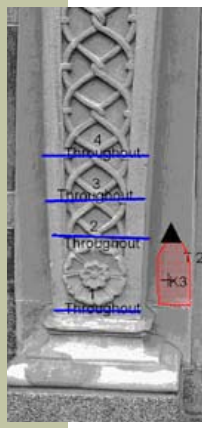
Riksantikvarieämbetet

Final Report for the Research and Development Project

Non-Destructive Field Tests in Stone Conservation

Field and Laboratory Tests

Rapport från Riksantikvarieämbetet 2006:4



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1. Summary

1.1 Summary of Field and Laboratory Tests

The aim of this project is to evaluate a few *Non Destructive Field Tests (NDT)* frequently used in stone conservation on Gotland sandstone. The following report is the second and final of the project and focuses on the field and laboratory tests that have been undertaken. The first report, *Report 1. Non-Destructive Field-Tests in Stone Conservation – Literature Study,* was based on a literature study that discussed NDT methods and stone conservation. The field tests were conducted on Gotland sandstone on three occasions (over the period of a year) on sixteen buildings in the centre of Stockholm. The stones were selected according to their age. Stones from the 17th and up to the 20th century were examined. The methods included a *Granular Disintegration Test* with Herma Labels invented by the NHB, *Ultrasonic Pulse Velocity (UPV)* with a portable instrument, colorimetric measurements with a *Spectrophotometer* and water absorption measurements with *Karsten pipes*. The moisture content of the stone was measured using a *TRAMEX Concrete Moisture Encounter*. [1]

The results of the field tests were complemented with three laboratory tests. The laboratory tests were conducted in order to test the methods in laboratory conditions as well as to understand some of the properties and behavior of Gotland sandstone in different circumstances. These tests are the first of a series of tests necessary to an understanding of the variations of the properties and weathering of Gotland sandstone. The tests were:

1 Variation of Ultrasound Pulse Velocity (UPV) due to change of relative humidity on Gotland sandstone
2 Variation of colorimetric measurements with a Minolta Spectrophotometer due to heat, cold and moisture content of Gotland sandstone
3 Measurement of the w- and B-value of Gotland sandstone from the Valar quarry. [2]

The results of the field study have not yet been fully analyzed. [3] One of the most important issues mentioned in the report is the necessity of knowing the conservation history of the particular stone that is going to be evaluated and tested to achieve accurate results. As such information is unfortunately often lacking in the most extensive of conservation reports, one of the recommendations of this report is that the conservator-restorer [4] should produce more precise conservation documentation in an organized and systematic way. The treatments and information gathered during conservation have to be mapped on drawings of an appropriate scale, approximately between 1:5 and 1:10, depending on the size of the object. Reference areas should be left for future evaluations of both treated and untreated stone.

Even though questions still remain about some of the methods and interactions with Gotland sandstone, two preliminary weathering indexes for Gotland sandstone have been created (that classify whether the stone is in good, intermediate or poor condition and severly weathered, somewhat weathered or in good condition) that can help to determine the condition based on UPV measurements and granular disintegration tests. However, further laboratory tests are required to confirm the accuracy of the indexes.

The Karsten pipes give important complementary information that, above all, helps to understand the absorption and penetration of water in the stone material. This knowledge is necessary, for example, to an understanding of the durability of a hydrophobic treatment. The Karsten pipe measurements are also useful to an understanding of the condition of the stone, although one immediate problem is how the data should be presented. In this report, the results are presented in graphs that facilitate an understanding of *how* water penetrates and also graphically demonstrates changes in water absorption. As the graphs do not give any comparable values that help to classify the condition of the stone, the w- and B-values might provide a better alternative, even though they comprise mathematical approximations to evaluate the condition of the stone.

It has been established that the UPV is the best NDT method to determine the condition of the stone, the reason being that the UPV measurement gives a quantitative value that directly corresponds to the properties of the stone. The method poses som uncertainties, however, such as possible disturbance by salts. The salt disturbance has not yet been fully tested. Measurement with the Karsten pipes and the calculated w-values from this measurement, include, on the other hand, a series of mathematical approximations that lead to further uncertainties. Correlations between the age of the stone, the Karsten pipes and the UPV were determined from the field tests and prove that there are correlations between the Karsten pipe and the UPV. These need to

be tested further in the laboratory, however. There is moreover a distinct correlation between the age of Gotland sandstone and the UPV; approximately a decrease of UPV of 3 km/s per 100 years (see Appendix 10).

Furthermore, the colorimetric measurements with the Spectrophotometer created difficulties, especially with the interpretation of the data. While the data is easy to compare, especially the differences in lightness (L* value), the question of the actual nature of the colour change arises. The L* value might be a good indicator of how far the stone has deteriorated, but could also depend on the presence of black crusts, dirt, biological growth and variation in moisture content. The method has already been tested by the NHB to look for changes in restoration mortars and encountered such problems. To achieve data that actually derives from changes in the stone itself it is necessary to take samples to check the nature of the change. It would seem that there are simply too many uncertainties. Despite this, colorimetric measurements can give reliable results in the field when the differences in lightness (L* value) are high. It is probably better for controlling resoiling after cleaning than to understand chemical change. The method is, above all, best suited to laboratory conditions.

The granular disintegration test has to be further analyzed before it becomes a "standard method". The result of the field tests demonstrates that the differences between the measurements were too small to be reliable. Hence, the test has to be further tested and developed in laboratory conditions if it is to be useful.

To some extent all the NDT methods depend on moisture content, except perhaps the granular disintegration test. The most common NDT instruments used for measuring moisture, which have also been used within this project, are disturbed by the presence of salts and only measure the moisture content at the surface. Some NDT methods, such as the microwave method and the neutron moisture meter measurement, are supposed to be better (even though more expensive – see Report I). Nevertheless, further testing is advisable.

The laboratory tests were designed to support tests in the field. Fresh Gotland sandstone from the Valar quarry had a relative low compressive strength depending on the lamination of the stone and a high water absorption capacity (relatively high w-value and B-value). The UPV test demonstrated that the UPV depends on the moisture content, the length measured, the direction of the measurement according to the lamination of the stone, and whether the measurement is indirect or direct. Colour measurements demonstrate that it is sensitive to moisture content and slightly to temperature changes, which confirms that colorimetric measurements have to be used with care.

2. Introduction

2.1 Objectives of the Project

For several years the NHB in Sweden has striven to monitor and evaluate stone conservation treatments. One of the reasons is that the conservation methods, which are frequently used in Sweden, sometimes fail. Another reason is that the evaluations will make it possible to recognize when it is necessary to treat the stone again. Above all, the evaluations may help to reject poor or disputable methods and improve conservation.

In previous evaluations conducted by the NHB, the methodology was first and foremost based on visual and tactile methods. Sometimes quantitative methods were also used, such as the Drill Hardness Meter and the Karsten pipes. The observations and measurements were compared with information found in conservation reports. This methodology has weaknesses, for example, information and data relating to the condition of the stone during and shortly after conservation are often lacking. Such information is necessary to an understanding of *if* and *why* the conservation failed.

The purpose of this project is thus to improve the evaluation of stone conservation in Sweden using NDT methods that give comparable quantitative data. To achieve this goal it will be necessary to adjust the conservation process to include a greater emphasis on pre-investigation and documentation. Pre-investigations should include a selection of areas with "zero values" taken with NDT methods. Each NDT method naturally has advantages and drawbacks and these are not always explained in the literature. The NDT methods used in this project have been evaluated in an attempt to find out more about their possible uses.

The project is divided in two stages or steps;

1 *A literature study* based on conference articles and conservation literature and complemented with interviews.
2 *Laboratory and field-studies*. Some chosen NDT methods were tested and evaluated. The methods are available in Sweden and easy to use *in-situ*. The tests were made on Gotland sandstone as it is one of the most frequently conserved stones in Sweden.

The ultimate goal is to create a manual with instructions regarding what kind of information is required before, during and after conservation (and how it should be collected). A preliminary manual has been compiled – see Appendix 1. It is hoped that the methodological manual will lay the foundation for regular routines within the conservation process. It will, for example, make it possible to evaluate whether the conservation has been successful and is durable. The full ambition is, unfortunately, not possible to achieve within this project as more research is needed together with an implementation strategy managed by the NHB.

2.2 Project Background

Between 1989 and 1995, the Swedish NHB managed and directed the ambitious "Air Pollution and the Cultural Heritage" programme. The programme resulted in a nationwide inventory of sculptures and decorative stone in buildings from early medieval times until the 1940s (published in the Series of Swedish Building Stones) and in a database containing an inventory of used stones, their age, location and previous treatment. Moreover the programme led to a greater awareness of stone deterioration, a tremendous number of new research projects, and further development of stone conservation methods in Sweden. As a consequence, the stone conservation field improved and many treatments were carried out. Since the programme's conclusion in 1995, only a few attempts have been made to evaluate the result of all these efforts. This project undertakes part of this work.

2.3 Description of the Project

The project has been divided into two parts, *Step 1* and *Step 2*.

2.3.1 Step 1

Literature study of NDT methods used in stone conservation and discussion with experienced scientists and conservator-restorers in Sweden and abroad. The aim is to learn more about the NDT methods and to establish their key advantages and disadvantages.

The methods studied include:

- Methods for measuring the relief/roughness of the stone's surface, such as profilometric stylus measurements and laser scanner methods.
- Methods for measuring the water-soluble salt content in the stone, for example, the Löfvendahl method.

- Methods for measuring the water absorption, for example, the Karsten pipe, the Mirowski pipe and the Italian contact sponge test.
- Methods for investigating the inner structure of the stone, such as tomographic methods.
- Methods for analyzing substances on the surface of the materials, for example, a portable FT-IR.
- Methods for measuring the strength and mechanical properties of the stone, i.e. a method that gives information about the condition of the stone, for example, ultrasonic measurements and micro drill resistance (which is destructive).
- Methods for measuring the moisture content in the stone, such as the microwave method.
- Methods for measuring colour change, for example, the Spectrophotometer.

Some of the theory behind these methods is discussed, together with their practice and use in stone conservation.

2.3.2 Step 2

The testing of four NDT methods *in-situ* on Gotland sandstone on fourteen buildings in Stockholm. Gotland sandstone is also tested in the laboratory. This step also included a visit to Gotland and some of the open and closed quarries. The individual parts include:

1 *Variation of **U**ltrasound **P**ulse **V**elocity (UPV) due to the change of relative humidity on Gotland sandstone*. A laboratory test programme designed to analyse how the UPV is changed depending on the relative humidity and water saturation in Gotland sandstone. The aim of this study is to analyse the stone material in laboratory conditions and compare this to observations made in the field. [5] The tests were conducted by Dr. Katarina Malaga at *SP, the Swedish National Testing and Research Institute*, located in Borås. The programme was initiated in July 2005 and concluded in June 2006.

2 *Variation of colorimetric measurements with a Minolta Spectrophotometer due to heat, cold and moisture content on Gotland sandstone*. Testing of the variations of colorimetric measurements with a Minolta camera. The camera was tested during different climatic conditions. The tests were conducted in the NHB's stone atelier in February 2006.

3 *Measurement of the w- and B-values of Gotland sandstone from the Valar quarry*. The aim was to learn more about the properties of Gotland sandstone. The test was conducted using the German capillary suction standard test DIN 52 617. The tests were undertaken in March 2006 in the NHB's stone atelier.

4 *Field test programme of four NDT methods used in stone conservation on Gotland sandstone objects in Stockholm*. The methods included:

   a. Measurement of water absorption using the Karsten pipe.
   b. Ultrasonic Pulse Velocity (UPV) measurements (conducted by Dr. Katarina Malaga, SP).
   c. A granular disintegration test with a "tape test" using Herma labels (invented by the NHB).
   d. Measurements of the colour of the stone using a Minolta camera.

   The methods were tested on three occasions over the period of a year and in different climatic condition (in August and October 2005 and in May 2006) in order to register variations in temperature and moisture. Eighteen stone objects on sixteen buildings in Stockholm were chosen (see Chapter 7.3). The criteria for choosing the objects were:

   - Accessibility of the building.
   - The age of the stone (with a range from the 16th to the 20th centuries).
   - Knowledge of the conservation history of the stone (for this purpose several art historians, conservators and architects were consulted).

5 A literature study of the geology, deterioration and conservation of Gotland sandstone. Archives, reports and articles have also been consulted in order to find out more about the history of stone conservation – especially on Gotland sandstone – in Sweden. The aim of this study was to formulate an understanding of what might have happened to the stone.

2.4 People Contacted

In order to find out more about the practice of NDT in stone conservation in other European countries several well-known conservation scientists were contacted by email or telephone. [6] Moreover, a visit was made to Florence, to one of the three governmental research institutes concerned with the conservation and restoration of works of art in Italy (ICVBC-CNR). The contact at the institute was Dr. Susanna Bracci, who kindly handed over the new Sponge test elaborated by Dr. Piero Tiano (see Report I).

3. Gotland Sandstone – Use and Characteristics

3.1 Mineralogy and Chemistry of Gotland Sandstone

Gotland sandstone (Burgsvik sandstone) is a Silurian sedimentary finegrained and homogenous sandstone. The colour is grey; the nuance varies depending on site and stratigraphic level. There are usually very few tints in the stone, although exposed stone often becomes brownish in colour as it ages. [7] The mineralogy and chemistry of the stone varies according to its location in the quarry and from quarry to quarry. According to Wessman, the stone from the Valar quarry sometimes has weak veins parallel to the bedding planes, which contain clay minerals. [8] The matrix of the stone is chiefly calcite and the calcite content is 5–15 wt percent. The relatively high CaO and CO_2 content, as well as the relatively high amounts of Al_3O_3, Fe_2O_3, MgO and K_2O, are typical to the stone. [9] A small amount of silica cement is often present in the stone as well. Some researchers describe the silica cement as amorphous and surrounding the quartz grains, while the calcite cement is located in the pores. [9] Wessman has examined thin sections of Gotland sandstone from the Botvide, Uddvide and Valar quarries and noted that the stone consists entirely of quartz grains with empty spaces in between (the calcite cement was hardly visible). [8] The grains consist primarily of quartz and feldspars and there are small amounts of mica and calcite. The stone furthermore contains small amounts of pyrite – seldom exceeding one per mille – and small amounts of glauconite, limonite and jarosite. [7] The quartz grains vary in size – the Botvide and the Uddvide sandstone grains are between 0.1 to 0.2 mm, while the sandstone grains from Valar are 0.05 to 0.15 mm. The clay minerals look like brown rods of between 0.2 to 0.4 mm in length and are normally oriented in the same direction as the bedding. [8] The stone has a high porosity, 5–23 percent per volume, and the compressive strength of the stone is ca 50–80 MPa. [10] The average pore size in one test was 13 µm. [8] The stone thus has a very high absorbance capacity; between 5 and 9 percent of the total weight. [10] The ultrasonic velocity of fresh Gotland stone is approximately 2.5–2.7 km/s, the true density 2680 kg/m^3, and the bulk density ca 2200 kg/m^3. The w-value of the Valar stone is ca 5.9 kg/m^2/ v h while the B-value of the Valar stone is ca 0.45 mm/ v h (for an explanation of the w- and B-values, see below and also Appendix 9).

3.2 Its Occurrence in Nature

The stone is found in the Silurian Burgsvik bedding layer, close to the coast in the south of Gotland. The formation outcrops along a 35 km horizon on the western banks of Storsudret in Grötlingbo parish. The stone is also found in Burs and När and in a small area of Fröjel (also in the south of Gotland). The sandstone is sandwiched in a limestone environment and the beddings are a maximum of six metres thick (the formation is all together up to 50 metres thick). The beddings are not homogenous – there are some calcareous and sand/clay layers between the sandstone beddings. The structure and orientation of the stone indicates that it has been formed as sandbars in shallow water close to an ancient beach. A survey made by a geological consultancy firm in 1989 concluded that the Valar stone is the best stone for building purposes. The Valar stone is different to other stones in that it is brighter in colour, more fine-grained and has a lower clay content. It is also lithified (and consequently stronger). [11]

3.3 Use as "Cultural Stone": Building and Sculptural Stone

Gotland sandstone has been used for sculpture and buildings in the entire Baltic region since early medieval times. It is one of the most widespread decorative stones in Sweden. The main reason for this is that it is easy to shape. In the Stone and Viking Ages it was used to make whetstones, tombs and tombstones. Some rare examples of the famous picture stones first erected on Gotland 300 – 100 A.D. and some later stones were made from Gotland sandstone. [12] It was not until medieval times that it really became widespread. It was, for example, used for baptismal fonts that were exported in the Baltic region during the 12th and 13th centuries. During the 13th century and until the middle of 14th century it was also used as building material, for sculptural friezes and portals on Gotland, mostly on churches. Some of the most famous churches entirely constructed in the stone are Öja, Sundre, Hamra, Fide and Grötlingbo. Use of the sandstone declined at the beginning of Danish rule in the 14th century. Nevertheless, Glimmingehus in the south of Sweden (which was part of Denmark at the time) was built in lime and sandstone from Gotland by Jens Holgersson Ulfstad in 1499. [12]

Influenced by the Dutch Renaissance, decorative stone became fashionable in the 16th and 17th centuries. This led to a reopening of the quarries. In the beginning the quarries were controlled by the Danish kings Christian III, Fredrik II and Christian IV. Initially the Danish kings took stones from Skåne, but at the end of the 16th century they began to explore the quarries of Gotland. The Danish kings send experienced stone masons to Gotland to restart production. Hence Kronoborg Castle in Copenhagen was built with sandstone from Gotland in the 1570s as well as Fredriksborg's Castle in Helsingör by Christian IV. The stone in the southern part of the Valar quarry was used by the Danish king. This fashion for stone led to the production of many facings, sculptures and portals in Gotland sandstone in palaces in Stockholm as well as in Denmark, Germany and Poland. The quarrying of stone continued when Gotland became Swedish in 1645 and well into the 18th century. [12] Some famous examples from this period include the Royal Palace in Stockholm and the Swedish King's Memorial Chapel at Riddarholm Church in Stockholm. The use of the stone declined during the neoclassic period at the end of the 18th century, to become very popular again in the 1890s until the beginning of the 20th century. The use of Gotland sandstone as building stone finally stopped in the 1920s. Nowadays the stone is quarried principally for restoration purposes. A few quarries are still open: the Valar quarry which is quarried by Slite Stenhuggeri, and the quarries in Husryggen and Botvide where small quantities are quarried by stonemason Jan Kviberg at Burgsviks stenmuseum (Burgsvik's Stone Museum).

