechanical properties of this grout, measured on prisms 40 mm by 40 mm by 160 mm are given in table 2. The injection in the masonry walls was made through vertical or slightly inclined boreholes, with a diameter of 50 mm. Compressive strength tests on control coring indicated strength of 3 to 6 MPa for the injected masonry.

Although the main objectives concerning the consolidation and strengthening of the foundation masonry was successfully executed with the cement based grout in phase I of the project, there were some disadvantages using this type of grout. Cement based grouts tend to remain very fluid for several hours, causing damage to several sarcophagi, located in the direct surroundings of the chain wall. Some valuable inscriptions on lime stone fragments were lost and even a skeleton was accidentally injected (see Figure 3).

Phase II: (august 2004 - 2006), injection with binary grout

In phase II it is attempted to prevent this unwanted filling of sarcophaguses, skeletons and inscriptions by using a different grouting material. The aim was to develop a mixture that not only satisfied all the requirements needed for structural strength and chemical compatibility, but also limits the fluidity in time. In that way, the unwanted consolidation of valuable artefacts is intended to be reduced to a minimum.

GROUT REQUIREMENTS

The first requirement is the ability to inject the mineral grout into the fine cracks and voids. Since a mineral grout is a dispersion of solid particles in water, the rheology of the grout and hence the injectability is a function of many parameters:

granularity of the binder, mixing procedure, the use of superplasticisers, the use of stabilising agents, etc... Tomazevic [4] and Toumbakari [5,6] indicated that the intrinsic mechanical properties of the grout do not or hardly influence the final compressive strength of injected masonry in case of comparable injectability. Adhesion of grout to stone and mortar is a more important. Therefore, it is preferable to focus on rheological properties of the grout and on tensile or adhesion strengths instead of on compressive strength.

A second category of requirements could be named "compatibility" with the original material. The grout needs to be adapted to the original material with regard to three aspects: chemical compatibility (including durability aspects), mechanical/structural compatibility and physical compatibility. Special attention is paid to the aspect of historical compatibility keeping in mind the cultural-historical value of the treated monuments and the original composition of the mortars.

Physical compatibility

The physical compatibility of the grout concerns properties such as stability, fluidity and the injectability in the masonry structure.

Stability is a first requirement for a grout to be admitted for injection purposes. A grout can be unstable in two major ways: bleeding and segregation. Segregation means that heavy or flocculated particles sink to the bottom. Bleeding and segregation are prevented by composition and mixing procedure [7]. Hereafter it will be shown that the bleeding and stability of the grout are achieved by adding only calcium hydroxide (air hardening lime), without using extra agents like bentonite or ultra fine admixtures.

The fluidity of the grout is a rheological property in the strict sense. The viscosity of mineral grouts is commonly measured using a flow time test. This test tries to capture the complex rheological (including thixotropy) behaviour of a grout in one single easy 'consistency' test. It measures the time needed for a fixed amount of grout to flow through a hole out of a standardised recipient. Mostly used is the Marsh funnel providing the Marsh viscosity expressed in seconds, according to ASTM C 939_87 or NF P 18_358.

The injectability of polymer or mineral grouts is mostly checked by injecting a glass tube filled with fine or coarser sand according to the French standard: NF P18-891 "sand column test". The filling of the sand columns is standardised; the granularity of the sand lies between strict limits. For testing the injectability of mineral grouts it is better to adapt the "sand column test" to produce a situation representative for the on-site boundary conditions. The viscosity and yield stress and hence the injectability of mineral grouts, highly depend on the water content of the grout. The dry masonry absorbs water from the grout. The particles stick to the original material narrowing the flow channels. When it has to be feared that the flow channels narrow due to excessive water loss, the injectability of the grouts should rather be checked in a column filled with crushed bricks (Figure 5). The crushed bricks show a water absorbing action comparable to the real situation.

The injectability of a cementitious grout depends upon the rheological parameters, but since such a grout is a dispersion of cement particles in water, the injectability depends also on the particle size of the cement grains, the stability and the mixing procedure. Different researchers mention a relation between the granularity of the cement and the smallest crack width of the medium to be injected. This relation is mostly expressed by the requirement that the maximum grain size of the cement is a factor smaller than the minimum diameter of the medium to inject. This factor lies between 1.5 and 10 [7]. According to the authors' experience, a more intensive mixing, capable of enveloping single cement grains with a water film, is much more important than cement fineness.

Mechanical compatibility

The most important mechanical properties that apply in this particular case are the tensile and adhesion strength, and the stiffness. Although mechanical properties are not the first concern when composing a grout, some minimum requirements exist. A minimum compressive strength f_c = 4 N/mm² with an average of 7 N/mm² and a minimum Tensile strength f_t = 0,8 N/mm² were prescribed for the injected masonry.

Chemical compatibility

Chemical compatibility is also very important. There is the possible growth of ettringite crystals when injecting cementitious grouts. This is why blast furnace slag cement is preferable over ordinary Portland cement. The alkali in the cement might cause efflorescence. Low alkali cement is recommended for grout injection. The formation of efflorescence or any expansive crystallisation causing surface damage and internal cracking must be prevented.

Historical compatibility

Lime based grouts are the most compatible with the original materials for the consolidation of ancient masonry. For centuries, lime of both types, air hardening and hydraulic lime, has been used for construction. The use of lime based grouts for consolidation of masonry should therefore be well accepted in practice. It must be noted that the water content of a fluid lime based grout is very high without the use of an appropriate superplasticiser. Strictly spoken, cement does not fully correspond to the binding agent used in most historic masonry buildings. The nature of the historical binding agents is air hardening lime or natural hydraulic lime. Cement is a mineral binding agent, just as lime, capable of enhancing execution speed. The physical properties with regard to moisture transport, thermal expansion, temperature household etc... are much closer to those of the historical materials than in case of polymers. Many buildings have been injected very satisfactorily using cement-based grouts.

GROUT DEVELOPMENT

In order to fulfil the requirements, it was decided to examine several mixtures of binary grout using cement and air hardening lime as basic materials. It is already stated that without the use of a superplasticiser, the water content for an injectable grout is too high. Table 3 shows the different mixtures that were tested in order to find a grout mix suitable for injections. It will be proven that by adding calcium hydroxide the stability of the grout is assured and the fluidity stays constant the first one and a half our and than increases rapidly. Table 3 mentions the W/B (water/binding agent – ratio) in stead of the W/C because the binding agent is a mixture of cement and air hardening lime. This W/B and the amount of superplasticiser (Glenium 27, polycarboxylic ether superplasticiser) were kept constant. Practical experience showed that higher amounts of superplasticiser increased shrinkage; lower amounts require too much water [7].

A two years test programme was implemented to study the long term effects of the grout mixtures (see Table 3). The tests were done on samples 40x40x160 mm according to the Belgian standard NBN B14-208 for compression and flexural strength. The environmental conditions of the samples were kept constant for the first 90 days at R.H. 96%; CO_2-amount 3 % (using a CO_2-incubator) and temperature of 20 °C. Than the relative humidity changed from 96 % to 85 % for the rest of the two years testing period (see Table 4). The idea is to study the long term effect of delayed carbonation of the air hardening lime on the cement-matrix (instantly formed during the hydraulic reaction). Therefore a CO_2-amount of 3 % is used (normally the CO_2-content in the atmosphere is 0.03 %) to accelerate the carbonation process. In [8] it was stated that the carbonation rate reduces dramatically with increasing relative humidity. For example, it has been proven that in a saturated environment the carbonation rate is zero because diffusion of CO_2 is completely blocked. By keeping the R.H. high (> 96 %) for the first 90 days, the hydraulic reaction of cement will dominate the curing process. By reducing the R.H. to 85 % after 90 days, the carbonation process will take part in the curing process and the long term effects on the mechanical properties and the durability can be studied.