3.4 Distribution in the Baltic Basin: Sweden, Denmark, Poland, Germany, Russia and the Baltic States

The distribution of Gotland sandstone in Sweden was surveyed during the air pollution programme. Hence, it is possible to trace the stone in Sweden by searching the database of decorative stone at the NHB's website (http://www.kms.raa.se/cocoon/nat/info.html). The database has registered 626 objects in Gotland sandstone. These are located from Umeå in the north to Ystad in the south. The stones are to be found in: Stockholm (341 objects), Sörmland (49 objects), Uppsala (41 objects), Skåne (35 objects), Gotland (30 objects), Östergötland (26 objects), Kalmar (24 objects), Västmanland (16 objects), Västra Götaland (13 objects), Örebro (10 objects), Gävle (10 objects), Blekinge (7 objects), Sundsvall/Hörnösand (7 objects), Jönköping, (6 objects), Halland (3 objects), Jämtland (2 objects), Umeå (2 objects), Dalarna (1 object), Kronoberg (1 object), and Värmland (1 object). In Denmark, ca 300 portals are made of the stone in addition to many facings and castles. [13] Gotland sandstone is also found in Germany, for example in Stralsund, Lübeck (the Lübecker Rauthaus), Wismar, Rostock and Greifswald as well as in the north of Poland, such as Gdansk. It is also found in St Petersburg and in the Baltic states. [14]

3.5 Weathering Behaviour, Deterioration and Damage of Gotland Sandstone

Gotland sandstone is often the subject of severe deterioration, mainly caused by calcite cement and clay impurities that easily dissolve and swell. The calcite content sometimes reacts with acidic constituents to produce gypsum, which is usually a constituent in black crusts. Anders Nord and Tore Ericsson have investigated black layers on Gotland sandstone (among other stones) in Europe. The samples were taken from different locations in Sweden, Poland, Denmark, Germany, Hungary, the UK and France. The layers they examined were thin: 0.02 to 0.2 mm. [15] Acid rain may also affect the pyrite in the stone and create iron composites that cause the stone to deteriorate. The rough surface of the stone also makes it easy for soot and metal particles to stick to it. [16] This deterioration is followed by granular disintegration, sanding, exfoliation and the formation of black crusts. The structure of the stone also leads to damage, as its high porosity makes it subject to water penetration, which in turn is followed by a series of synergic damaging effects caused by acid pollution, salts and freeze-thaw cycles.

3.6 Paint and Gotland Sandstone

It has been known since medieval times that Gotland sandstone deteriorates easily. Thus, the stone was often impregnated with oil and painted for protection. The paint also had a decorative function. The use of paint for protection was documented during the construction of the Royal Palace in Stockholm. The architect noted that the fresh Gotland sandstone had to be impregnated with linseed oil and painted to prevent it deteriorating. The Royal Inspector, Carl Gustav Tessin, wrote in 1748: "furthermore should the old and the recently erected stone at the Royal Highness's new Palace, that is subjected to rain and bad weather, be painted with oil paint." He also noted that the paint was for the "conservation" of the stone. [17]

The paint of the Royal Palace was not maintained, however, so that by the end of the 19th century the stone was in a critical state of conservation. A scientific committee was set up to investigate the state of conservation of the facade. The committee concluded that the paint on the stone had no protective function. It was believed that the paint was used for aesthetic reasons to hide the natural defaults in the stone. The paint remains were removed in 1897 in order to establish the true condition of the stone. This coincided with the fashion for bare unpainted stone. The removal of the paint epitomized the aesthetics of the time – a desire for "pure stone" without any "false colour." Paint was thus

regarded as somewhat deceitful and hiding the true structure and natural material. This influenced the restoration of buildings. During the entire 20th century paint was removed from many stone facings and sculptures.

The southern portal at Jacob's church in Stockholm is one example of how the fashion for pure stone influenced decision-making. It was restored between 1909 and 1910 and a newspaper article explained the situation like this: "The portals have been treated with piety. No sharp tools have touched them – quite the contrary – the old paint has been heated and afterwards blown or brushed away. According to government inspector Carl Möller, the work could not have been conducted in a better way or with more care. Thus they are (i.e. the portals) now found in a remarkable state of conservation, where each original mark of the chisel has been fully recovered." This quotation demonstrates that paint was seen as something that needed to be removed in order to achieve an authentic appearance.

In the 1980s the first conservator-restorers in Sweden continued to remove paint layers (there are examples where the paint was left in-situ). Sometimes they documented the paint, such examples being Kagg's Memorial Chapel in Floda Church 1989, Nikolai Church in Örebro in 1992 and Fiholm Castle in 1994, but not always. Nevertheless paint was removed without examination. It was stated that the paint was harmful to the stone, since it wouldn't let the stone "breathe" and the conservator-restorers tried to extract the oil and remove the paint (using paint strippers, ammoniac or hydrogen peroxide). Despite these actions a lot of paint still remains. It was not until the end of the 20th century that the paint was finally noted for its decorative and possibly protective function. However, this does not make it easy to repaint the stone. As the stone has been left unprotected for a long time it has deteriorated and been subjected to various treatments, such as ceresin (wax), waterglass and acid cleaning, all of which may have left salts. In addition it has not yet been scientifically established that linseed paint actually has a protective function. There may be better alternatives. All being well this will be tested in a forthcoming project managed by the NHB.

4. Conservation of Gotland Sandstone in Sweden

4.1 Gotland Sandstone and Conservation

Gotland sandstone has always caused conservation problems. Problems occurred over a long period of time and some buildings have thus been repeatedly conserved, such as the Karolin Memorial Chapel at Riddarholm's Church, the House of Lords, Saint Jacob's Church and many portals in the Old Town in Stockholm. Several examples are also to be found outside Stockholm, such as of portals and memorial chapels like Vadsbro and Tyresö in Sörmland and on several manor houses and buildings in the south of Sweden. Many examples are also found abroad, such as the Rathaus in Lübeck which has been examined and conserved throughout. [9]

Until the 1980s the conservation of stone was conducted by stone masons. They used traditional handicraft techniques and worked for architects; sometimes with scientific aid from engineers. The deterioration of stone was sporadically studied by scientists, for example the Royal Palace in Stockholm in 1897 and the House of Lords in the 1890s. New stone conservation methods were sometimes tested. Two examples are the "Deckosit" method in the 1940s and silicic acid esters in the 1970s. When important sculptures needed conservation in the 1940s and 1950s painting conservator-restorers, for example Erik Olsson on Gotland and Bo Wildenstam in Stockholm, were often employed to do the work. They were not especially knowledgeable about stone, but had experience in mural painting.

4.2 Conservation Methods in the First Half of the 20th Century

Stone masons that worked with stone conservation in Sweden in the first half of the 20th century cleaned the stone with abrasives (abrasive sandpaper and knives), heat, acids and alkali solvents. Paint remains were removed with different kinds of chemical paint strippers, with calcium hydroxide or heat. The stone was consolidated with linseed oil or "Ceresin", an industrially manufactured mineral wax that was used to impregnate gypsum and stone (diluted with carbon tetrachloride, CCl_4). According to "Varulexikon" (The Book of Goods 1894), "Ceresin" was a mixture of mineral wax melted with sulphuric acid and stearin. It was thereafter treated with potassium hydroxide and filtrated. Casein, resins, limewater, paraffin, fluats and waterglass solutions might also have been used. There are some documented examples of the use of waterglass, for example, it was used on the portal of Hablingbo Church in Gotland in 1955. The engineer Wibeck wrote that the weathered parts were consolidated with "Silicaseal "and the rest of the stone with "Snöland Everdry". "Silicaseal" was probably a kind of waterglass and "Snöland Everdry" might have been a hydrophobic treatment. Different kinds of "artificial stone" was used to repair the stone, such as "Deckosit" from Denmark. This was a kind of synthetic stone made from ground sandstone mixed with nitrocellulose and used to fill in and cover faults in the stone. The product was probably introduced to Sweden by the architect Ove Leijonhufvud. Another "fake stone" method, the "Håkansson method" (see the description below of the German Church) was used in the 1920s in Stockholm. Naturally, cement was also used and sometimes the stone was replaced by new natural or cast stone.

The Royal Palace architect, Ove Leijonhufvud, (in the first half of the 20th century) became especially interested in stone conservation. He made conservation proposals for several important buildings paying special attention to the stone, such as the Royal Palace, the House of Lords, the German Church and Saint Jacob's Church in Stockholm. In order to learn more about stone conservation he wrote to the Director of Works at Westminster Parliament, Frank Baines, in 1926. Baines supervised a commission set up to investigate the conservation of the damaged stone. Baines' report gives an idea of the state of the art in stone conservation in the 1920s. He wrote, for example, that the commission had not been able to find any conservation method or product that was effective and durable enough. He thought that it was better to use a simple lime-wash than limewater to consolidate the stone. But no durable and efficient conservation methods were available and all the methods that had been tested in England and France had failed (such as waterglass). This was the situation until the 1970s when alcoxysilanes entered the field.

4.3 Examples of the Conservation of Gotland Sandstone in the 20th Century

The southern portal in Gotland sandstone at Saint Jacob's church in Stockholm is an example of how conservation was conducted in Sweden during the 20th century. The paint was removed in 1910 and the portal conserved by the firm of Augusto Conte in 1929 (which specialized in stucco work) according to Leijonhufvud's conservation propos-

al. The portal was cleaned with brushes (whether dry or with water is unknown) and consolidated with an oil-resin mixture. In 1941 the portal was conserved again, this time with "Deckosit". It was conserved again in 1968–1969 under the surveillance of engineer Ingemar Holmström. This conservation included cleaning with caustic soda (NaOH) mixed with lime (to remove all paint). After cleaning the portal was washed several times to neutralize the stone and remove the salts. Finally the stone was consolidated with limewater sprayed four to five times.

Silicic acid esters were used early on in Sweden for stone consolidation. One example of this is the House of Lords in 1971. The architect Ramel employed a Danish restoration company, "Convestol", to conserve the stone. This company specialized in a "new German method" that consolidated the stone. The façade was first cleaned with an "alcali product", "neutralized" with a weak acid and then cleaned with water. The damaged ornaments were consolidated with a silicic acid ester mixed with silicone. The stone was repaired using an artificial stone, "Minero", made of hydraulic lime, sand and trass. All the stone and brick was finally impregnated with 5 percent "SIOTOL 50" (probably a hydrophobic treatment). [18]

4.4 Tord Andersson and Modern Stone Conservation

Until the 1970s, stone conservation was not a specialist field of interest in Sweden. The mending and replacing of stone was, as we have seen, undertaken by stone masons. Modern Swedish stone conservation was established by Tord Andersson at the end of the 1970s. Andersson worked at the NHB from 1972 until 1989. In the mid-1970s he was working as an archaeologist when a new conservation laboratory was established at the technical institution. Andersson became the stone expert and above all a promoter of stone conservation in Sweden. For example, he contributed to the development of the profession by encouraging the education and training of stone conservators. Andersson had learned stone conservation at the ICCROM course in Venice in 1976 and continued to travel in Europe to learn more about stone conservation. During his time at the NHB the stone department expanded and by the end of the 1980s approximately five stone conservators were employed.

Technically Andersson also introduced new cleaning methods, such as paper pulp and/or clay compresses made from Italian recipes (Mora & Mora such as mixtures of ammonium hydrogen carbonate, EDTA and other solvents such as ammoniac). The consolidation of Gotland sandstone was an important issue to address: acrylate dispersions were tested and finally he introduced the silicic acid esters. The German tetraethylorthosilicate (TEOS) – Wacker Stone Strengthener OH – became a standard product (it is still the main product in Sweden). It was probably during the restoration of House of Lords in 1980 that Andersson used the Wacker OH for the first time on Gotland sandstone. In the beginning Andersson recommended the removal of paint remains by using a paste made of Bentonite clay, Carbamid and Glycerol (made from a recipe used by the conservator-restorer Kenneth Hempel at the Victoria and Albert Museum). [19] Later in his career he became an ambassador for repainting the stone with linseed oil. At the beginning of the 1980s caustic soda was used for disinfection, and later on, biocides such as Cetavlon (Cetrimoni Bromidium), Raffex, Arrow Super Clean and Beloran (it was for instance used at Stånga church, Gotland 1988–1989). These products proved to be useless in the long-term and were abandoned at the beginning of the 1990s. Sometimes hydrophobic treatment was conducted (using Wacker Stone Strengthener H or wax). The hydrophobic treatment was disputed among conservators, however (see below). For mending the stone, Billy's stone glue ("Billy's stenlim" – a polyester based glue used to mend the stone had existed on the market since the 1950s) and Billy's replacement mortar (acrylic based solution mixed with grinded stone, and some cement and lime) was used. Other synthetic glues were also used, such as epoxy resins for major cracks and Paraloid B-72 for repairing minor damages, e.g. small flakes.

4.5 The 1980s: RIK and New Private Conservation Firms

During the 1980s stone conservators at the NHB worked almost alone in Sweden. There were no private stone conservation companies and almost all stone conservation work in Sweden was conducted by the NHB. This changed at the end of the 1980s, however, when many former NHB employees set up private firms. This was a natural development in the field's growth. *Stenkonservatorn* opened in 1987 led by conservator-restorer Marie Klingspor and in the following year the Polish conservator-restorer Leszek Zakrzewski joined the company, together with Dr. Daniel Kwiatkowski (both had been educated at the Kopernicus University in Torun, Poland). *Prolithos* opened in 1988 led by conservator-restorers Jarema Bielawski and Gert Öhrström (both taught by Andersson). The conservator-restorer Karl Gustaf Eliasson (also taught by Andersson) became established on Gotland at the beginning of the 1990s.

The end of the 1980s was therefore a dynamic period for stone conservation in Sweden. In part this was due to Polish influence, but in the main was influenced by the *Air Pollution and the Cultural Heritage* programme, launched by the newly established Conservation Department (RIK, led by the engineer Dr. Ulf Lindborg) at the NHB between 1989 and 1995. This campaign enlightened the field enormously. Stone conservation work at the NHB grew considerably and five to ten people were employed (both conservators and scientists), many educated at the new conservation school at Gothenburg University. RIK planned, supervised, managed, controlled and furthermore conducted the con-

servation of stone monuments in Sweden (approximately 245 works). The Polish influence was on the other hand academic; Kwiatkowski had conducted research on Gotland sandstone and methods like Billy's replacement mortar were tested scientifically in the laboratory by Marie Klingspor in Poland. They were the first academically educated stone conservator-restorers in Sweden, and were closely followed by the first educated stone conservator-restorers from the University of Gothenburg.

A lot of research was initiated by RIK, such as the study of alcoxysilanes and stone weathering by Oliver Lindqvist and Pernilla Elving at Chalmers University of Technology, work on the frost resistance of natural stone by Lubica Wessman at Lund's Technical University as well as work undertaken by Göran Fagerlund at the same university, surveys on building stone types and quarries, studies on the weathering of stone by Paul Frogner, P. Schweda and L. Sjöberg at Stockholm University, and so forth. A lot of these research efforts were performed on Gotland sandstone. The NHB also conducted research, such as the investigation of black crusts on Gotland sandstone by Anders Nord and Kate Tronner. Runo Löfvendahl invented methods for documentation and salt evaluation. Furthermore, a comprehensive inventory of decorative building stones in Sweden was initiated and resulted in several publications and reports (Natursten i byggnader), together with a database of all Swedish decorative building stone (see above). NDT methods were also tested, such as UPV measurements on the Gustav Adolf monument in Gothenburg and studies on NDT methods were carried out at the Royal Institute of Technology in Stockholm. These efforts led to an increased contact with European researchers in the field. One particular area of interest concerned hydrophobic treatment. In this Swedish stone conservation forged its own way. We have seen that conservators sometimes used hydrophobic treatment, although it was suspected that the methods actually might harm the stone. This led to discussions and finally, in 1993, it was decided that such treatments should stop. After this hydrophobic treatments are rare. At the end of the 1990s and beginning of 21st century, historians "discovered" that Gotland stone had been painted. The question was raised as to whether it provided better protection for the stone. Tord Andersson agreed and a campaign to repaint the stone with linseed oil was initiated. In some places the stone was painted, although without scientific examination or proof. Today the question is still an open one, and much debated.

4.6 The Situation Today

When the Air Pollution programme suddenly ended in 1995, Swedish stone conservation became almost entirely privatized and many of the research and development efforts came to an end. Almost all of conservator-restorers and researchers at the NHB either had to leave or change occupation. Today approximately only three individuals work at the NHB with stone questions (two conservator-restorers and one geologist). This naturally limits possibilities. Not even universities are conducting any research in this area – one exception being Malin Myrin whose PhD work from 2006 at Chalmers University of Technology concerned the evaluation of stone conservation on Gotland sandstone. There are approximately five to ten private stone conservation firms operating in the field. They use more or less the same methods and products that were introduced during the 1990s. A few new materials have been introduced, though, such as the "Arte mundit" in 2005 (a kind of latex EDTA film that strips off the dirt) [20] and some research is being conducted by the NHB, albeit on a small scale. This includes research on injection mortars by Misa Asp and the testing of mending mortars in Källa church at Öland. Despite these efforts it is apparent that research in many other European countries, as well as that in the USA and Canada, is much more extensive. It is lamentable that results of this work and research are not followed up (if so, only sporadically) by Swedish conservator-restorers due to lack of time, contacts and financial resources.

5. Previous Research

5.1 Recent and On-going Research

On the international scene there is now rapid advancement in the field of NDT conservation methods, which makes it difficult to attain a complete picture of the situation. Some projects of interest are presented in the first report, *Report 1. Non-Destructive Field-Tests in Stone Conservation – Literature Study*. One current trend in scientific conservation is to create strong and formal networks that use and develop NDT methods; sometimes supported by the European Commission. Some of these include LABSTECH, *EU-ARTECH (Access Research and Technology for the Conservation of the European Cultural Heritage)* and the *LACONA network* (*International Conference Lasers in the Conservation of Artworks)*.

Some interesting stone conservation projects using NDT methods are also being undertaken in Sweden, such as the Lidar Laser Project at Lund University, and research work at the NMK School at Chalmer's University by PhD candidate Pär Meiling.

5.2 Evaluation of Stone Conservation in an International Context

In his 1996 report on the state of art in stone conservation, the scientific conservator Clifford A. Price divided evaluations of stone conservation into two categories: 1) those that characterize the stone shortly after treatment has taken place, and 2) those that are concerned primarily with monitoring long-term performance. [21] Test methods used to determine the properties of the stone include surface hardness, strength, ultrasonic pulse velocity and acoustic emission. In most of the examples described in various published articles, evaluations have been carried out in the laboratory on fresh stone.

The evaluations sometime use destructive methods. One interesting example is the study of the durability of hydrophobic treatment of the sandstone facades of Alte Pinakothek and Schillingfürst Castle in Bavaria on different occasions from 1984 until 2001. The methodology was found to be a success, even though the methodology was essentially destructive despite the use of Karsten pipes. The results demonstrated that the laboratory and field evaluations could be correlated and that Karsten measurements could indicate the durability of a treatment. [22–24]

Another interesting example is the evaluation of stone sculptures and monuments that have been treated over the last twenty years in Austria (evaluated between 2000 and 2002 by Nimmrichter and co-workers). It comprise both oral information and the testing of objects; both using NDT methods (Karsten, UPV, drill resistance, electrical conductivity, knocking by hand, colour description and so forth) and sampling. The results were quantified: in 55 percent of the conservations the long-term effect of the conservation was good, while in 10 percent of the cases the conservation treatments had actually caused new deterioration. Moreover, Nimmrichter and co-workers pointed out that conservation reports weren't sufficiently systematic and lacked necessary data. This is a comment that is often found in evaluations! The final conclusion was that more scientific pre-work and scientific follow-up controls, such as UPV, are both important and necessary in conservation work. [25]

Recently a lot of *in-situ* evaluations of previous conservations have appeared in publications. This is a natural development, since the field of stone conservation has grown considerably during the second half on the 20th century and it is now time to evaluate what has been done. As we have seen in the Austrian case, evaluations also expose difficulties since all the parameters that cause damage are not known. The reason for this is that conservation documentation doesn't always give sufficient data and also that conservator-restorers seldom leave reference surfaces untreated. Nevertheless, there are some recent examples of successful evaluations, such as the evaluation of the "Bologna Cocktail" [26] and the conservation of the Four Virtues in Porta dell Carta in the Ducal Palace in Venice. [27] Another particularly interesting example is the evaluation of consolidation with Brethane™ in Great Britain. [28]

Conservation scientist Marisa Laurenzi Tabasso has frequently been involved with evaluations of stone conservation. She has both listed and examined some of the stone conservation evaluations conducted in Europe between 1985 and 2004. She noticed that it is often difficult to estimate the durability of the treatments. An assessment would be easier if the conservator-restorers had left a reference area after the conservation; *a zero point*. This area could then be monitored regularly to detect changes. She suggests a methodology for this purpose that measures: "surface colour by reflectance spectrophotometry, water absorption under low pressure (Karsten pipe), amount of deposited dust

per unit surface, amount of water-soluble salts (extracted using Japanese paper poultices wetted with deionzed water), surface roughness (using a portable rugosimeter), and biological contamination." Tabasso moreover noted that despite the immense development in the field of conservation the crucial conservation question is still: "Are the material parameters currently in use suitable for judging conservation treatments, and is it possible to determine treatment durability?" Tabasso posed this question at the Dalhem Workshop in 1996 and found that it was still valid in 2004. Participants at the Dalhem Conference concluded that there still was a lack of professionalism when conservation measures and treatments were planned and implemented and that there was no defined quality control. [29] Hopefully this will change. Tabasso's methodology and questions are good staring points for such a project.

5.3 Previous Evaluations Conducted by the NHB in Sweden

Previous evaluations conducted by the NHB focused on stone conservation treatments shortly after treatment; most of them being performed on Gotland sandstone. However, a few studies with the aim of monitoring the long-term effect of weathering and pollution on Swedish stone have also been conducted by the *Swedish Corrosion Institute*, as well as within the framework of the *EU-marble project*. [30]

The first evaluation was executed in 1995 to 1996 by conservator-restorer Misa Asp, geologist Runo Löfvendahl and engineer Erik Österlund. This evaluation was based on a survey directed at Swedish stone conservator-restorers and *in-situ* examinations of eleven stone objects conserved between 1988 and 1995 under the stewardship of the NHB. The examination was both destructive and non-destructive – including salt measurements both directly on the surface of the objects and from core samples (ø18 mm) according to the Löfvendahl and Asp method, measurement of the moisture content (conductivity) on the stone surface with a Protimeter, measurement of the moisture content in the core samples (by weight before and after drying) and finally using a Durabo Drill Hardness Meter (DHM) to try to measure the hardness of the stone. Visual and hands-on inspections were also carried out. The visual observations were noted on an evaluation leaflet and mapped on drawings. In some places Karsten pipes were used to evaluate the water absorption, although this was not conducted systematically. The report mentions problems in analyzing the DHM and the results were therefore not presented. [31] The results of the tests confirmed that there were often problems with rising damp, colour change of the restoration mortars, and that consolidations with Wacker OH were sometimes efficient and in a few cases not. Moreover, the authors state that hydrophobic treatment and the painting of stone for protection needs to be further explored, and that mending mortars also need to be investigated (both these areas have and still are being explored by the NHB). In 1993 a more systematic testing of the Karsten pipes was conducted by Erik Österlund and Misa Asp. This study resulted in a report entitled "*Karstens mätrör som oförstörande provmetod på sten*" (see below). [32]

In 2003, conservator-restorer Dr. Agneta Freccero undertook a survey of the evaluation that had been conducted by the NHB. She found that 245 conservation works had been carried out and that 60 of these had been evaluated. The evaluations were all different, both in methodology and form. Freccero noted that this inconsistency made it difficult to gain any clear view of the situation. She stated that both the conservation documentation and the sampling methodology varied too much, as did the evaluations themselves. Freccero therefore concluded that in the future it would be necessary to establish a system of evaluation that included a defined, common terminology.

5.4 NDT Methods used in Stone Conservation in Sweden

NDT evaluation methods are not so often used in stone conservation in Sweden. Conservators-restorers normally use salt compresses to determine whether salts are present or not. Colorimetric measurements and Karsten pipe methods have been used by the NHB within different projects. The results of these measurements have not yet been fully evaluated. One exception is the Österlund report (from 1993) that evaluates several Karsten pipe measurements (he also tried Mirowski pipes) conducted by the NHB in the laboratory and in the field. Österlund also calculated the w- and B-values and found that the calculation model was too sensitive. Small changes in the measured data distorted the values too much, and he therefore developed his own simplified mathematical model. [32]

In her licentiate thesis (2004), Myrin has used evaluation methods to investigate the conservation of Gotland sandstone and describes the current situation of stone conservation in Sweden. The main part of her thesis consists of a survey of ten conserved Gotland sandstone objects in the centre of Stockholm and in the countryside with the aim of evaluating previous conservation treatments. Myrin also placed Gotland sandstone samples (consolidated with Wacker OH) outdoors with the aim of studying the durability of the consolidation. In addition, she has tried to evaluate the efficiency of a mending material commonly used in Sweden, namely, Billy's mortar. [10] She used visual assessment – making comparisons with old photographs and information found in conservation reports – and Karsten pipes to measure the water absorption. She concluded that the old reports weren't good enough and that no NDT methods were available to assess the condition. This remark demonstrates that her choice of methods was based on cost, since

many NDT methods were available, albeit quite expensive. [10] In her recent PhD work from 2006, she used ultrasonic and colorimetric measurements.

Some sophisticated NDT methods have nevertheless been tested in Sweden. One early example was the investigation of the base of the Gustav II Adolf sculpture in Carrara marble in Gothenburg between 1992 and 1999. Germans Wolfram Köhler and Stefan Simon measured the ultrasonic pulse velocity (UPV) of the stone within the framework of the *Eucare-Euromarble* project. Köhler also measured some Carrara marble sculptures in Stockholm in 1992 within the same project [33] and Bylund and co-workers also measured the outdoor Carrara marble sculptures at the National Museum of Fine Arts in Stockholm in 1995–1996. [34] Stefan Simon presented his results on Swedish sculptures using ultrasonic tomography to study the interior of marble in his PhD thesis on the weathering of marble. [35] Moreover, Anders Bodare at the Royal Institute of Technology in Stockholm also tested the stone with Hammer wave propagation (see below) in combination with an impact-echo technique. [36] Furthermore, Simon has used ultra pulse velocity, UPV, on the marble sculpture Flora in Gothenburg's Botanical Garden. [35]

During the Air Pollution Programme, the NHB financed several research projects using NDT methods. Anders Rehn at the Department of Electromagnetic Theory at the Royal Institute of Technology tested acoustic and electrical parameters in 1995 and 1996 on behalf of the NHB on different Swedish natural building stones. The electric method consisted of high resolution radar; transmission line radar that can detect contrasts in the electric parameters in the stone. Knowing the parameters of the fresh stone, the measurement can demonstrate if the stone has weathered. The test was performed on both homogenous and inhomogeneous stones: Gotland sandstone, Ekeberg marble, Red Öved Sandstone, Gotland limestone from Norrvange, Lingulid sandstone from Lemuda, chalk and Köpinge sandstone. The measurements were conducted on dry stone, on stones saturated with water, on weathered Gotland sandstone from the Royal Castle in Stockholm, as well as weathered Öved sandstone. Moreover, Gotland sandstone was impregnated with alcoxysilane and these stones were measured dry as well as water saturated. The technique can detect flaws in the stone, although the report demonstrates that this works well when the stone is dry (the signal can penetrate 0.2 – 2 metres). It doesn't work particularly well on wet stone, however, since the penetration isn't deep enough, but it is possible to detect cracks inside the stone. [37]

Rehn also measured the acoustic parameters of the same stones using ultrasonic waves. He tried two methods: one where the samples were placed in a water tank and where the sound was reflected and received by a transducer and recorded afterwards, and one that transmitted the ultrasound through the stones and where the sound was also recorded afterwards. The result shows that the velocity of the sound may differ in different directions of the stone (which is common in stones that aren't homogenous). When the sound was transmitted through dry and fresh Gotland sandstone the velocity ranged between 2.2 km/s and 2.5 km/s. When the stones were saturated with water, the velocity was higher: 2.6 km/s. The sound that was transmitted through impregnated Gotland sandstone with alcoxysilane gave an even higher velocity: 3.2 km/s. When the impregnated stone was saturated with water the velocity was 3.4 km/s. On the other hand, measurements of the reflections in the water tank demonstrated that it was not possible to measure stones that have cracks. This method is thus not as useful and moreover requires sampling which seems unnecessarily complicated. Nowadays portable ultrasonic apparatus is available for measuring the transmission. [38] Rhen's tests only give us the measured velocities on fresh stone. The tests have to be complemented by testing on weathered stone in order to understand the quality of the stone. Furthermore, the measurements have to be compared to other test methods, such as the compressive strength and the tensile strength, to find out where the actual critical breaking points or intervals are. This has been done with other stones, such as Carrara marble (see below).

6. Conservation and NDT Methods

6.1 Conservation and NDT Methods

Scientific analytical methods are used in conservation to evaluate both the materials (in themselves – such as the stone type) and the effects of the conservation and weathering processes. K. Janssens and R. van Grieken have divided conservation analytical methods into three groups. All the areas have been studied and are:

- The chemical nature/composition of selected parts of cultural heritage artefacts and materials
- The state of alteration (of the surface and/or internally) of objects as the result of short-, medium- and long-term exposure to particular environmental conditions
- The effect/effectiveness of conservation/restoration strategies during and after application. [39]

There are many different methods to choose from depending on the aim of the analysis. It is obvious that one single analytical method can't possibly provide all the wanted information, which means that the conservator-restorer has to design a test series to give complementary information. That isn't always enough, however, as further requirements restrict the choice, for example, that tests should be *non destructive*, *fast, universal, economic, reproducible, easy to use, objective, available, sensitive and harmless to the environment*. As mentioned above, not all the tests correspond to these requirements; some are micro destructive (such as micro drilling resistance), very expensive or require experienced personnel. The criteria therefore must be seen as an optimal aspiration. The conservator-restorer will have to keep these requirements in mind when designing the analytical programme.

The search for NDT methods has been ongoing since the beginning of conservation. The reason for this is obvious – the conservator-restorer always strives to prevent damage to the objects. The more sophisticated NDT methods have usually been developed for engineering or medical purposes and are thereafter adopted and modified for conservation purposes. Thanks to this, it is today sometimes possible to understand, characterize and evaluate conservation work without taking samples. NDT methods are increasingly gaining in relevance and many articles published within the field. A survey made within the LABSTECH organization (published in 2004) demonstrated that NDT and micro destructive tests are not yet common among conservator-restorers (100 conservator-restorers were asked about their work and 32 responded. Only a few of them used NDT methods). [40] The reason for this is evident; lack of equipment, experience and routines.

NDT methods are based on different physical phenomena. They are usually divided into different groups depending on their scientific background:

- Geophysical methods; measure mechanical and electrical properties of the material
- Spectral analytical methods; analyze surface properties by the use of electromagnetic radiation that is absorbed or emitted by the material
- Tactile and visual assessment.

Katinka Klingberg Annertz divides NDT methods into three groups, depending on what the method is able to do with the material:

- Geophysical methods that investigate the bulk of the material (seismic methods such as the ultra sonic methods, hammer methods, acoustic emission methods and radar methods)
- Spectroscopical and chemical methods that investigate the surface of the material (absorption spectroscopy, diffusion spectroscopy, emission spectroscopy and radio chemical methods)
- Imaging techniques that investigate the bulk and/or surface of the material (laser scanning, analytical photography/reflectography, thermography, radiography, Computer Tomography and photogrammetry).[41]

Some of these methods are discussed in this report. However, as some of these methods are expensive and difficult to use *in-situ* they are therefore discussed in brief.

Anders Bodare (1996) has divided NDT methods within the realm of geophysics into two types depending on the kind of wave used:

- *seismic methods,* such as ultrasonic methods, Schmid hammer method and acoustic emission methods
- *electrical methods,* such as radar, resistive and electromagnetic methods. [36]

6.2 NDT and Stone Conservation

In stone conservation, the use of NDT is restricted by the fact that the stone objects are often found in buildings. Movable objects are, on the other hand, possible to take into the laboratory (where several NDT techniques have been devel-

oped). In architectural stone conservation, the NDT methods must be portable and possible to use in the field in varied conditions (such as on scaffolding in bad weather).

The advancement of this trend depends on improvements made in detector technology, instrument-computer interfacing, focusing optics, and the radiation sources suitable for use in various parts of the electromagnetic spectrum. For the methods that need to be used *in-situ* there is also an immense improvement in the miniaturization of components, making the design more compact, portable and sometimes including handheld instruments.

6.3 Problems to Be Analyzed in Stone Conservation

Some problems are characteristic to the conservation of building stones, due to the fact that they are situated outdoors and are often part of a large structure. The investigation and conservation of building stone is determined by these circumstances. Some of the questions that need to be understood include:

- The water absorption, the water content and the source of the water
- Whether salts are present, what kind, their distribution, source and quantity
- Climatic conditions that effect the weathering, such as air pollution, wind and variations in humidity and temperature
- The condition of the stone, for example, the degree of weathering and the rate of deterioration
- The stone type and its characteristics.

Several NDT methods are available for these purposes, although they do not cover the whole spectrum and, in some cases, sampling is required. Moreover, important facts need to be known during and after the conservation to ascertain whether the conservation has succeeded or if re-conservation is necessary and can be monitored and controlled with NDT methods:

- Changes in colour (with colorimetric measurements).
- Changes in strength and hardness (ultrasonic, micro drilling resistance and so forth)
- Water content and source (moisture measurements)
- Loss of material (surface relief or roughness measurements)
- Changes in the stone's water absorption capacity (pipe methods)
- Changes in salt content after treatment (measurements of salts extracted with paper pulp)
- Durability of conservation treatments (a mixture of the methods mentioned above).

7. Description of the Field Tests

7.1 Description of the Field Tests

Four NDT methods were tested in the field on three occasions on nineteen objects (on fourteen buildings) in August and October 2005 and May 2006. The methods used were *Karsten pipes*, *Minolta Spectrophotometry*, a *Granular Disintegration Test with Herma Labels* and *UPV measurements with a portable AU 2000 Ultrasonic tester from CEBTP.* Moisture measurements were also taken using a *Tramex moisture meter* and a *Protimeter* (the latter was only used on one occasion) together with the air temperature and surface temperature of the stone. The surface temperatures were close to the air temperatures, apart from when the stone had been in direct sunlight. In this case the surface temperatures were higher.

7.2 Weather Conditions

The weather conditions were very similar when the first two measurements were taken; sunny Swedish summer weather with long periods of warmth and dryness. The temperatures were between 12 °C and 25 °C, and the moisture content measured with the Tramex instrument was often reasonably high; around 3–4 (maximum 5). In some places, such as Svartmangatan 6 in Stockholm's Old Town, the measurements were outside the measuring scale, whereas other places, such as the Gustavian Memorial Chapel at Riddarholm's Church had a low moisture content. On the two measuring days (i.e. on each measuring occasion) the weather was very similar, whereas on the second day in October 2005 there was rainfall in the morning and then sun for the rest of the day. As cold weather hindered the measurement in March the third measurement was not conducted until May 2006. On this occasion the temperature changed during the two days of measurement. The air temperature was between 10 °C and 15 °C. For a week before the measurement the weather had been dry and sunny and the stones therefore contained less moisture; the values of the Tramex instrument often being between 1.5 and 2.5 (see Appendix 2).

7.3 Methodology and Instruments

7.3.1 Granular Disintegration Test with Herma Labels (or Tape)

The "tape methods" are not very common in conservation and no articles describing the methods were found in the literature study. However, an ASTM standard for testing the adherence of paint using a tape (Scotch tape test) does exist. Marisa Laurenzi Tabasso believes that this is useful for the evaluation of surface deposits (and sanding), but not for quantitative evaluations. The NHB has nevertheless invented a "tape" method that uses ready-made labels. The methodology was initially based on the difference between the weights of the deposits:

1 In the laboratory, seven prefabricated self-adhesive labels 32x44 mm in size and manufactured by HERMA are weighed and the average ($A_{initial}$) weight is calculated (from seven labels).
2 In the field, three HERMA labels are attached to the stone's surface. After a few seconds the labels are taken off, folded and put into a sealed plastic bag.
3 In the laboratory, each label is weighed and the average of each sample (A_1, A_2 ...) is calculated (A_{field})

$$A_{field} = \frac{A_1 + A_2 + A_3}{3}$$

These are then compared with the previous average to calculate the difference

$$(D) : D = A_{field} - A_{initial.}$$

This methodology proved complicated. The total weights of the labels were compared to each other (both the label and the deposit) and the results divided into three categories according to the weight (see below): 1) Poor condition

Figure 1. Labels attached for the granular disintegration test.

and severely weathered/dirty, 2) Medium weathered/dirty and 3) Good condition/clean. It is important to remember that this is a preliminary weathering index that needs further testing.

7.3.2 Water Absorption Test with Karsten Pipes

Several pipe methods are available for measuring the water absorption: *the German Karsten pipe, the RILEM pipe, the Italian pipetto and the Polish Mirowski pipe*. All are NDT methods that can be used *in-situ* to evaluate the water absorption of a porous material. The water absorption of the material corresponds to the pore structure of the material and thus gives information about the condition of the material. The pipe methods are used to evaluate the result of conservation; often a hydrophobic treatment.

The Karsten pipe was developed in 1958–1960 in Germany. The method is non destructive, easy to use *in-situ* and is therefore often used by conservator-restorers. The pipe consists of an open cylindrical body which is attached to a surface of the material being measured (horizontally or vertically – there are two kinds of pipes for these purposes). A graded pipe emerges from the body and this is filled with distilled water. The water absorption is determined with the aid of a time-bound schedule and registered according to the gradations on the pipe and the time that has elapsed. The pipe always points upwards and the body is attached to the surface using a recommended sticky gum, such as PLASTIC FERMIT or TEROSTAT 9. A Bostic sticker has been used in Sweden for a many years, although this is hard to find nowadays and other sticky gums have been substituted. There are two pipe sizes: one that holds 4 ml and one that holds 10 ml of water. The inner diameter of the larger pipe's body is 4.5 cm and the thickness/height of the body is 3 cm, the total height of the pipe is 18 cm and the pipe's inner diameter is 0.9 cm. The smaller pipe's body has an inner diameter of 2.5 cm, the thickness/height of the body is 2.4 cm, while the total height of the pipe is 15 cm and the inner diameter of the pipe is 0.9 cm. The different sizes have been made for measurements on different kind of stones. The larger pipe should be used for strongly absorbing stones and the smaller pipe for less absorbing stones; the reason being that the absorption of the small pipe may be too fast.

The pipe is attached to the stone in such a way that it will stick for at least an hour. It is important that the sticky gum doesn't spread into the body volume in such a way that it diminishes the contact area of the water. The pipe is then filled with distilled water until it reaches 4 or 10 ml. The measurements are made according to prefixed time-schedule: after 1 minute it is noted how much water has been absorbed and the same procedure is repeated every minute until 5 minutes have passed and hereafter is every 5th minute noted until 30 minutes have passed and thereafter every 10th minute until 60 min have passed.

Figure 2. Measurement with Karsten pipe at Riddarhuset.

The result can be plotted on a graph (where the absorbed water volume kg/m^2 or ml/cm^2 is plotted as a function of time, min) or by calculating the capillary water absorption coefficient – the w-value (kg / m^2 x h ^{0,5}), that is comparable to the DIN-standard of the water coefficient that is measured on drill cores and the water penetration coefficient – the B-value (m / h ^{0,5}) – DIN 52 617. The mathematical model for this was developed by Wendler and Snethlage in 1989 and is commonly used in Germany. [42] Both values depend on the porosity and capillary force of the material. Wendler and co-workers have developed a computer program; the BASIC-program called *Calkarow* (**Cal**culative Evaluation of **Kar**sten Measurement for **O**ptimation of **w**-Values) that calculates the w- and B-values when using the Karsten pipes. [43]

It has been suggested that the pipe methods have problems because they are not completely repeatable and that the result may differ depending on the dexterity of the person conducting the measurement. [44] It is true that the pipes often leak and fall down during the measurements. However, Wendler and Snethlage have proved that it is reproducible and is consequently reliable and frequently used in stone conservation. [42] The methodology gives good results, is cheap and relatively easy to handle.