The following mixing procedure was used:

Compositions 2, 3, 4 and 5:

- dry mixing of cement and calcium hydroxide
- addition of 90 % of the water and 2 minutes mixing (2400 r/min)
- after 2 minutes rest, addition of 5 % water with 50 % of superplasticizer amount and mixing for 3 minutes (2400 r/min)
- after 2 minutes rest, addition of the final amount of water (5%) with the last 50 % of superplasticizer and mixing for 2 minutes (2400 r/min)

Composition 1: see 2.2.

Physical properties

Stability: bleeding -- The stability is checked, as mentioned before, by measuring the bleeding which can be read from the scale on a lab tube in which the grout is poured. Table 5 shows the percentages of bleeding of the different compositions tested for phase II. The bleeding was measured after 0', 15', 30', 60', 90' and 120'. It is concluded that the higher the content of cement, the higher the bleeding will be (compositions 1 and 5 produce the most bleeding). Air hardening lime seems to function as a very good stabiliser. Composition 1 (the reference cement-based grout with bentonite as stabiliser) produces the most bleeding, but still keeps bleeding under 3 %, which is regarded to be tolerable for grout mixtures.

Fluidity: Marsh funnel -- This test is performed with a Marsh funnel Viscometer after 0', 15', 30', 60', 90', 120' (cfr. ASTM C 939_87). The Marsh cone used was an OFITE (OFI Testing Equipment Plastic Marsh Funnel Viscometer) and is calibrated so that it takes 26 ± 0.5 seconds for 947 ml of water (21 ± 3°C) to pass the funnel. Figure 4 gives the Marsh cone flow times of the different compositions tested for phase II. The flow times were measured after 0', 15', 30', 60', 90' and 120'. As mentioned before, it is the aim to develop a grout who's fluidity stays constant the first one and a half hour and then decreases rapidly. Figure 4 clearly shows that compositions with an air hardening lime content above 30 % fulfil this special condition needed to prevent the filling of the valuable artefacts.

Injectability: injection test -- Like stated before, for testing the injectability of mineral grouts it is better to adapt the "sand column test" to produce a situation representative for the on-site boundary conditions. Two different tests were performed.

The first one consisted of the injection with grout under atmospheric pressure of a Plexiglas column, filled with brick, natural stone, and mortar from the site (see Figure 5). The grout injected was composition 3. It was observed that in all cases the grout filled completely the present voids. In Table 6, the compressive strengths on samples made in the laboratory by means of injection under a hydraulic fall of 1 m of a tube filled with the different kinds of materials found in the foundation. The curing period was 28 days.

The second injection test consisted of the injection with grout (composition 3), under a constant pressure of 1 bar, of a Plexiglas column, which was filled with gravel (broken bricks). The crushed bricks show a water absorbing action comparable to the real situation. The size of the brick particles varies between 1 mm and 2 mm. It was observed that it took approximately 5 seconds to fill the Plexiglas tube of 50 cm height. After injection and a 7 day curing period, the tubes were sliced to check the filling of the voids (see Figure 6). The grout proved capable of consolidating the gravel.

Mechanical properties

Compressive strength, dynamic modulus of elasticity -- The tests were done on samples 40x40x160 mm according to the Belgian standard NBN B14-208. The tests will be executed after 28, 90, 180, 365 and 730 days. Also the dynamic modulus of elasticity will be measured after 7, 28, 90, 180, 365 and 730 days (cfr. NBN B15-229). At the time of writing, the tests were executed after 7, 28 and 90 days. Figure 7 gives the evolution of the compressive strengths of the different compositions, measured after 7, 28 and 90 days. Higher cement content results in higher compressive strengths. Figure 8 shows the dynamic modulus of elasticity of the different compositions, measured after 7, 28 and 90 days. The same conclusion applies here, higher cement content results in higher compressive strengths

Flexural strength -- Figure 9 shows the evolution of the flexural strengths of the different compositions, measured after 7, 28 and 90 days. The initial flexural strength (after 7 days) depends on the amount of cement. Less cement results now in higher initial flexural strengths. It is believed that slaked lime makes the grout more hygroscopic and tough, diminishing micro cracking in the hydraulic phase of the curing. After 28 days the flexural strengths augmented for all the compositions and again lesser content of cement results in higher flexural strengths. After 90 days however, it is observed that the flexural strength diminishes for all the compositions. A possible explanation is that, although the R.H. is higher than 96 % and therefore carbonation is thought to be limited, the carbonation initiates between 28 and 90 days because of the high CO_2-content of 3 %. A simple carbonation test using phenolphthalein showed that the outer skins of the samples were indeed carbonated after 90 days. The drop of flexural strength is probably due to microcracking occurring at the interior of the samples. It is assumed that the reason of this microcracking is the difference between areas of the grout situated towards the exterior of the specimen that are carbonated and other areas towards the interior, that are still hydrating. Hydration causes chemical shrinkage and induces tensile stresses (and thus microcracking) at the interface of a carbonated (and thus inert) part of the material and a non carbonated (and thus hydrating) part of it. A similar phenomenon was already observed and described in [6] for grouts containing silica fume. A new PhD.-research recently started at the Department of Civil Engineering of the Katholieke Universiteit of Leuven, studying this competition between carbonation and hydration[*]. The evolution of the compositions will further be followed during the coming two years.

Grout selection

After considering all the objectives, it was decided that composition 4 (70 % cement, 30 % slaked lime) corresponded with all the requirements stated above and was used on site.

ON SITE TESTING AND VERIFICATION OF THE INJECTIONS

Some test injections were performed on site with composition 4. Three injection holes were drilled, forming an equilateral triangle with a distance of 60 cm, and filled with grout under atmospheric pressure. After curing, a core was drilled in the equilateral triangle. Due to the presence of very hard stone material in the foundations and the resulting difficulties experienced during the drilling of the core, the core itself did not present a good image of the injection degree of the masonry. To verify the injection, an endoscopical survey of the drilled hole was executed. Figure 10 gives a view from the surface of the hole drilled in the injection test area. The endoscopical survey of the hole showed a well consolidated foundation masonry. The injected grout itself was also tested and controlled. Every day the Marsh funnel flow time evolution was checked and every 3000 litres some samples of 40x40x160 mm were moulded according to the Belgian standard NBN B14-208 for compression and flexural strength. Also the dynamic modulus of elasticity was measured (cfr. NBN B15-229). The physical and mechanical properties of the grout samples tested correlated with the results from the laboratory tests.

CONCLUSIONS

Making an archaeological cellar under an existing monument is a challenging project, in which both archaeologists and engineers must discuss, persuade and compromise. The presence, location and magnitude of archaeological remains are unknown beforehand and archaeologists tend to excavate more, deeper and wider than originally planned. The design engineer must protect the monument as well as the archaeologists, but he also has to give them all the necessary help to

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[*] Cizer O., "Competition between hydration and carbonation in lime-cement mortars", PhD thesis, in preparation, KULeuven

discover and uncover as much as possible of the hidden objects, evidence and magnitude. Stability reasons made grouting inevitable, and the specific conditions required some special properties for the grout. The fluidity of the grout must be sufficient during injection, but has to decrease rapidly after a pre-determined period. Combined with an effective injection procedure, only the foundation masonry will be filled.

The binary grout developed is able to fulfil the physical, chemical, mechanical and historical requirements. An extensive test programme including laboratory and on site experiments proved that grout mixtures of cement and slaked lime act complementary, producing the physical properties (fluidity, stability, injectability) needed in this project.

Further research is necessary to study the durability of such binary grout mixtures, in particular the competition between carbonation and hydration.