Within the field study both the small pipe (4 ml) and the big pipe (10 ml) were used to test their differences. Both the Bostic gum and the German Fermit were used as sticky attaching gums.

7.3.3 Methods for analyzing the condition of the stone – Ultrasonic Pulse Velocity (UPV)

Today, *ultrasonic pulse velocity* (UPV) methods are well established in stone conservation. The reason for the popularity of the method is that it is rapid and easy to use in the field. It is used for detecting cracks and flaws and to control concrete.

The testing of stone with ultrasonic wave measurements started early in the history of stone conservation. The testing was developed in the 1950s by the conservation scientist Mamillan in Paris. Today it is one of the most used NDT methods in stone conservation. Many articles using UPV are consequently presented in conference publications. Acoustic methods provide data that can evaluate the condition of a stone (the state of conservation), give important information relating to the result of consolidation treatments and can also help to detect flaws in the material such as cracks and voids. They moreover help to characterize the mechanical properties and the degradation of the material. The method analyses the structure of the material and hence only indirectly the strength of the material.

The classic sound method involves the transmission of a pulse of sound of a single frequency into a structure. The time required for the pulse to be reflected back from a feature, such as a void, is measured; the higher the frequency of the sound, the smaller the distance that can be measured. [45] The waves are in fact a kind of transmitted energy, and this energy moves in different typical patterns. The speed of the energy is the *speed of wave* or *wave velocity* (mm/s or km/s). The individual particles that move around their points of equilibrium and retain their position after the wave has passed are measured. The mechanical waves move in different ways in relation to the direction of the propagation – *longitudinal* or *transversal*. The longitudinal wave travels with a higher speed and is known as the *P-wave*. The transverse wave is slower and called the *S-wave*. There are also so-called surface waves that travel along surfaces of discontinuities between the material, such as the *Rayleigh wave* (*R-wave*) where the waves move the particles in ellipsoidal orbit (the speed is 93 percent of the S-wave) and the *Love-wave* (*L-wave*). The speed of the waves correlates to the strength of the material. The waves travel at the same speed in all directions if a material is homogenous and isotropic, but the speed may vary in different directions if the material is inhomogeneous or anisotropic, such as sandstone. Another effect is of importance – the *attenuation*. In the short-term, the consequences of the attenuation are that the amplitude of the wave diminishes as the wave propagates. The attenuation is determined by Baer's law. [36] There may therefore be differences in speed if one measures long or short distances. Differences in the frequency used must also be considered.

Ultrasonic methods use ultrasonic waves consisting of several methods (such as *ultra pulse velocity (UPV), ultra pulse echo, seismic echo* and *acousto ultrasonic,* also see *tomography*). The vibration uses waves of a higher frequency than can be heard by the human ear – usually around 20,000 Hz. Some researchers recommend different speeds for different measuring lengths. [46] The UPV in air is 330 m/s, in water 1480 m/s and in stone up to 6000 m/s (sandstone ca 2860 m/s, limestone ca 4310 m/s, marble ca 6690 m/s and concrete ca 4430 m/s).[46] It is the P-wave that is usually measured. If it is possible the velocity measured is transmitted through the material (*direct*), or if this is not possible on the surface (*indirectly*). The frequency can differ from equipment to equipment; from 45 to 10,000 kHz. The difference in measurement methods naturally affects the result. The velocity depends on the properties and structure of the material. The denser the material, the faster the sound travels. Thus, the velocity is faster in denser material and slower in air. It is possible to locate damage by measuring the differences. When there is a crack in the material the signal is reflected; the stronger the differences of the material, the stronger the reflection. [47] Furthermore, it is possible to assess the degree of deterioration of the stone if the "normal" value of the stone is known. [47–49]

Several famous marbles in Europe, such as the Carrara marble, have been tested with UPV techniques within the *Eucare-Euromarble* programme in order to understand the degree of weathering. For example, Köhler established a classification of the state of deterioration of Carrara marble using UPV based on an empirically derived correlated function between the V_p (the velocity of the P-waves) and the porosity. Weiss and co-workers also performed similar tests on the Italian Lasa marble and on a Polish marble. [33] In Sweden the UPV has been used only infrequently, e.g. tests performed in the 1990s by Köhler who examined the marble base of the sculpture of Gustaf II Adolf, by Simon on the Flora sculpture in Gothenburg's Botanical Garden and by Bylund and co-workers on sculptures at the National Museum of Fine Arts in Stockholm. Moreover, laboratory tests with UPV were made on some Swedish stones by Anders Rehn at the Royal Institute of Technology. In addition, Katarina Malaga and Malin Myrin tested UPV on conserved Gotland sandstone in 2004–2005 as part of Malin Myrin's PhD work on Gotland sandstone and conservation. [50]

According to D'Avis, drawbacks with the UPV method include:

1 Black crusts may influence the result (and give inaccurately high values).
2 Irregular surfaces may hinder the measurement (depending on the transductor's shape and size).
3 Badly weathered stone surfaces may be affected by pressure caused by the measurement.
4 Moisture content in the stone may influence the result.
5 Salts in the stone may influence the result. [46]

The second and third drawbacks have not caused any problem within this project. The influence of salt has not yet been thoroughly examined, however, and the extent to which the salts actually influence the result is uncertain; for example how high a salt concentration must be to cause problems and how water and salt in combination affect the result. Other drawbacks are that the equipment is expensive, requires experienced personnel and that the velocity usually differs in laminated sandstone depending on the direction measured. Moreover, it can be difficult to couple the equip-

ment on rough surfaces and on complex shapes. One recent article also claims that problems arise when correlating the UPV data with the Unaxial Compressive Strength. [51]The method has nevertheless proved to be very useful in that it is easy to use, gives quick answers and is relatively accurate. For example, in one article the accuracy is stated to be as high as 0.5 percent. [48] Marini and others have tried the method in the laboratory on Carrara marble and found it to be satisfactory for weathering tests. [52]

In this study, the measurements undertaken in the field and in the laboratory were made with a portable ultrasonic tester; *AU 2000 Ultrasonic tester from CEBTP*. The P-wave frequency used was 60 kHz, the sampling frequency 10 MHz and the time resolution 0.1 s.

7.3.4 Moisture Measurement with a Tramex Instrument

Many methods are available for measuring the moisture content in building material. Some methods are good for high moisture content and others are suitable for low moisture content, while some are only applicable in the laboratory and some in the field. The methods are usually divided between *direct* and *indirect* methods. The direct methods measure the moisture content directly by weighing the water in a sample (gravimetric methods). The indirect measurement measures properties in the material which can be related to its moisture content, for example, the electrical conductivity. Another way of differentiating is between *destructive* and *non destructive methods*.

The moisture measurement methods are divided according to the methodology:

1 Absolute measurement methods (gravimetric measurements and chemical methods)
2 Hygrometrical methods
3 Electrical measurements
4 Other methods, such as the thermographic method, radar methods, microwave methods and methods using gypsum blocks with electrodes that are inserted into the wall.

As the electrical method has been used in this study it is therefore the only one described (for further information see Report no 1).

Electrical methods measure the conductivity of the material and are thus *indirect*, *non destructive* and can be used *in-situ*. They depend on the difference of the electrical properties of the measured material and the properties of water. Several cheap portable instruments are available.

Electrical methods can be based on two principles:

1 the resistivity
2 the capacity

Resistivity methods are carried out by measuring the resistance between two electrodes that have been tapped into the material. The measurement is based on the principle that the electrical resistance decreases when moisture is present in a material. The measurement is compared with a calibrated curve for the specific material. This, together with measurement of the temperature makes it possible to measure the moisture content by mass (u).

Figure 3. Ultrasonic measurements undertaken at the German Church.

Figure 4. Moisture measurement with a Tramex at Karolin Chapel.

The capacity method, on the other hand, uses a condenser with two electrodes that are isolated from each other by a *dielectric material*. Several moisture measurement methods are based on the determination of the *dielectric constant*. The constant is much higher for water (ca 80) than for most of the building materials (usually between 3 and 6). This makes it suitable for moisture measurements. A dielectric material is defined as a material that has modest or no electrical conductivity. When the measurement is carried out, the measured material becomes the dielectric material in the condenser that creates the electrical circuit. The instrument measures the change of frequency when the dielectric properties in the material change. The result is plotted onto a calibrated curve and the moisture content calculated. The portable instruments that are available usually measure frequencies around 100 MHz.

The available electrical instruments have several defaults in that they do not penetrate more that a few millimetres, and the conductivity and resistivity are increased when salt is present in the material. A wall or stone containing salt will therefore give the impression of too high a water content.

A *TRAMEX Concrete Moisture Encounter* was used for measuring the moisture in the material in the field tests. The methodology is such that on parallel surfaces low frequency signals are transmitted ca 12 mm into the surface. The surface has to be ca 10 cm wide due of the size of the instrument. The instrument is thus based on the electric moisture measuring principle that is disturbed by salt. The results are given in the moisture ratio of 1 percent to 6 percent of H_2O. However, the instrument is made and calibrated for concrete, which naturally contains some water. The values are thus only relative on stones.

Moreover, a *Protimeter Aquant moisture indicator* was used on one occasion and in the laboratory. This instrument also uses electrical signals, is designed to give an idea of the moisture content a few millimetres into the material (5 – 50 mm in depth) and is disturbed by salts. The area that is measured is only ca 5 cm in length and ca 2 cm wide, which is an advantage compared to the Tramex instrument. Like the Tramex instrument, the Protimeter can only be used to estimate the moisture differences in a material relative to the same material. The measuring principle consists of the difference in the dielectric constant between water and other materials. It uses a high frequency signal (radio waves).

7.3.5 Colour measurement with a Spectrophotometer

Colour measurement is used in stone conservation to control the effect of cleaning and to monitor the re-soiling of the stone after conservation. Moreover, it is used to identify pigments. The methods are not only important in monitoring colour changes for aesthetic reasons but colour changes may also help to understand weathering, since alterations in colour sometimes indicate chemical changes. These changes can be chemical processes of dissolution, alteration of minerals and formation of ageing patinas in stone materials. For example, a recent article describes how Italian researchers have tested a methodology based on a computer-aided colour analysis to evaluate chemical change and salt concentrations in stone masonry. [53] The colour measurement methods are non destructive and can be used *in-situ*.

Special *colorimeters* and *spectrophotometer*s have been developed that measure the reflected or transmitted visible light of an object and are also now available as portable instruments. The *Colorimeter* measures light emission using receptors of red, green and blue and results in isolated numerical values in the different colour notations. The *Spectrophotometer* measures the light in the 380–780 nm wavelength area. The colour is plotted onto a curve obtained by joining the values measured at each wavelength. [54] Such a *Spectrophotometer* has been tested in this project.

Spectrophotometers/colorimeters are usually constructed to calculate colour differences for industrial usage and are often based on the CIELAB values. [55][53] The instrument makes it possible to store data from one measurement and compare the result with later measurements. The colour parameters measured are L* (Lightness), a* (red-green) and b* (yellow-blue). From these measured values one can define chroma C $[(a^*)^2 + (b^*)^2]^{1/2}$ and hue = $\tan^{-1}$ (b*/a*). These values can be plotted in an x – y diagram vs. L*-value.

Changes in chroma can also be expressed in ΔC* and in lightness as ΔL* and the colour difference in $\Delta E = (\Delta L^*)^2 + (\Delta a^*)^2 \times (\Delta b^*)^2]^{(1/2)}$. [54] Some of the drawbacks of the method are that it can be difficult to re-measure the same spot and that moisture and temperature changes might influence the result. These factors have been tested in this study.

A portable spectrophotometer measures the light reflected from an object. The spectrophotometer used is a *Minolta CM-508i*. It is constructed according to CIE, d/o recommendations as well as ISA, DIN and ASTM t/o standards. The light comes from a Xenon lamp. The light is reflected from the specimen surface at an angle of 8° to the normal and collected. The range of measurement is 400 to 700 nm at 20 nm pitch, the accuracy of the colorimetric values within 0.2 percent and the colorimetric values within ΔE about 0.05. The data can be displayed as colorimetric values ΔL* Δa* Δb* or in a Hunter ΔLΔaΔb colour difference graph. Numerical values can be given in XYZ, Yxy, L*a*b*, L*C*h*, Hunter lab, MI, CMC, among others. The instrument has to be calibrated at least once a year and is easy to handle in the field.

7.4 The Chosen Sites

Sixteen objects were tested in the field (i.e. eighteen locations in total). All are situated in Stockholm, either in Östermalm or the Old Town – see table 1. The information in the table has been collected from archives (ATA and the stone atelier in Stockholm), by talking to the owners of the buildings, from some of the conservator-restorers and from visual inspections. Since information about previous conservation is often missing, a lot of important details – such as treatments and facts about the condition of the stone during previous conservations – have not been able to be included in the table. The age of the measured stones is also often uncertain, which means that conclusions about correlations between age, former treatments and data obtained during the field tests are often unreliable.

Figure 5. Colour measurements using a Minolta CM-508i at Narvavägen 30.

Table 1. Some information about the stone at the test locations in Stockholm

Place	Age	Paint	Consolidation	Cleaning	Other
1. The German Church	1890	It looks as though the stone has been impregnated with linseed oil.	?	?	The stone was not included in the 1991–1992 conservation and conservation from the beginning of the 20th century is almost unknown.
2. Strandvägen 45	1893	It looks as though the stone was originally impregnated with oil.	Wacker OH in 1993–1994.	Cleaned with ammonium hydrogen carbonate in bentonite clay compresses in 1993–1994.	
3. Narvavägen 30	1905	?	Wacker OH in 1992.	Cleaned with ammonium hydrogen carbonate in bentonite clay compresses in 1992.	
4. Skeppargatan 82	1914	?	No	Probably with abrasives.	
5. The House of Generals at Skeppargatan 61	1924–1926	?	?	Probably with abrasives.	
6. Engelbrektsgatan 21	1912–1914	?	No	?	There are remains of an anti-graffitti treatment.
7. Strandvägen 7C	1907	?	No	Probably with abrasives.	
8.1 The Karolin Chapel	Stone type 1) 1750		Impregnated with linseed oil and painted with oil paint.	Wacker OH in 1991.	Cleaned with ammonium hydrogen carbonate in bentonite clay compresses in 1991.
8.2 The Karolin Chapel	Stone type 2) 1650		Impregnated with linseed oil and painted with oil paint.	Wacker OH in 1991.	Cleaned with ammonium hydrogen carbonate in bentonite clay compresses in 1991.
8.3 The Karolin Chapel	Stone type 3) 1992		No	No	No
9. The Gustavian Chapel	1633	Impregnated with linseed oil and painted with oil paint.	Partially consolidated with Wacker OH in 1993.	Micro abrasive cleaning in 1993.	
10. The Bernadotte Chapel	1854–1856	Impregnated with linseed oil and painted with oil paint.	Partially consolidated with Wacker OH in 1993.	Micro abrasive cleaning in 1993.	
11. Lilla Nygatan 2	1698	Originally impregnated with linseed oil and painted with oil paint.	Wacker OH in 1993.	Cleaned in 1966. Cleaned with ammonium hydrogen carbonate in bentonite clay compresses in 1992.	During the restoration in 1993 a lot of water soluble salts were found.
12. Skeppsbron 21/ Brunnsgränd 1	1901	?	?	Probably cleaned with abrasives.	The surface has been treated with an anti-graffiti treatment.
13. Slottsbacken 2	1790	?	?	?	
14. Bollhusgränd 3A	1635	Originally painted.	Wacker OH in 1992.	Water, brushes and scalpels in 1992.	Augusto Conte renovated the portal 1972. The portal was treated with anti-biological treatment (1 % Bradophen) 1992.
15. Stortorget 5	1790	?	?	?	The sandstone is very dirty – almost black, a black crust. The surface also has a fat/ waxy feeling.
16. Svartmangatan 6	1650	Originally impregnated with oil and painted with oil paint.	Wacker Steinfestiger OH in 1982. Wacker Steinfestiger OH again in 1994.	Cleaned with a micro-abrasive method and with compresses containing chemicals in 1982. Cleaned with compresses with 15 % solution of ammonium hydrogen carbonate in 1994.	Salt samples were analyzed in 1993. They were analyzed with SEM/EDX and contained gypsum and NaCl.

7.4.1 The German Church

The German Church, which has a long medieval history, was consecrated as part of the evangelical German Church during the 16th century. The church was completely restored and rebuilt after a fire in 1878 by the architect Rauschdorff from Berlin and by the Swedish architect Magnus Iseaus. The church is constructed in brick with architectural details in Gotland sandstone and Mälarsandstone. The stone may have been painted with oil paint, although this has not yet been evaluated. Small vestiges of what is probably paint were found on the stone in the tower.

The first restoration was completed in 1911 under the leadership of architect Ernst Stenhammar. According to the newspapers of the time, the sandstone was badly weathered and completely re-chiselled and impregnated (with oil or waterglass). The worst weathered stone was replaced with new stone. It is also mentioned that the whole facade was chemically cleaned (the substance is unknown). [56] In 1947 once again the facade demonstrated weathering problems. "Byggmästare" Håkansson was employed to restore the stone. He had invented a kind of restoration mortar (stenmassa) that had been used on Storkyrkan and on other buildings in Gamla Stan. The method was analyzed by conservator Gillis Olsson at the National Board of Antiquities and was found to consist of ground sandstone and an organic binder which was soluble in acetone – probably nitrocellulose. The method is similar to the Danish Deckosit method (used at Riddarhuset and Riddarholm's Church among others – see above). Olsson remarked that the Deckosit mortar had porosity closer to Gotland sandstone and was therefore preferred. Which method was actually used is unknown. In 1991–1992, the upper part of the tower and the Memorial Chapel was conserved and restored. The cleaning was carried out with 3 percent HFl in water, the re-pointing with Billy's mortar (see above), the consolidation with Wacker Steinfestiger OH and a hydrofobic treatment was used (Wacker Steinfestiger H).

The area chosen for investigation is found close to the ground in the eastern corner of the southern yard (on the corner stones). The stone probably derives from the restoration at the end of the 19th century. The stones are in various states of conservation. The stones close to the ground are badly weathered; the damage probably being caused by rising damp and salts, followed by heavy spalling, granular disintegration and exfoliation. There are, however, no visible signs of biological growth and black crusts (there are black crusts in other parts of the building). Some of the stones show yellow iron stains and are more weathered. Four stones were investigated; one stone with iron stains on the left side and being less weathered and grey on the right side, one stone with yellow stains, and two stones close to the ground in extremely bad condition.