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Table 1 -- Composition of the cement-based grout mix injected during phase I (1999-2001)

Component	Quantity
Cement IIIA 42,5	100 kg
Bentonite CV15 (sodium montmorillonite)	2 kg
Water	67.7 kg
Superplasticizer Rheobuild 716 (sulfonated naphtalene)	1.0 kg

Table 2 -- Mechanical properties of the injected grout (NBN B12-208)

	Tensile strength MPa	Compressive strength MPa
After 7 days	4.4	26.8
After 28 days	4.0	31.8

Table 3 -- Compositions of the binary grouts for the injections during phase II (2004-2006)
Remark: composition 1 is used as a reference, it is the cement-based grout used in phase I

	CEM III kg	Bentonite kg	$Ca(OH)_2$ kg	W/B ratio	water litres	Glenium 27 kg
Composition 1	100	2		0.675	67.5	1
Composition 2	50		50	0.675	67.5	1
Composition 3	60		40	0.675	67.5	1
Composition 4	70		30	0.675	67.5	1
Composition 5	80		20	0.675	67.5	1

Table 4 -- Storing conditions of the samples

storing conditions	0 - 90 days	90 - 730 days
$C0_2$-amount [%]	3%	3%
R.H. [%]	96%	85%
Temp. [°C]	20 °C	20 °C

Table 5 -- Percentage bleeding of the different compositions tested for phase II. The bleeding was measured after 0', 15', 30', 60', 90' and 120'

	0 min	15 min	30 min	60 min	90 min	120 min
composition	%	%	%	%	%	%
1	0	1.5	2	2.5	2.5	3
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	1	1	1
5	0	0	0	1	1.5	2

Table 6 -- Compressive strengths on samples made in the laboratory by means of injection under a hydraulic fall of 1 m of a tube filled with the different kinds of materials found in the foundation.

Sample	Compressive strength f_c after 28 days			
	Mean value (:) [N/mm²]	deviation (F)[N/mm²]	variation (100F/ :) [%]	Number of samples [#]
natural stone fraction	15.5	11.1	72	3
mixed fraction	14.7	0.9	6	3
porous stone	11.8	0.7	6	3
brick fraction	14.3	3.1	22	3

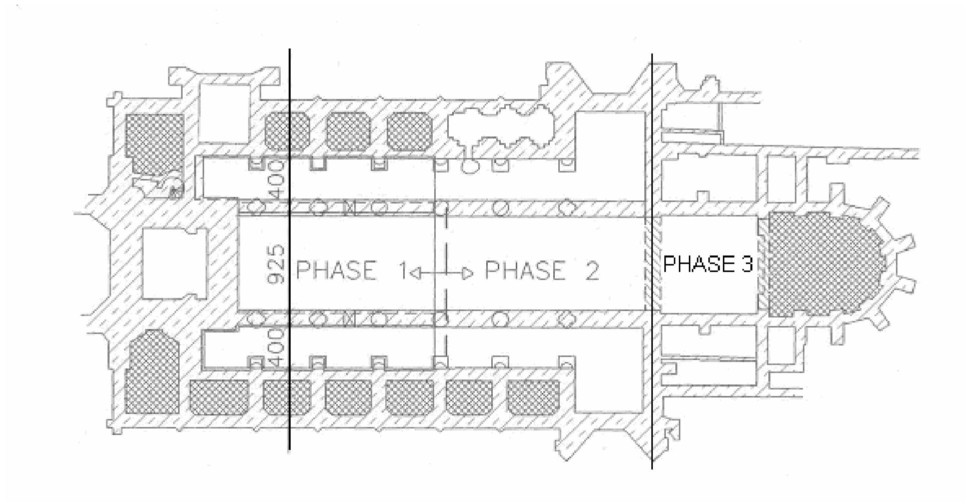

Fig.1 -- Plan of the church with excavation phases I and II

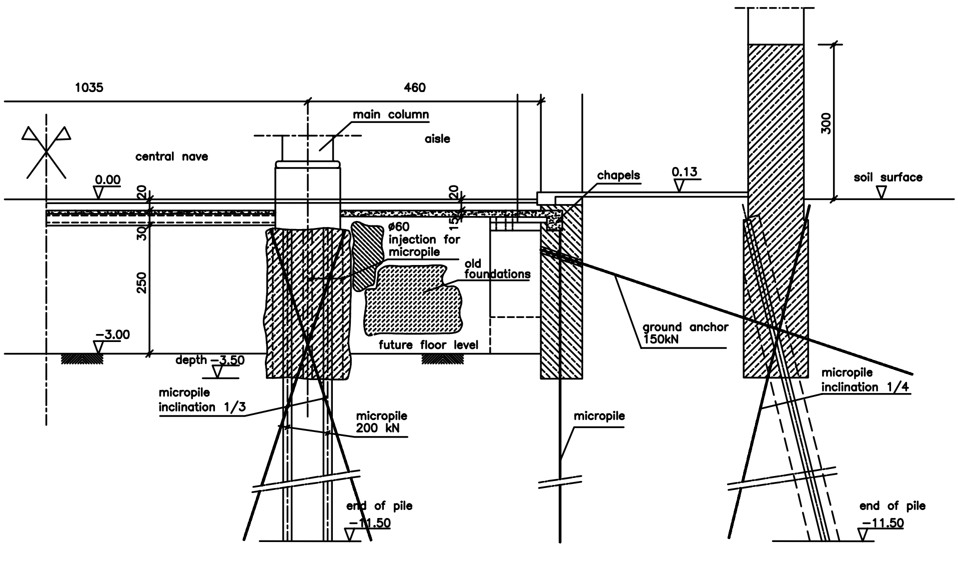

Fig. 2 -- Cross-section of the archaeological cellar

Fig.3 -- Left: tower of Our Lady's Basilica at Tongeren (Belgium)
Middle: unwanted "consolidation" of a skeleton caused by the pronounced fluidity in time of the injected cement based grout (phase I)
Right: sarcophagus next to the chain wall (excavated in phase II)

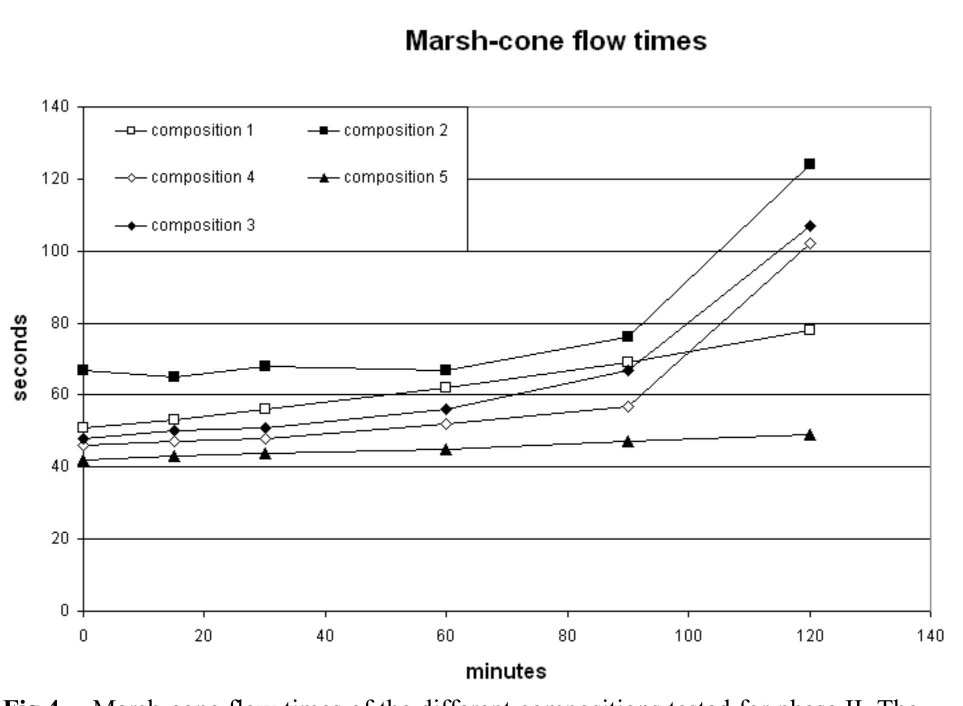

Fig.4 -- Marsh-cone flow times of the different compositions tested for phase II. The flow times were measured after 0', 15', 30', 60', 90' and 120'

Fig.5 -- Injection with grout (composition 3) under a hydraulic fall of 1 m of a tube, filled with brick material from the site. The curing period was 28 days.