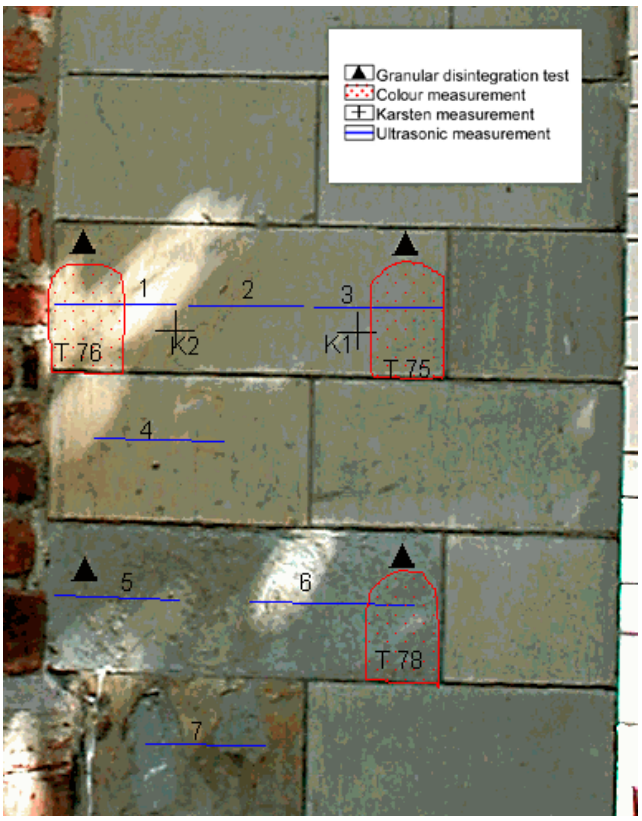


Figure 6. The chosen area of investigation at the German Church.

7.4.2 Strandvägen 45

The portal at Strandvägen 45 is made from Gotland sandstone. The house dates from 1893 and was designed by architects Ullrich & Hallquist. The sandstone was conserved by the firm Stenkonservatorn in 1993–1994. The stone was cleaned with water and consolidated with Wacker Steinfestiger OH. Previous treatment is unknown.

The portal is situated on the south side of the building in direct sunlight. The chosen area of investigation is on the left side of the portal. The stone is in good condition, with an even grey colour and no black crust or granular disintegration or biological growth. The ornamented front piece is somewhat yellowish in colour. The colour may be the remains of an oil treatment.

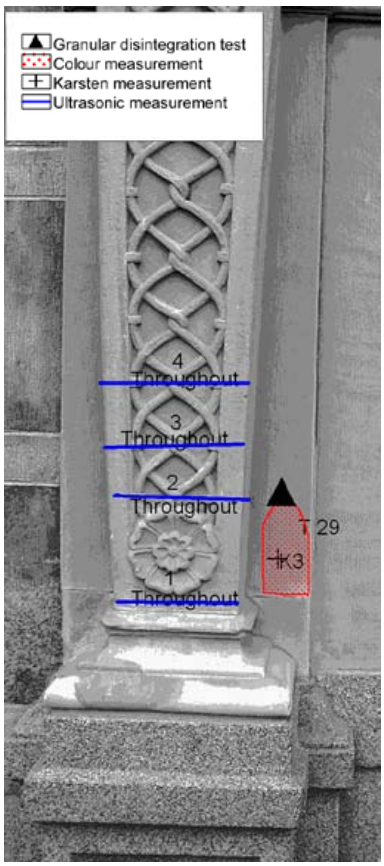


Figure 7–10. The chosen area of investigation at Strandvägen 45.

7.4.3. Narvavägen 30

A portal constructed in part with Gotland sandstone with female figures at Narvavägen 30 was examined. The house, dating from 1905, was designed by architects Hagström & Ekman. The two sandstone figures, both holding a lamp, are to be found on both sides of the portal. The chosen investigation area is the left side of the portal. The figures were restored by Prolithos in 1992, who cleaned and consolidated the portal with Wacker OH.

The Gotland sandstone is grey in colour and shows signs of deterioration, such as granular disintegration and black crusts in some protected areas on the upper part of the figures. The sandstone also contains natural faults, such as shells and fossils, and these areas have deteriorated.

7.4.4 Skeppargatan 82

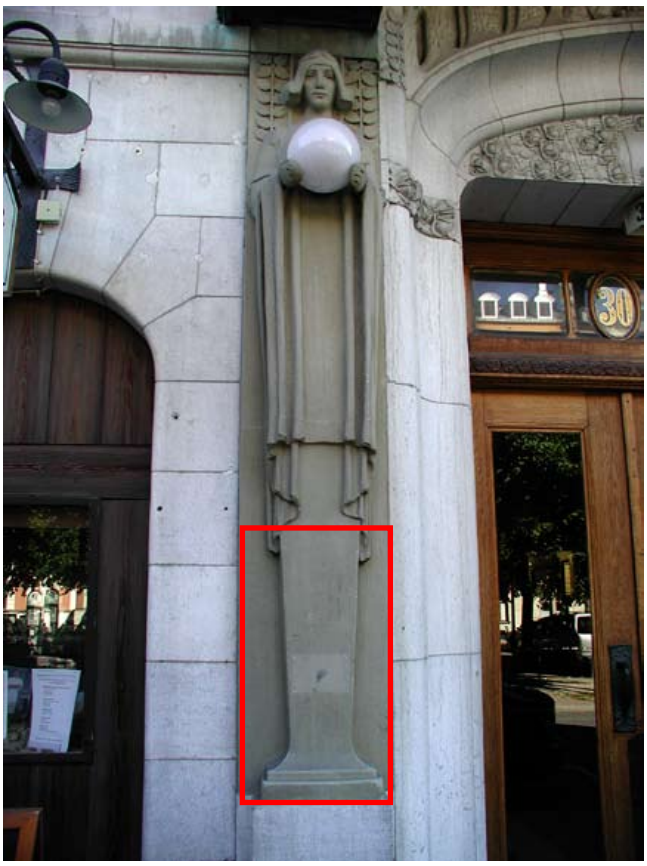
The socle and portal of the Manor House at Skeppargatan 82 are constructed in Gotland sandstone. The house was designed by Östlihn & Stark in 1914 and the restoration history is unknown. One stone in the socle was investigated.

The stone has deteriorated and is dirty. It may have been cleaned with abrasives since the chiselled surface is badly worn. There is very little granular disintegration and little sign of biological growth or black crusts.

7.4.5 The House of Generals at Skeppargatan 61

The socle, portals and decorative stone at the former House of Generals (Generalitetshuset), situated between Östermalmsgatan, Artillerigatan and Skeppargatan, are of Gotland sandstone. The building complex, of late Baroque style, was erected between 1910–1914 and 1924–1926 by the architect Ernst Josephsson. The chosen site for investigation is situated at Skeppargatan 61; this part of the building dates from 1924. One stone in the socle was investigated. The stone was restored in 1960 (it is not known how) and in the 1990s under the surveillance of conservator Tord Andersson. His conservation report confirms that the stone had been subjected to granular disintegration, exfoliation, black crusts, damage deriving from iron defects in the stone, frost damage, ugly old repairs and graffiti. The stone – mainly the decorative stone – was cleaned in different ways and consolidated with Wacker OH. The more architectural stone investigated in this study had probably only been cleaned.

Today the stone shows severe deterioration and is disintegrating and sanding. The chiselled surface has been destroyed, probably by some kind of abrasive treatment. This abrasive treatment has also left ugly marks. The stone is thus very porous and has a strange yellowish coloured top layer; more "fresh" grey sandstone being found underneath this layer. No biological growth or black crusts were evident on the investigated part of the building. The vestiges of removed black crusts are still visible, however.



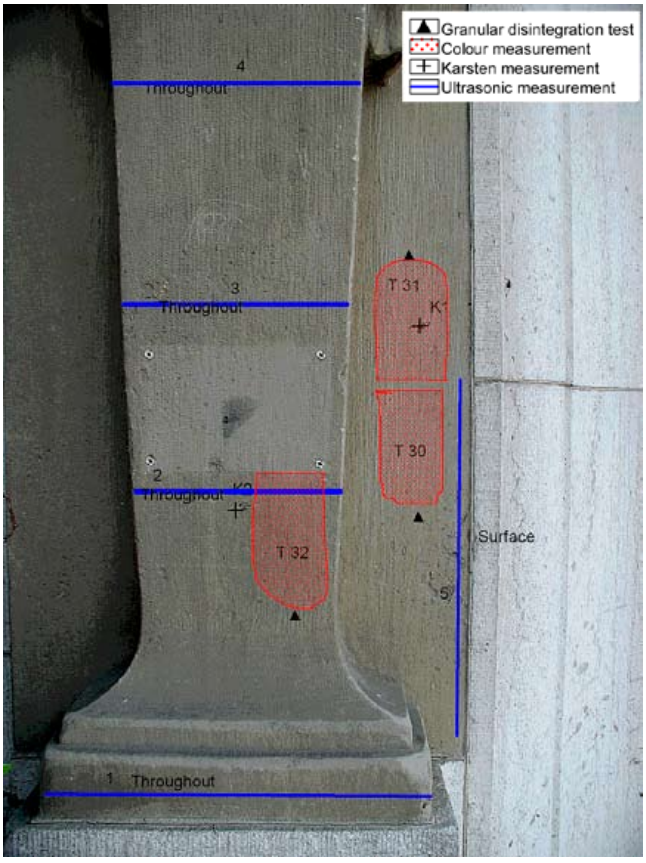


Figure 11–12. The chosen area of investigation at Narvavägen 30.

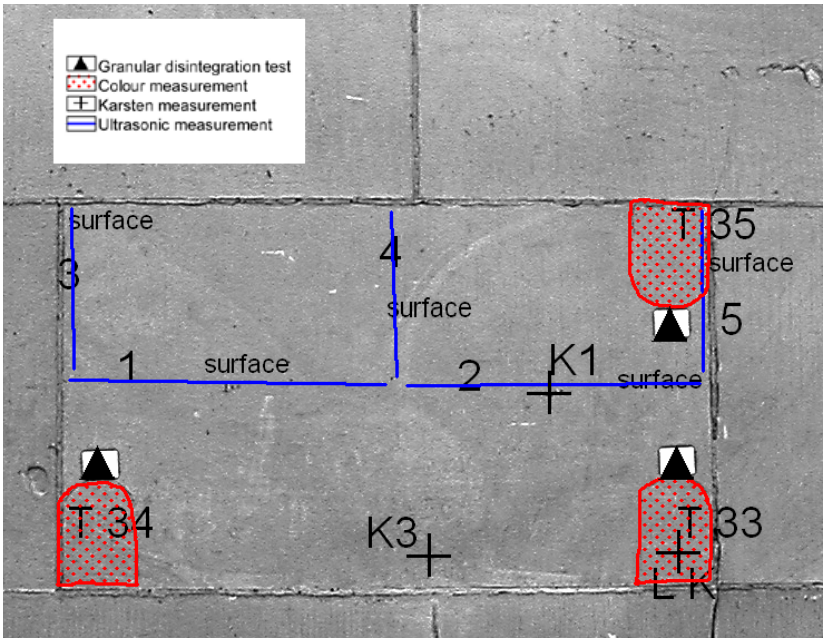


Figure 13–14. The chosen area of investigation at Skeppargatan 82.

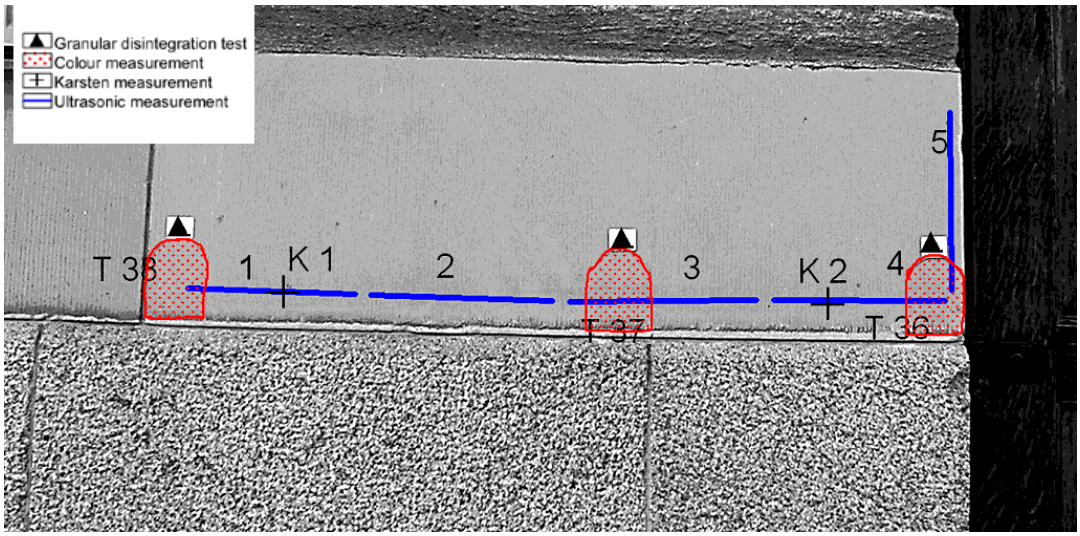


Figure 15–16. The chosen area of investigation at the House of Generals at Skeppargatan 61.

7.4.6 Engelbrektsgatan 21

Engelbrektsgatan No 21 is situated on the east side of the street. The house was designed by the architects Hagström & Ekman in 1912–1914 and the portal and some other decorative stone is of Gotland sandstone. The conservation history is not known.

Apart from being rather dirty the stone is in good shape, and no biological growth or black crusts are evident. The surface has a ”fat” texture – as though it has been treated with water repellent. This could be an anti-graffiti treatment. Vestiges of white oil paint can be seen on the surface.

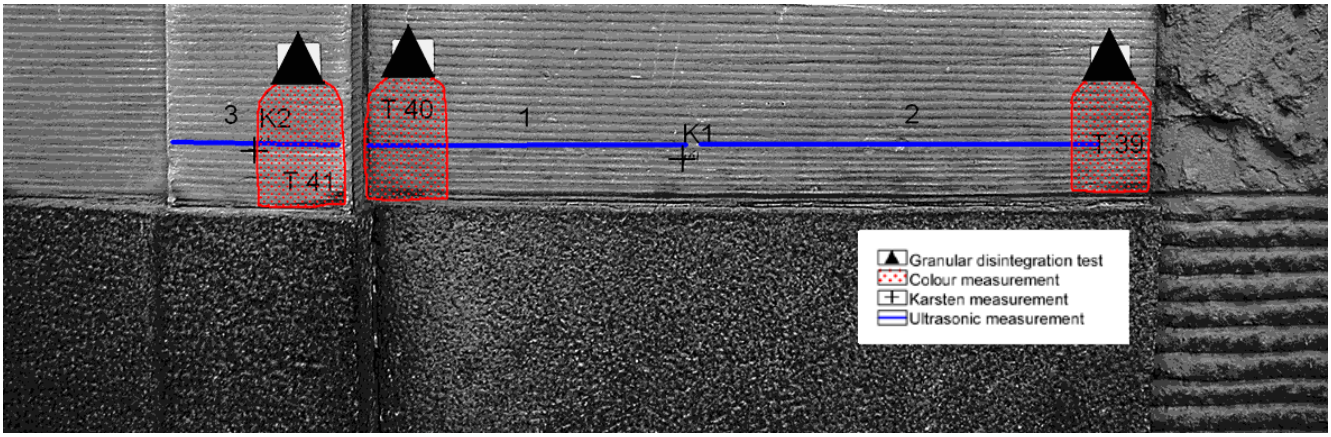
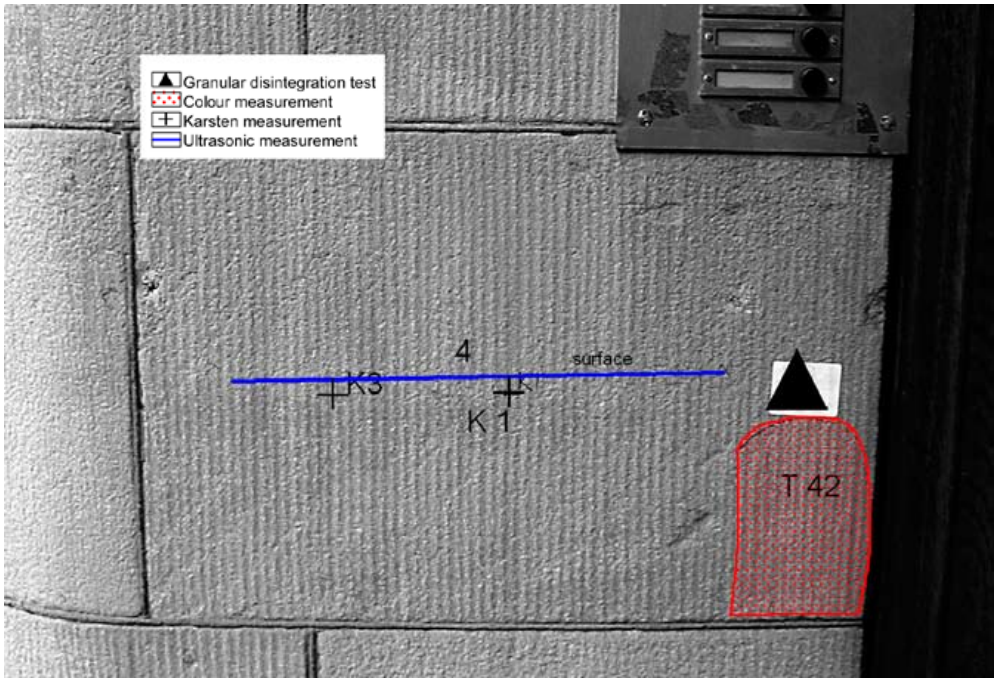


Figure 17–18. The chosen area of investigation at Engelbrektsgatan 21.

7.4.7 Strandvägen 7C

The Gotland sandstone portal at Strandvägen 7 C is included in the Diplomat Hotel complex. The house was erected in 1907 and was designed by architect V. Bodin. The investigated Gotland sandstone portal is to be found in the inner courtyard. The left side of the portal was investigated. The conservation history is unknown. The Gotland sandstone is in good condition and there is no biological growth or granular disintegration or exfoliation. However, the original chiselling was damaged by an earlier treatment; probably cleaning with abrasives.



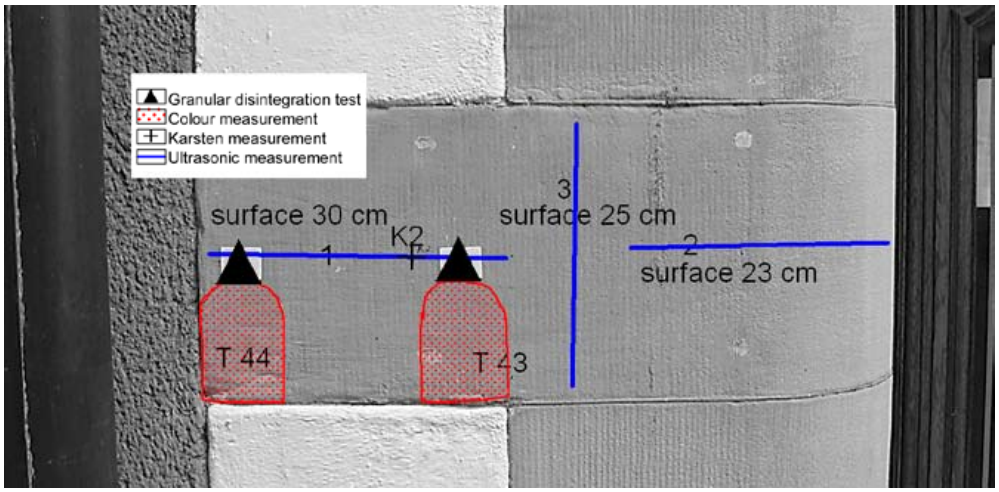


Figure 19–21. The chosen area of investigation at Strandvägen 7C.