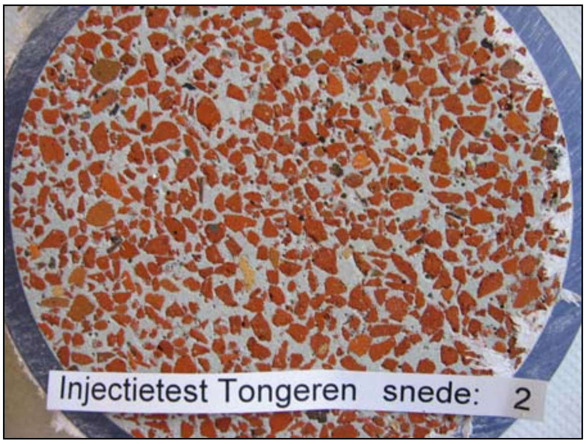

Fig.6 -- The size of the gravel particles varies between 1 mm and 2 mm. After a 7 day curing period, the tube was sliced to check the filling of the voids. The grout proved capable of consolidating the gravel.

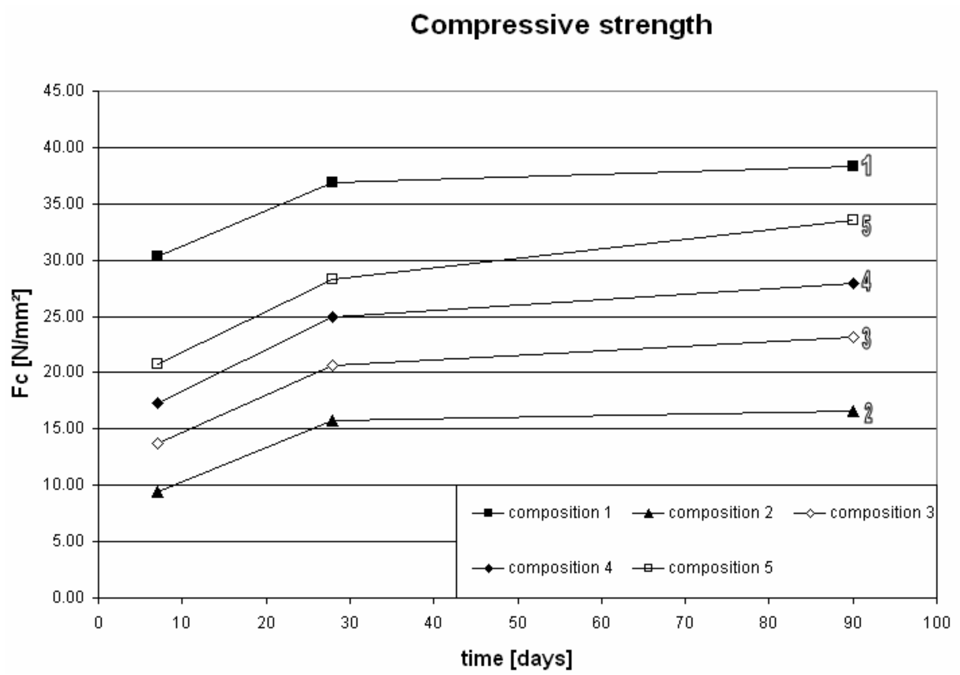

Fig.7 -- Compressive strengths of the different compositions, measured after 7, 28 and 90 days.