7.4.8 Riddarholm's Church and the Karolin, Gustavian and Bernadotte Chapels

Riddarholm's Church is medieval in origin. The first church was erected around 1290 by the Franciscans and has been enlarged and remodelled several times. In medieval times the brick facade was painted red with white stripes to achieve a more even brick appearance (the natural brick's colour and shape were not regular enough). The window tracery was accordingly painted red, green and grey. The coloured facade remained intact until the 1890s, when repainting stopped and the paint gradually eroded, with the consequence that the paint is hardly visible today. The colour had a protective function as well as being decorative. King Gustav Adolfus made Riddarholm's Church his Royal Memorial Church. Hence, in 1633 the first Memorial Chapel, "the Gustavian Memorial Chapel", was erected. It was made in brick with details in Gotland sandstone and placed close to the choir. It was followed by several Swedish noble families. The next Royal Chapel, the "Karolin Memorial Chapel", was constructed from Gotland sandstone. The architect was Jean de la Vallée (1686), but he was replaced by Tessin the younger and by Carl Hårleman. Due to wars and a lack of resources the chapel was not completed until 1743. The socle of the building that has been investigated was built between 1675 and 1697, although most of the sandstone dates from the 18th century.

In 1806 the church ceased to function as a parish church and instead became a Memorial Church for the Swedish kings. The church was neglected for a long time and in 1811–1817 the architect Fredrik Blom commenced the restorations. He had a romantic idea about the church and the restoration was meant to respect and enhance the church's medieval aspect. The interior was nevertheless completely redesigned in French Empire style. In 1835 the church was struck by lightning and both the roof and tower were destroyed by fire. Axel Nyström led the restoration in 1838–1846, when the interior was redesigned in Neo-gothic style. A new tower of cast iron was also designed by Göthe and C. G. Blom Carlsson. In the 1850s the architect Scholander restored the Karolin Memorial Chapel, which by now had problems with rising damp. He also designed a new Memorial Chapel for the Bernadottes in 1854–1856 in historic style. The next architect, Ernst Jacobsson, continued to restore the Karolin, Gustavian and Bernadotte Chapels between 1885 and 1889. He too noted severe damp problems in the Karolin Chapel, as well as serious deterioration of the stone. He recommended replacing the weathered stones to prevent the water from penetrating and painting the façade with a protective colour. The entire facade was restored by "byggmästare" Thavenius. Damaged stone was removed and replaced and other stones were repaired with Portland cement. This did not solve the problems, however. The next responsible architect, Ludvig Pettersson, restored the exterior of the Lodesk and Karolin Chapels in 1900–1903, followed by the northern portal in 1904.

From 1914–1922 a major interior restoration was initiated by archeologist Martin Olsson and architect Gustaf Lindegren. He had been in charge of the church since 1907. Both the stone and brick were restored by engineers Sahlin and Rikard Jonsson between 1914 and 1922. At this time the attitude towards restoration had changed. Based on archaeological historical research conducted by Martin Olsson it had now become a scientific operation. Despite this, attitude differences between Olson and the architect – who was schooled in the 19th century's stylistic principles – towards the restoration became evident. Olsson proved to be the stronger, however and the results of his research were published in two volumes in the series "Sveriges kyrkor" (The Churches of Sweden, 1928). Care of the church was handed over to architect Ove Leijonhufvud in 1926–1930. Still under Olsson's guidance, the exterior continued to be restored in 1926–1929. The stone and brick were once again found to be weathered. Restoration began on the exterior of the Lewenhaupt Chapel in 1926–1928, with Ceresin mixed with carbon tetrachloride (CCl_4). Ceresin was a kind of industrially manufactured wax used for the impregnation of gypsum and stone. According to the "Varulexikon" from 1894, it was manufactured with mineral wax melted in sulphuric acid, mixed with stearin, and thereafter treated with potassium hydroxide and filtrated. The Danish Deckosit method was also used (made of ground sandstone mixed with a nitrocellulose binder). In some places new Gotland sandstones and bricks were inserted marked with an R. The new stones were patinated with black "bone pigment." Both the Karolin and Gustavian Chapels were treated in the same manner in 1929.

Deterioration of the Gotland sandstone accelerated during the 1960s. The architect Torbjörn Olsson led a new restoration campaign from 1967 until 1970. There had been problems with rising damp and salts in the church ever since the middle of the 19th century, especially the Karolin Chapel. Despite measures to prevent the water from penetrating, the problem had remained. Engineer Ingemar Holmström investigated the climate in 1966, and the salts were analyzed in the same year by Arne Strömberg. In 1972 a new climate analysis was undertaken by the National Board of Antiquities. Measures were taken in 1973. From 1987 to 1996 the church was in the care of architect Erik Langelet. Under his guidance, the façade was restored by Prolithos. The Karolin Chapel was restored in three different stages between 1989 and 1992, the Gustavian Chapel in 1991, followed by the rest of the exterior in 1995.

In this study the chosen investigation area of the Karolin Chapel is in the niche heading northwest. This part of the building was conserved during the second stage by conservator Jarema Bielawski. In the first stage, at the back of the chapel, the stone was cleaned with abrasive methods

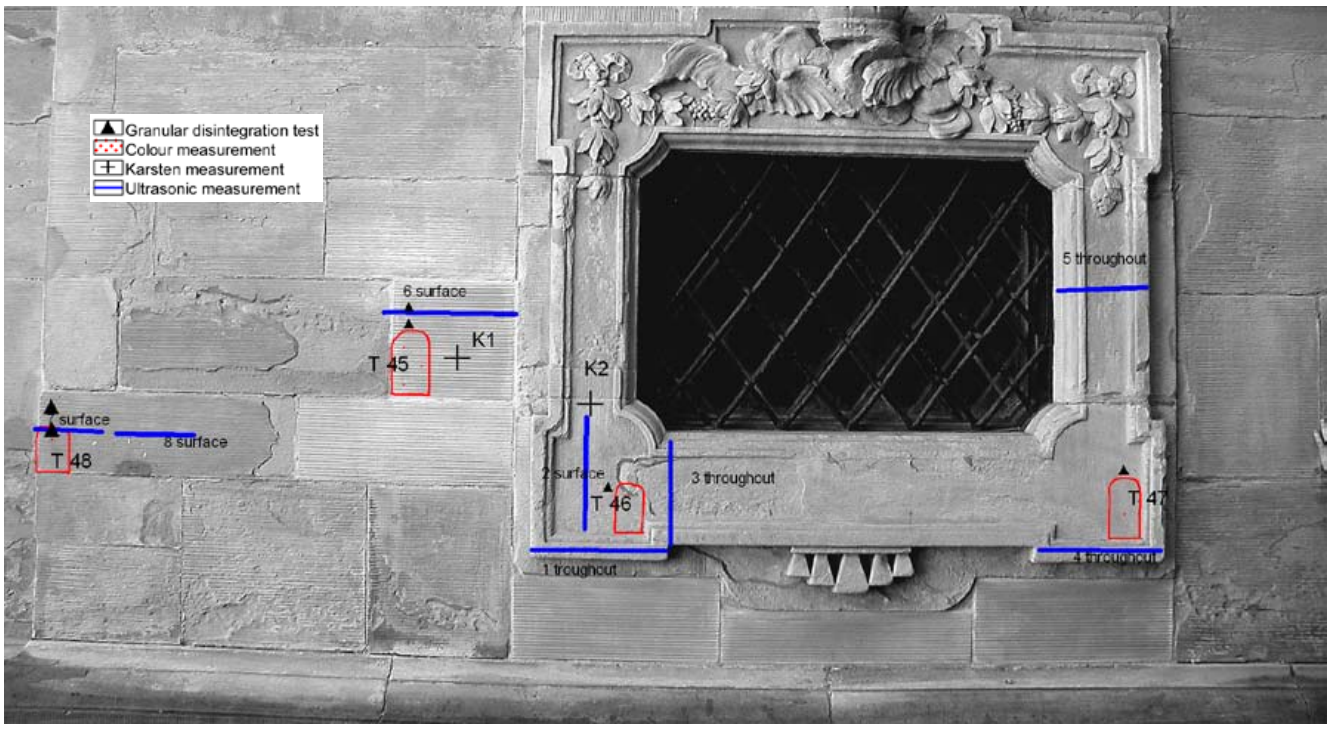


Figure 22–23. The chosen area of investigation at the Karolin Memorial Chapel.

(abrasive paper, knives and brushes) and the weak deteriorated stone totally consolidated with Wacker Steinfestiger OH. When Bielawski took over the cleaning, the stone was first pre-consolidated with Wacker Steinfestiger OH and afterwards cleaned with Bentonite clay compresses containing water and ammonium hydrogen carbonate. In the third stage the method changed again; Bielawski now tried a low pressure abrasive method using fine grained dolomite sand and water. After the cleaning the salts were extracted with paper pulp compresses and the weak stone was finally consolidated with Wacker Steinfestiger OH. A few new stones were also inserted, delivered by Slite Stenhuggeri. The guiding conservation principle was that no new sculptures or ornaments were to be created and only minor repairs were to be undertaken (except on the upper cornisch where the ornaments were replaced by gypsum copies). Billy's stone replacement mortar was used (grinded pigmented sandstone mixed with acrylate dispersion).

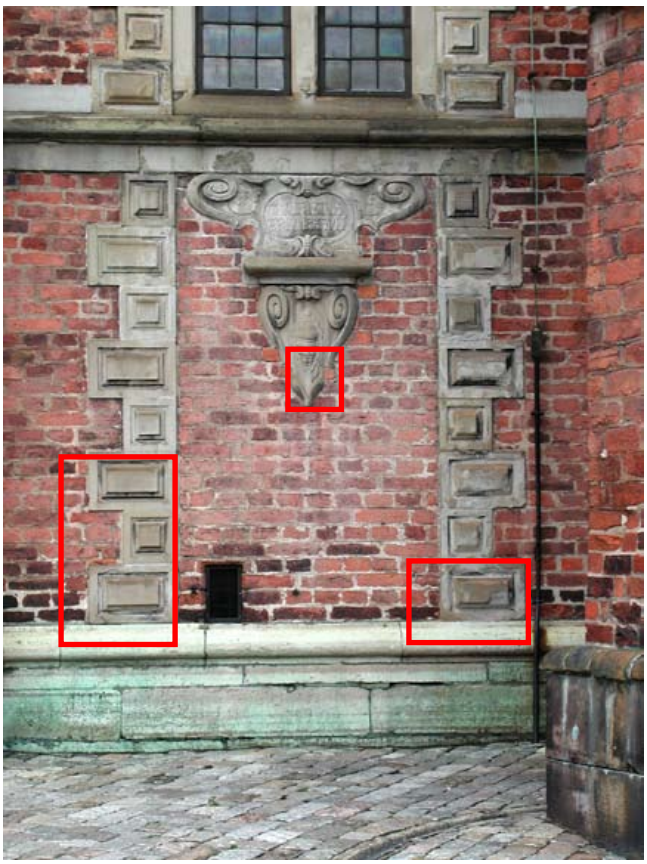
The Karolin Chapel is constructed in Gotland sandstone (ashlar stone) deriving from different periods and in various states of conservation. The chapel was painted right from the very beginning, although all the original paint has since been removed. The chosen area for investigation is found in the niche heading northwest. The investigated area consists of at least three kinds of stone: 1) Gotland sandstone in yellowish colour. The yellow colour probably derives from a previous oil treatment. This stone is weathered and subjected to some granular disintegration, but has no black crusts and no biological growth. 2) Light yellowish sandstone. The stone presents exfoliation and some granular disintegration, although no biological growth or black crusts. 3) New light grey chiselled stone. The stone was inserted in 1989–1992

by Slite Stenhuggeri. This stone is clean and has no granular disintegration, biological growth or black crusts.

Three kinds of stone were investigated; one new inserted stone from 1992 (type 3), one yellowish stone that probably dates from the 18th century (type 1) and an ornamental window frame from the 17th century (type 2).

The Gustavian Chapel. Gotland sandstone is found on the architectural details. It demonstrates signs of deterioration, such as granular disintegration and exfoliation. Moreover, the stone is dirty and has black crusts on the upper side. The upper parts are also sometimes covered in algae.

The Bernadotte Chapel. The chapel has been constructed



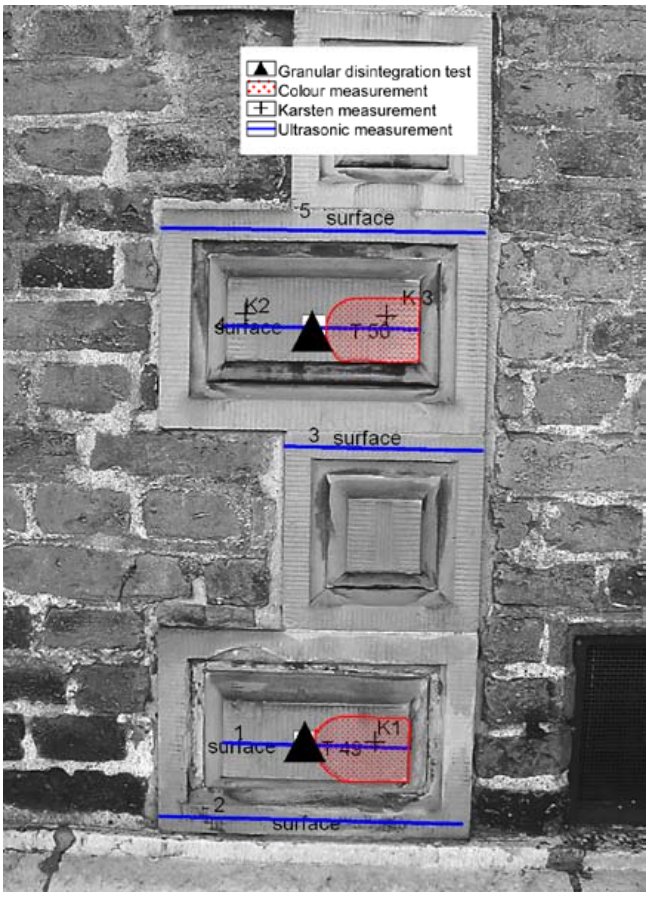


Figure 24–26. The chosen areas of investigation at the Gustavian Chapel.

to look like the Gustavian Chapel. It is thus made of brick with architectural details in Gotland sandstone. At least two different periods of stone are present; one dating from the 19th century and some from the restoration in the beginning of the 20th century. Some of the bricks from the latter are marked with an R. The state of conservation depends on the age of the stones. Some stones have a yellowish appearance. This kind of stone shows more deterioration and has been subjected to granular disintegration and exfoliation. The stone is not dirty, however, and there is no biological growth. The yellow colour may have been caused by a previous oil treatment.

7.4.9 Lilla Nygatan 2

The Gotland sandstone portal under investigation is situated in the Petersen's building (Petersenska huset). The building was erected by the German artist-architect Kristian Julius Dödteber in 1698. The chosen area of investigation is to be found at Lilla Nygatan 2. The portal's original paint was removed. Stenkonservatorn found buff colour remains during the restoration in 1992. The portal was restored in 1966 by Videlius Stuckatörsverkstad (there is no conservation report). The next restoration was conducted by Stenkonservatorn in 1992 as the stone was found to be in bad condition. The restoration comprised the pre-consolidation of weakened stone and cleaning with ammonium hydrogen carbonate in bentonite clay compresses. Green copper stains and organic growth were cleaned with ammoniac and hydrogen peroxide, as well as with brushes and scalpels. Old repairs

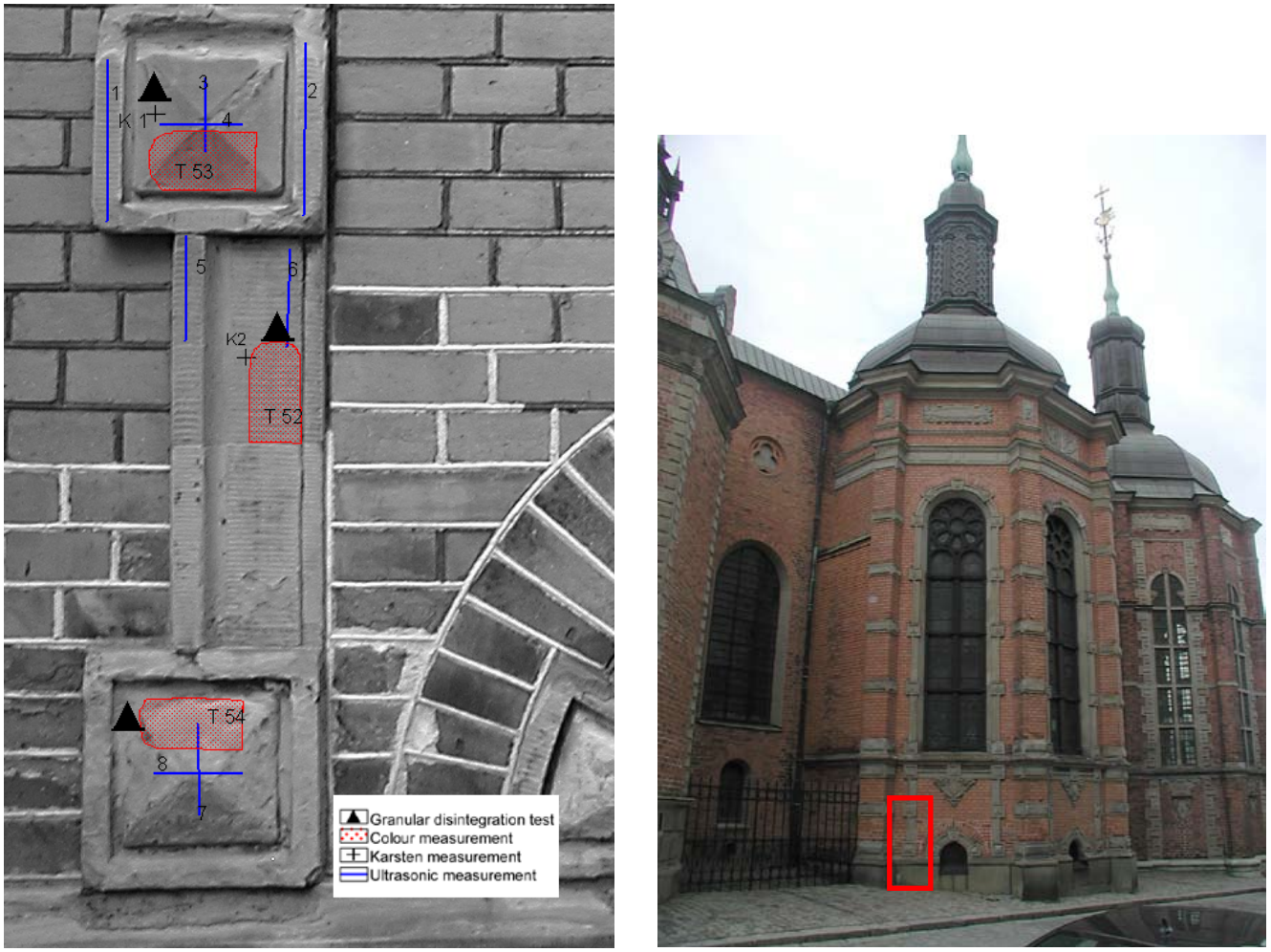


Figure 27–28. The chosen area of investigation at the Bernadotte Chapel. To the right the Gustavian Chapel can be seen as well.

were replaced. The cleaning salts were then extracted – three to five times – with paper pulp compresses. A hydraulic mortar was used for the re-pointing, while Billy's restoration mortar was used for the reconstructions. Finally, the portal was consolidated with Wacker Steinfestiger OH (52 l). The investigated area is on the left side of the portal. The stone appears to be in a stable condition, and there is no evidence of granular disintegration, biological growth, black crusts or exfoliation.

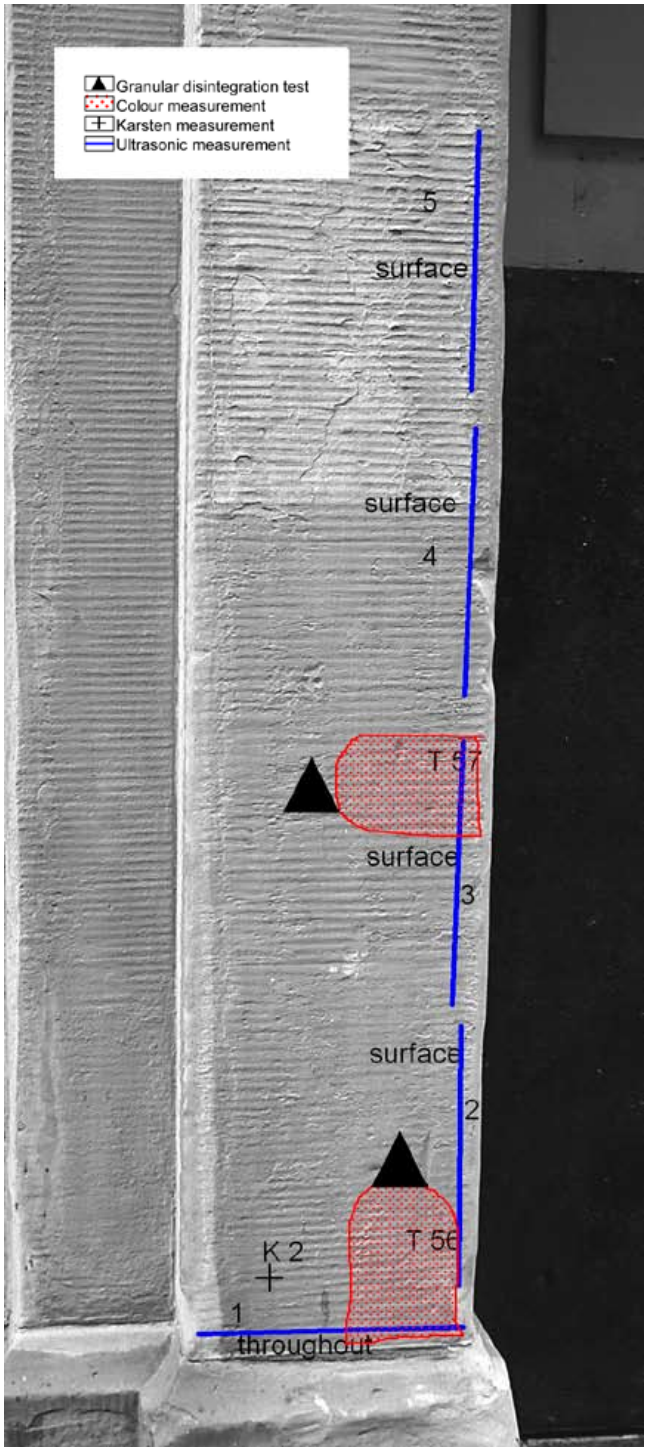
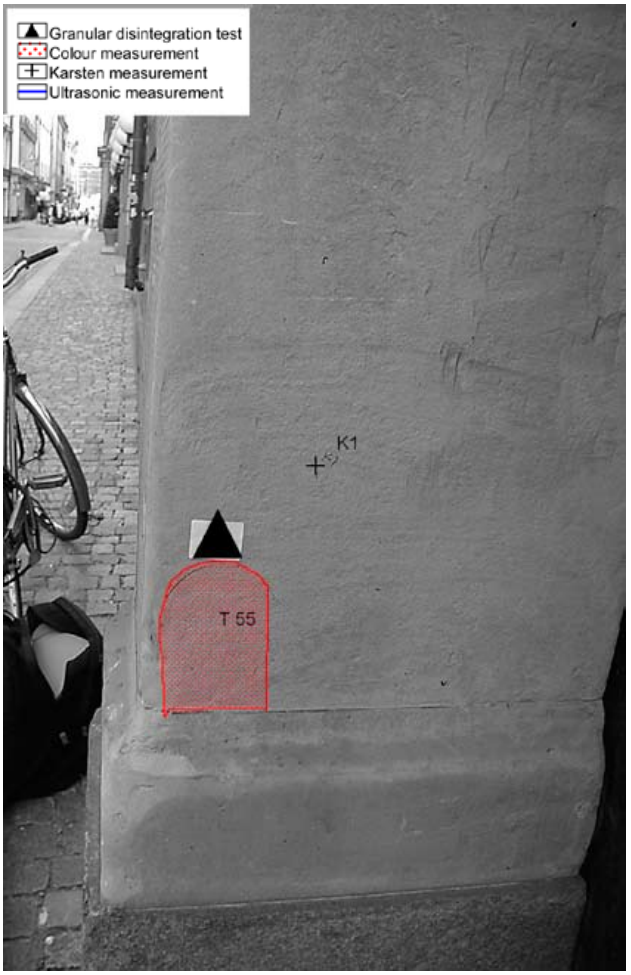


Figure 29–31. The chosen areas of investigation at Lilla Nygatan 2.



7.4.10 Skeppsbron 21 / Brunnsgränd 1

The building at Skeppsbron 21 dates from 1901 and was designed by the architect I. G. Clason. The socle and the building's ornaments are constructed in Gotland sandstone. The facade was restored in 1998. The stone work was led by conservator-restorers Tord Andersson and Gert Öhrström. Some stones were replaced with new stone from Slite Stenhuggeri, and Billy's glue and Billy's restoration mortar were used for re-pointing the lime mortar. Some of the stones were consolidated with Wacker Steinfestiger OH.

The chosen area of investigation is found on the right hand of the building at Brunnsgränd 1. The chiselling of the sandstone has been destroyed by an abrasive treatment. The colour of the stone is yellowish-grey and is in good condition. Although it is dirty, there are no biological growths, black crusts or granular disintegration. The new stones have a different colour and chiselling, however. The surfaces closest to the ground have been treated with an anti-graffiti treatment (what kind is not known). The surface is thus whitish and the treatment is in need to attention (it has qrackelures).

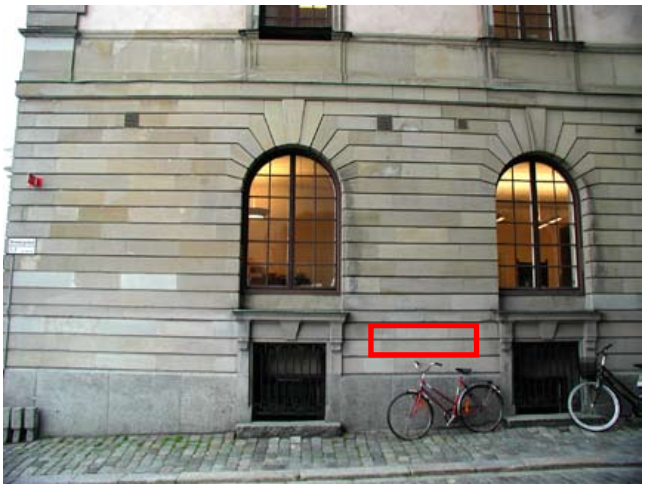
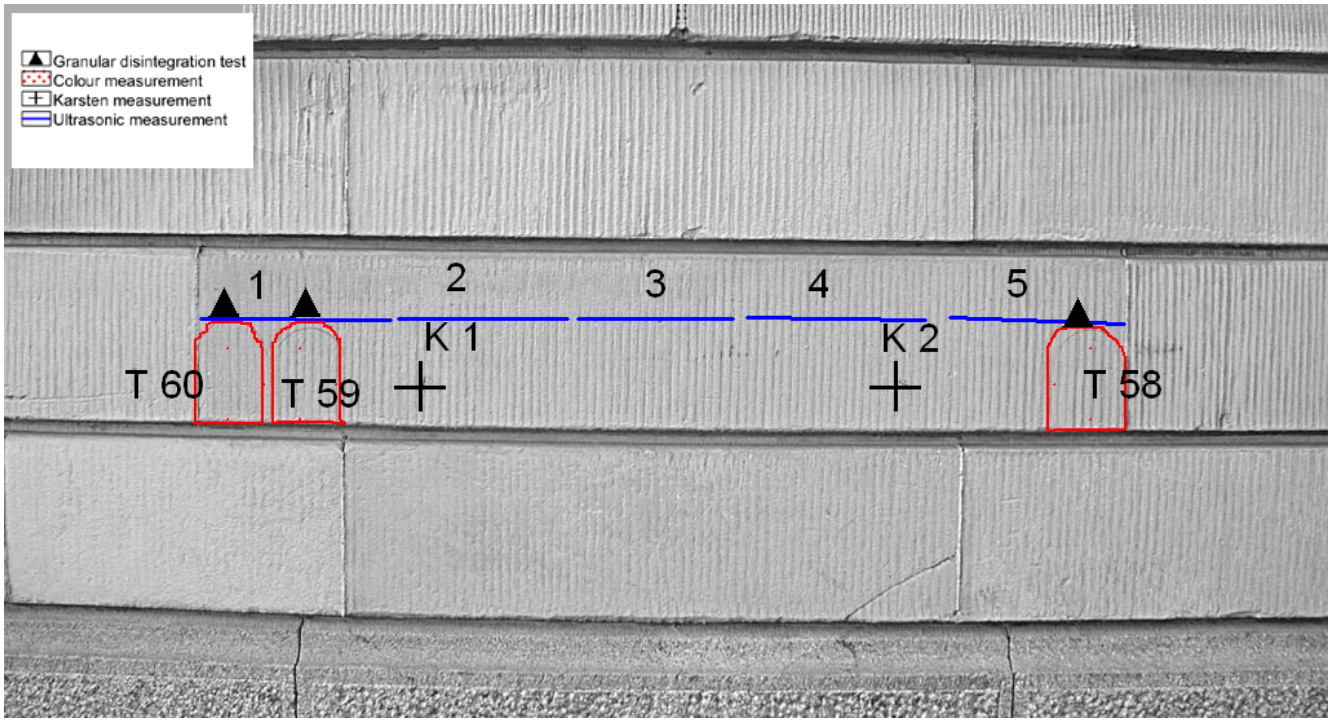


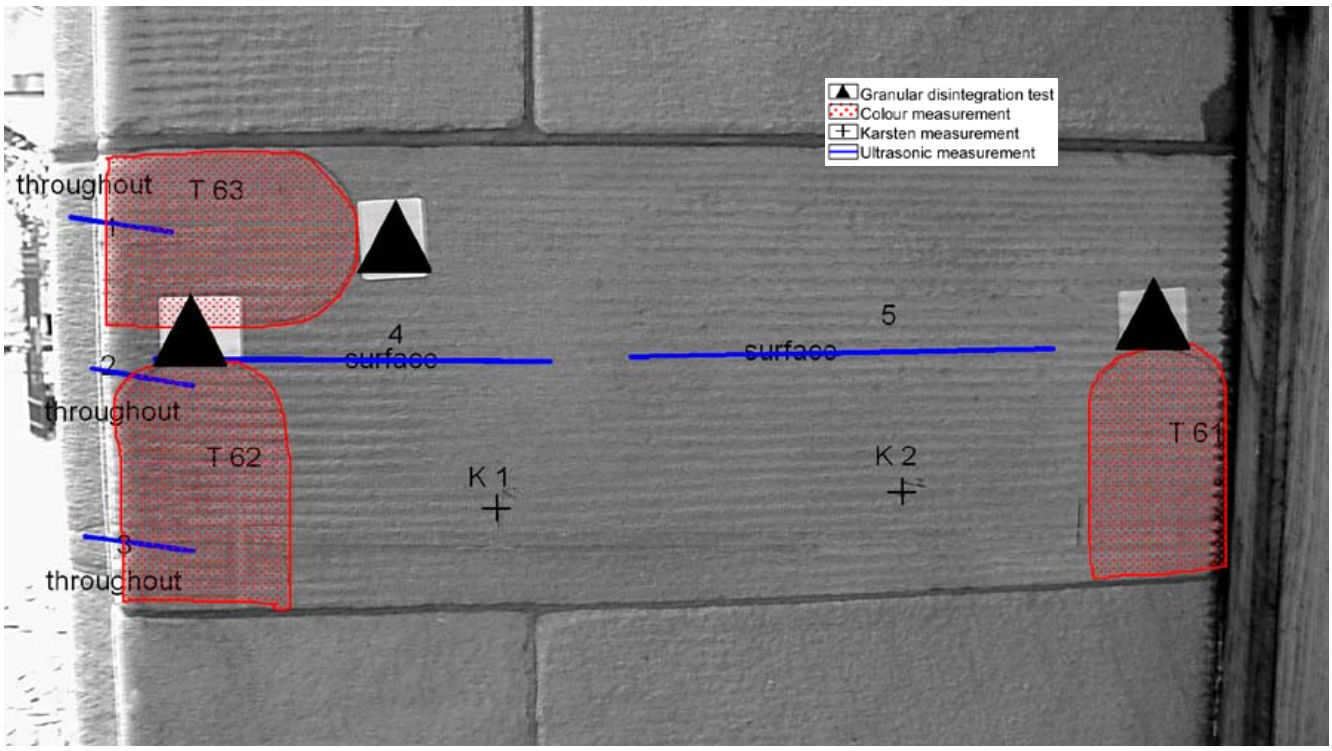
Figure 32–33. The chosen areas of investigation at Brunnsgränd 1.



7.4.11 Slottsbacken 2

The house at Slottsbacken 2 dates from the 18th century and has been restored many times. The chosen portal in Gotland sandstone is found inside the courtyard and the investigation area is found on the left side of the portal. The conservation history is unknown. However, one can see that the stone has been cleaned with abrasives and that the treatment has damaged the stone. While the stone is subjected to heavy granular disintegration and the surface is dirty, there is no biological growth. The stone closest to the ground has serious problems caused by salt and rising damp, which provoke exfoliation and spalling. The bedding planes are vertical.

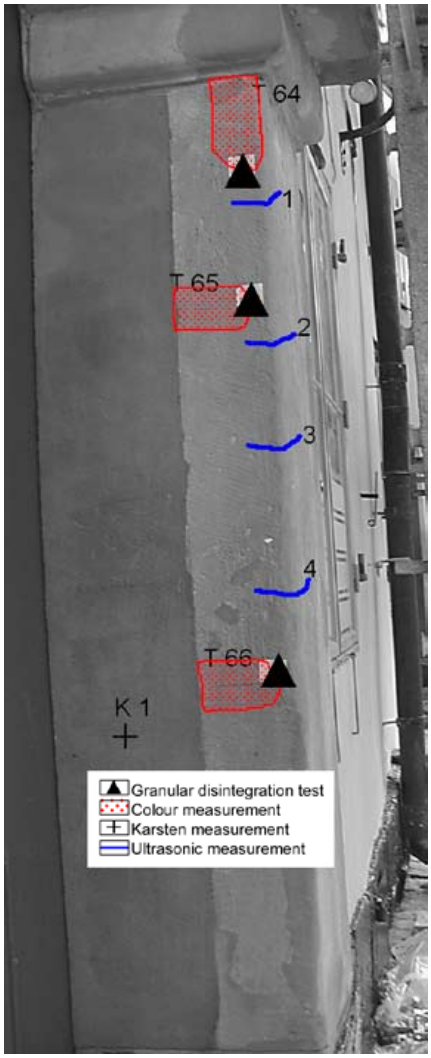
Figure 34–35. The investigated portal at Slottsbacken 2.



7.4.12 Bollhusgränd 3A

The decorative Gotland sandstone portal at Bollhusgränd 3 A was erected in 1635. The stone was originally painted. The builder of the house and his wife, Peter Banér and Hebbla Flemming, are commemorated in that their heraldic emblem is carved on top of the portal. The portal seems to have been constructed using old portals – or it might also be the result of a renovation in the 18th century. The appearance is thus slightly inhomogeneous. The portal has been restored several times; in 1971 by Augusto Conte (it is unknown how), and in 1992 by Prolithos and Leszek Zarzewski. The portal was found to be dirty, with black crusts, algae, material losses, cracks, old failing repairs and demonstrating salt problems. The state of conservation was described as "critical". The conservation included pre-consolidation, fixing of loose stones, cleaning with water, brushes and scalpels (in such a way that the paint remains should be left). The cleaning results were not satisfactory, however, and the conservator changed method, this time using compresses with ammonium hydrogen carbonate in bentonite clay, sand and cellstoff and micro-abrasive cleaning (aluminium oxide

Figure 36–38. The chosen area of investigation at Bollhusgränd 3.



powder). Most of the older repairs were removed, salts were extracted with paper pulp compresses, the consolidation was made with Wacker Steinfestiger OH (30 kg) and, finally, the portal was treated with an antibiological treatment (1 percent Bradophen). Quite a lot of the reconstruction was done using Billy's restoration mortar. The chosen area of investigation is on the right side of the portal. Today many of the reconstructions need attention, although the sandstone is stable and has no biological growth, black crusts or granular disintegration.

7.4.13 Stortorget 5

The house at Stortorget 5 was erected during the 18th century and the Gotland sandstone portal probably derives from the same period. The style is classical. The conservation history is unknown. The right side of the portal was chosen for investigation. The sandstone is very dirty – almost black, and has a black crust. The surface has a fat/waxy feel to it. There is no biological growth or granular disintegration. The bedding planes are vertical.

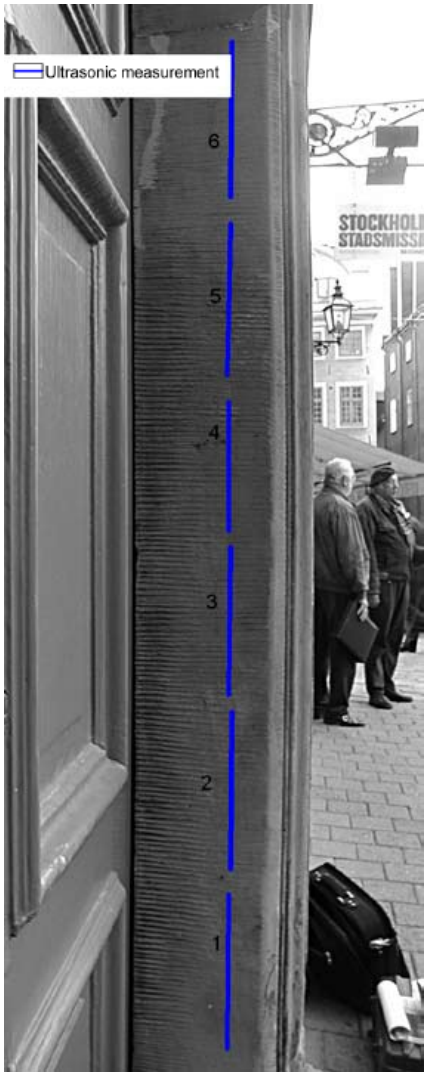
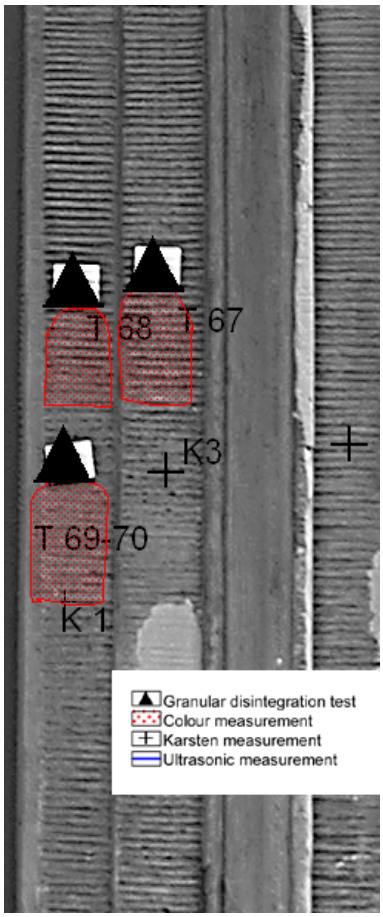


Figure 39–41. The chosen area of investigation at Stortorget 5.