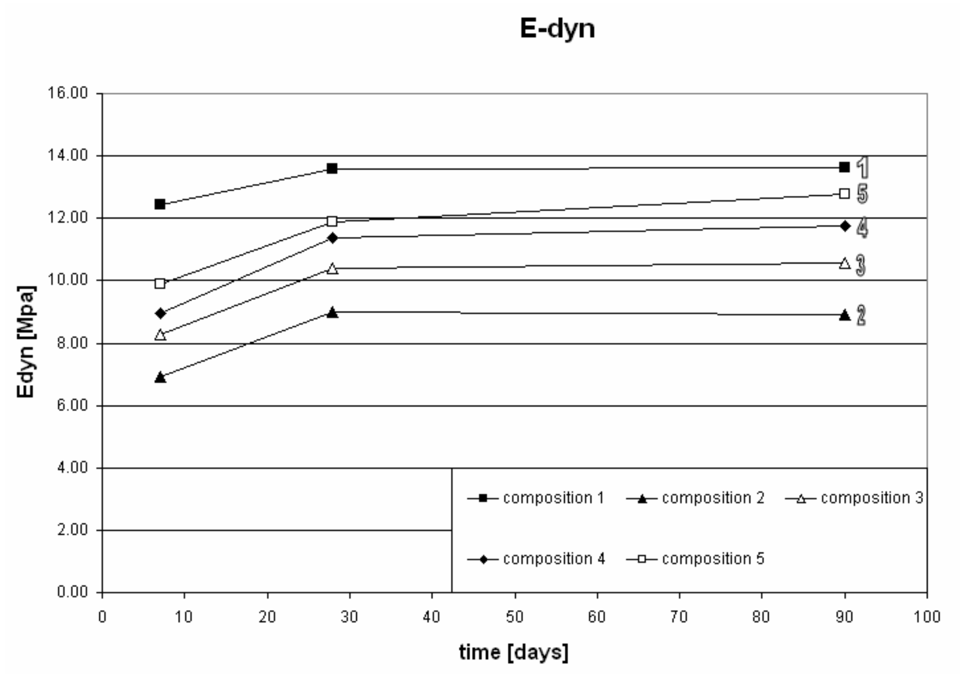

Fig.8 -- Dynamic modulus of elasticity of the different compositions, measured after 7, 28 and 90 days.

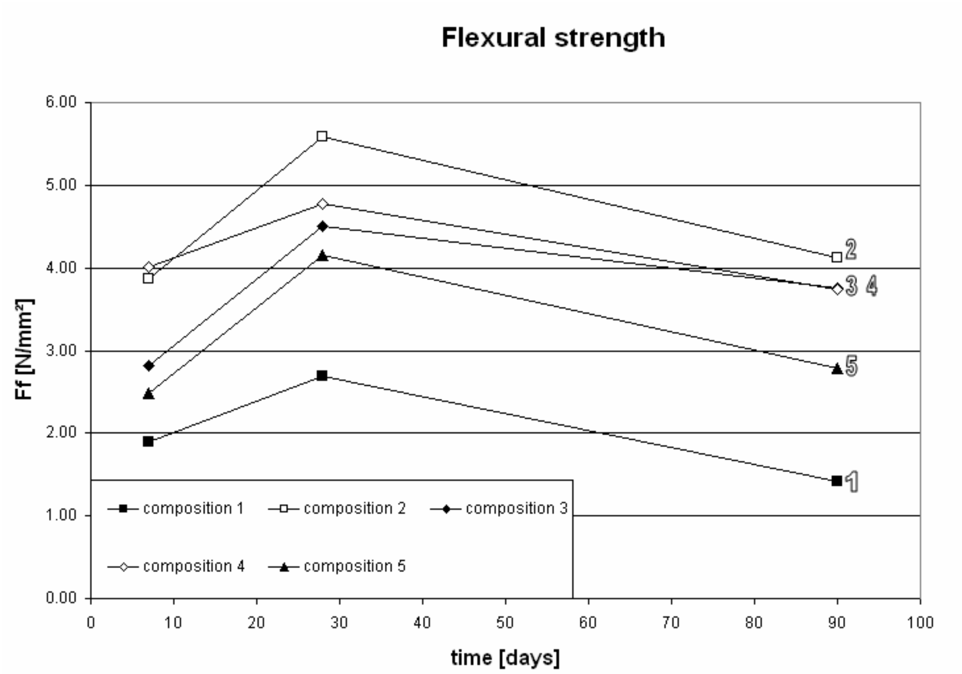

Fig.9 -- Flexural strengths of the different compositions, measured after 7, 28 and 90 days.

Fig.10 -- View from the surface of the hole drilled in the injection test area.