7.4.14 Svartmangatan 6

The Gotland sandstone portal at Svartmangatan 6 dates from the middle of the 17th century. It has probably been composed of remains of older portals and painted. The married couple, C. M. Lewenhaupt and Maria Cruus, owned the house when the portal was constructed and their heraldic emblem is included in the portal. The portal was restored and conserved by Tord Andersson and the NHB in 1982. On this occasion the stone was badly weathered – especially on the upper parts. The portal was pre-consolidated with Wacker Steinfestiger OH, cleaned with a micro-abrasive method and with compresses containing chemicals. The repairs were done using Billy's restoration mortar. The portal was restored again in 1994 by Prolithos and Svante Nilsson. On this occasion the stone was dirty, although there were no black crusts. Some of the dirt was believed to derive from biological growth. Some of the original paint still remained but the portal had severe material losses, probably due to the presence of salts. The conservation included preconsolidation, cleaning with brushes, water and compresses with 15 percent solution of ammonium hydrogen carbonate. The old reconstructions were removed and extraction of the salts effected with bentonite clay and paper pulp compresses. The original paint was completely removed during this process. The portal was finally consolidated with Wacker Steinfestiger OH (30 l) and a few reconstructions were made with Billy's restoration mortar.

The portal is found in a house that hosts a school on a narrow street with a lot of movement. The portal is thus in danger, since many people go through the portal every day (humans, cars and bicycles pass close by). The sandstone is in a stable condition, but has an uneven colour. The stone was probably damaged during a previous treatment. There is no biological growth, black crusts or granular disintegration. The bedding planes on the column are vertical but the bedding planes on other stones could not be examined.

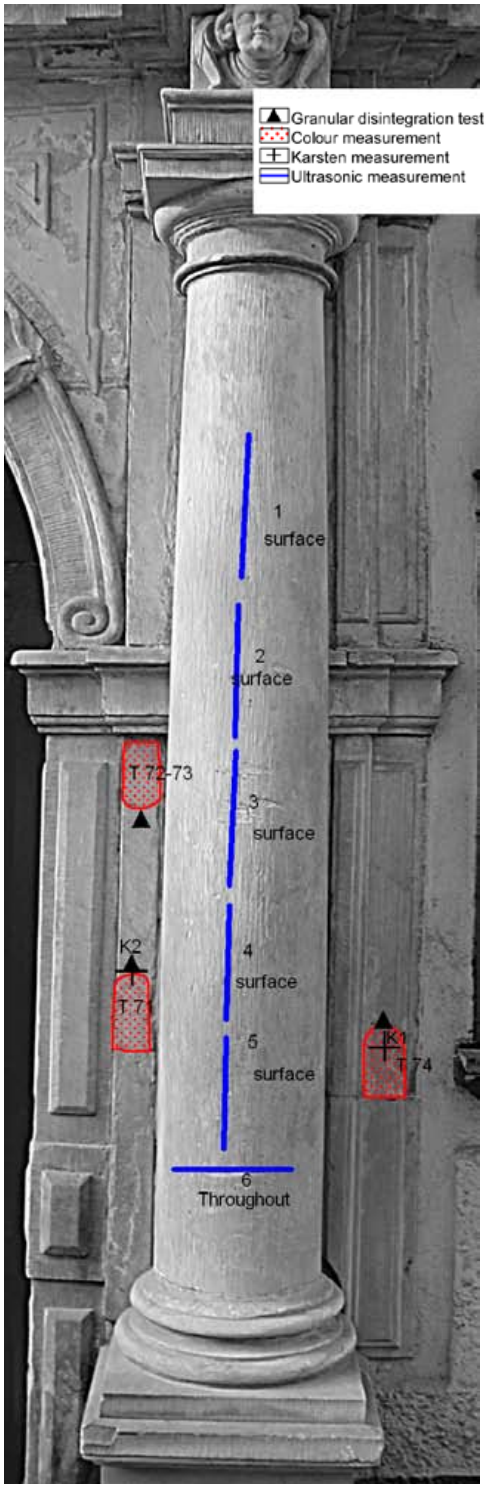


Figure 42–43. The chosen area of investigation at Svartmangatan 6.

8. Results

8.1 Results from the Field Test

8.1.1 Water Absorption Test with Karsten Pipes

Both large and small Karsten pipes were tested by four different individuals in the field. The results demonstrate that both the small and the large Karsten pipes are interchangeable (the results were plotted on graphs showing time versus water absorption, where the water absorption was calculated to ml/cm², see Appendix 3). Depending on the day minor differences were registered between the measurements, although these were small and appeared to be random. It is possible that small variations in the measurements depend on the different weather conditions, small cracks in the stone and the dexterity of the different individuals. The small pipes were much easier to handle and thus preferred. The larger pipes sometimes fell off due to problems in sticking the pipes to the surface, especially on severely deteriorated stone. Using Karsten pipes on severely damaged Gotland sandstone is not therefore to be recommended. One important factor is that Gotland sandstone has a high absorption capacity and water absorption may be too rapid for the small pipe (it is standard to measure per hour). The choice of size is dependent on the location and the condition of the stone (for example, the small pipe can be used if the stone has a hydrophobic treatment).

The data obtained with the Karsten pipes can be presented in different ways. The choice of presentation depends on the reason *why* the measurement is being made, for instance, if one needs to know the condition of the stone or whether a hydrophobic treatment has been successful. Some of the possibilities are:

1 Graphical; in diagrams and graphs that demonstrate the correlation between water absorption (in ml/cm² or kg/m²) and time (in minutes or hours). The advantage of the graphs is that the entire progression of the absorption process is shown. For example, if it is linear and the water absorption suddenly breaks through a surface treatment the absorption will suddenly increase. One can also compare the curves to one and another to verify whether the absorption has changed after conservation. The drawback is that the graphs do not give a quantitative value of the absorption capacity of the stone, which makes the results more difficult to compare with other stones.

2 Quantitative; in a table that demonstrates how much water (kg) has been absorbed after 1 hour. Although it can be useful to know the absorption capacity, it doesn't necessarily help to understand the entire absorption process (see above).

3 Quantitative; in *w-* and *B-values*. The w-value measures the water absorption coefficient and the B-value the water penetration coefficient. It is possible to calculate the values from Karsten measurements with the help of a computer program developed by Dr. E. Wendler in Germany (see above). [42, 43] The w- and B-values are useful for understanding the properties as well as the condition of the stone. The values give an indication as to whether the stone has deteriorated (if the "normal" values of the stone are known). Moreover, the w- and B-values help to estimate the quantity of consolidation needed, as well as evaluate the efficiency and durability of conservation treatments. Despite this advantage the w- and B-values have one serious drawback, which is that they do not demonstrate *how* the water actually penetrates, since they are calculated by a series of mathematical approximations relating to the behaviour of water. [42] This was noted within this study and also observed by Österlund ten years previously. [32] For example, the water is sometimes absorbed close to the surface around the opening of the pipe rather than being absorbed into the stone in the shape of a torus as both Wendler and Snethlage assumed in their calculations. Furthermore, the calculations are based on the assumption of linear absorption until a certain level or breaking point is reached, when the absorption then starts to level out. In our measurements, on the other hand, water is sometimes absorbed in a series of leaps. The reason for this could be previous treatments or natural structures and cracks in the stone.

4 Quantitative in a *treatment efficiency index* (TEI). The TEI index helps to evaluate the efficiency and durability of a treatment and is useful in evaluating the extent of improvement in surface performances achieved by hydroprotective treatments, the effectiveness of treatments and for estimating an accurate point of time for re-treatment. [57] It does not, however, demonstrate the whole absorption process (see above).

8.1.2 Colour change with a Spectrophotometer

The Spectrophotometer is easy to use in the field and gives comparable results. The measurements are repeatable if the measurement location is properly marked. The change of colour can be caused by dirt, biological growth or chemical alterations in the material. Despite the fact that it is easy to use, the Spectrophotomer has serious drawbacks, especially when it is used outdoors on stones that have deteriorated in different ways. For example, the result varies according to the moisture content in the material, and black and biological growth crusts disturb the measurement. Hence, both the climatic conditions and moisture content have to be noted (not an easy task) as well as the condition of the stone. This means that only significant differences in colour can be taken into account. If the results are to be relied on, the method has to be combined with sampling that verifies that chemical changes really have occurred.

In the field tests, significant changes in colour on different measuring occasions have sometimes been detected – especially in the L* value (that measures lightness/darkness), as for instance, at Svartmangatan 6 and Stortorget 5 (they demonstrate 10–14 percent differences in L* value). These changes can only be explained by variations in the moisture content. For example, less moisture was present in the stone on the third measurement occasion and sometimes the L* values were higher (the stone was brighter), and sometimes lower (see Appendix 4)! There is no explanation for this inconsistency. The a* and b* values change less (they are within +/– 1) and the variations are thus negligible.

To summarise, before measuring with the Spectrophotometer in the field one has to measure the temperature of the stone and the moisture as well as take samples to verify the chemical reason for the colour change. This leads to the conclusion that the method is the least helpful of all the NDT methods tried within this study. There are simply too many uncertainties when analyzing the result. The method is probably most useful for monitoring re-soiling after cleaning, although this is also possible via a visual comparison of Munsell or NCS colour sticks.

8.1.3 Granular Disintegration Test with Herma Labels

A granular disintegration test was invented by the NHB and consists of prefabricated Herma labels being attached to the surface of the stones for a few seconds. The labels are thereafter folded and put into a sealed plastic bag and weighed. Initially a scheme based on calculation of the weight differences of the deposit was followed (see above). One problem was that the differences in weight were very small. The methodology was thus simplified and the label together with the deposits were weighed and compared instead. Three preliminary weathering categories for Gotland sandstone were created from the measurements (total weight of the label and deposits). The differences between the categories are still very small and this might be a problem. The differences in weights ranged from 0,114g to 0,151g, where the main part weighed between 0.117 and 0.119 g (see Appendix 5).

The preliminary categories are:

1 Severely weathered = >0.120 g
2 Medium weathered = 0.118 g–0.120 g
3 Good condition = 0.114 g–0.117 g

The material removed from the surface can either be dirt, biological growth or deteriorated stone material. In order to be certain about what has actually been removed an examination of the labels under a microscope is recommended. It was not possible to do this in the context of this project due to the limits of time. Despite this it is clear that the test gives an indication of how much the stone has deteriorated and can be used in conjunction with other methods. However, if the test is to become "standard", further analysis is necessary. For example, the size of the label would seem be too small since the differences in weight are too small. The test furthermore needs to be compared on artificially weathered stone in the laboratory using, for example, UPV and the Karsten measurements.

8.1.4. Ultrasonic Pulse Velocity (UPV) measurements

Field tests with the UPV instrument generally show relatively stable values, even though the measurements were taken on different occasions. Small variations in measurement can be explained by variations in humidity, although this relation is not completely clear (the UPV do not follow the changes in moisture proportionally). The reason could be that the changes in moisture were too small. Other explanations might be that it is difficult to re-measure the same area in the field. The results confirm that there are differences between the indirect and the direct measurements (see below). The indirect measurements have slightly lower UPV (with differences up to 0.8 km/s on the same stone).

The worst deteriorated stone and the lowest UPV were found at the German Church (the mean value being 1.7 +/– 0.1 km/s with the lowest value of 1.2 km/s, and fresh Gotland sandstone has a value of ca 2.6–2.8 km/s). The UPV ranged from 1.2 km/s – 3.1 km/s – although most of the values were between 1.9 km/s – 2.3 km/s, which indicates that many of the stones are in good condition. The results facilitated the construction of a preliminary condition index of Gotland sandstone (see Appendix 6):

1 Good condition: over 2 km/s
2 Intermediate condition: between 1.7 km/s and 2 km/s
3 Poor condition: below 1.7 km/s

The index is to be regarded as preliminary as it needs to be established in the laboratory by correlating the UPV to the compressive strength and porosity of the stone. It would

then be possible to achieve something similar to the Köhler index of Carrarra marble [33] for Gotland sandstone, although the natural variations in the stone might be too great. The field tests demonstrate that it is important to know the history of the treatments in order to understand the results. One example of this is the interpretation of one of the highest UPV values found in this study, at Skeppsbron 21/Brunnsgränd 1. The measurements were indirect and thus only on the surface. It is assumed that the high values reflect the fact that the surface has been treated with an anti-graffiti substance. Hence, it is the surface treatment that has been measured.

Some tests designed to correlate the UPV with Karsten pipes and the age of the stone were also conducted by Katarina Malaga (see her report in Appendix 10). Even though some difficulties were encountered in correlating the Karsten pipes and the UPV, the overall measurements proved that when the UPV is low, the water absorption with the Karsten measurement is high. The correlation between the age and the UPV was also problematic, but despite this there was a clear indication of deterioration with time; the natural decrease in the UPV was calculated to be ca 0.3 km/s per 100 years. This must be confirmed by laboratory studies of natural weathered stone, however.

To summarise, before measuring the UPV it is important to note:

1 Whether the measurement is *indirect* or *direct*
2 The *moisture content*
3 The *direction* of the bedding plane
4 The *presence of salts*.

These parameters must therefore be taken into account during an evaluation of the result, even though some of these parameters may be difficult to establish in the field. For example, lamination is not very easy to detect and yet, despite this, UPV provides a good way of understanding the weathering and condition of the stone. There are indications in the literature that other acoustic parameters, such as energy, count duration and the regression of amplitude, are less irregular to understand deterioration of stone than the UPV, although this has not been evaluated within this particular study. [58]

8.2 Results of the Laboratory Studies

8.2.1 Variation of Ultrasound Pulse Velocity (UPV) due to change of relative humidity of Gotland sandstone

A laboratory test programme was designed for Gotland sandstone in order to relate the ultrasound pulse velocity (UPV) measurements taken in the field to tests in a controlled laboratory environment (see Appendix 7). The aim of the test was to analyze how the UPV varies with changes in the relative humidity. Six samples of Gotland sandstone from the Valar quarry were examined. First of all some properties of the stone were examined: the water absorption (which was 5 percent by weight according to water absorption test EN 13755:2002, which is quite low for Gotland sandstone), the density (2210 kg/m^3) the compressive strength both parallel to the lamination (61 MPa) and perpendicular to the lamination (85 MPa). These properties can be related to the UPV measurements.

The UPV measurements demonstrated that the samples have a detectable lamination and that there is a difference between the totally dry and totally wet samples; the values ranged from 2.1 km/s to 2.7 km/s. The UPV changed depending on a moisture content of between 0.3 and 0.5 km/s. The UPV was surprisingly lower for the water saturated stones. This is contradictory to former results, such as Rehn (the UPV of Gotland sandstone ranged from 2.2 km/s to 2.5 km/s, when the stones were saturated with water the velocity was 2.6 km/s, impregnated with alcoxysilane, 3.2 km/s and when the impregnated stones were saturated with water, 3.4 km/s. [38] The result complicates the interpretation of the UPV measurements. The UPV of water is 1500 m/s, of air 330 m/s and in stone can be up to 6000 m/s. This implies that stone with a high porosity (with a lot of pores filled with air) has a low UPV and that the UPV should be higher when the air is replaced by water. This was not the case in this laboratory test however. The phenomenon of the UPV being lower when the stone is saturated with water has also been noted on other stones. There are suggestions that this is caused by the disintegration of cementation products inside the stone as a result of the increased amount of water. This is obviously something that needs to be evaluated further.

It is not clear to what extent the UPV depends on the dimensions of the stone. There is, however, a difference in the UPV between the direct and indirect measurements and, interestingly, an increase in the difference of the UPV depending on the dimension when the samples were saturated with water. The indirect measurements generally demonstrate a slightly lower UPV than the direct measurements.

To conclude, the laboratory tests confirmed that UPV measurements are conditioned by:

1 The position of the measurement in relation to the bedding of the stone
2 The moisture content of the stone
3 Whether the measurement is indirect or direct
4 The porosity of the stone.

These parameters must be taken into consideration when taking UPV measurements in the field.

8.2.2 Variation of colorimetric measurements with a Minolta Spectrophotometer due to heat, cold and moisture content on Gotland sandstone

Three stones with the dimensions 10 x 10 x 10 cm from a quarry close to Burgsvik and quarried by Kettelvik's Stone Museum were measured with a Minolta Spectrophotom-

eter (see Appendix 8). The tests were conducted according to variations in:

1 Temperature (ca 25 °C to 70 °C)
2 Moisture, ranging from dry (after a week in an oven at 70 °C) to completely water saturated (the samples were immersed in water for 24 hours).

The result demonstrates that the spectrophotomer is sensitive to changes in humidity as well as in temperature. Temperatures around +/– 0 °C are especially sensitive – where the L* values changes a lot. One possible explanation is that the stone starts to absorb moisture from the air at this temperature and that this provokes colour change. Colour change due to moisture content is much greater than the change due to temperature (in the case of moisture the variations in colour ranged in L* values from 46 to 65, a* values from –1.18 to –0.87 and b* values from 5.08 to 4.38. Some colour changes were sometimes visible to the eye, such as changes resulting from variations in moisture content, while in other cases they were not visible at all, such as changes that depended on the variations in temperature. One interesting conclusion is that when it is influenced by heat the colour change appears to have a symmetrical behaviour that is not yet understood (See Appendix 8.2). Measuring colour with a spectrophotometer thus depends on both the moisture content and the temperature of the material being measured. Hence, the method should be used in the field in conditions that are similar if any comparisons are to be made; otherwise only significant changes could be taken into consideration. Special care must be taken after heavy rainfall and temperatures close to 0 °C.

8.2.3 Measurement of the w- and B-value of Gotland sandstone from the Valar quarry

A capillary suction standard test (DIN 52 617) was performed on Gotland sandstone to calculate the w- and B-values of the particular stone (see Appendix 9). Seven samples from two different beddings in the Valar quarry were measured. Hence only fresh stone from one quarry was tested. In order to gain an overall picture of the variations in the w- and B-values of Gotland sandstone, the test also has to be conducted on stones from other quarries and on weathered stone. Wessman and Myrin made similar water absorption tests on Gotland sandstone with an EN norm (EN 13755:2002), although they did not calculate the w- och B-values. Their results therefore only give graphic results. [8, 10]

The results (the mean values) were as follows: porosity 11.49–11.6 percent, bulk density 2.22–2.25 g/cm^3, true density 2.54–2.5 g/cm^3 , w-value 5.9 kg/m$^2\sqrt{}$h (5.84–5.97 kg/m$^2\sqrt{}$h) and B-value 0.45 mm$\sqrt{}$s (0.42–0.48 mm$\sqrt{}$s). The result indicates that Gotland sandstone (i.e. from the Valar quarry) has a relatively high water absorption capacity as well as a high water penetration capacity.

9. Discussion

9.1 Problems and Trends

Today, very few conservator–restorers use NDT methods in Sweden. The main reason for this is that the conservation process isn't customised for profound pre-investigations in that there are no standard conservation processes or official requirements for testing the stone before and after treatment. Additionally, professionals sometimes mistrust the NDT methods, and some of the instruments are too expensive and difficult to access. Pre-investigations usually consist of brief descriptions of the condition based on visual and tactile inspections. The impressions are sometimes mapped on drawings and photographed, and sometimes the presence of salts is evaluated and Karsten pipe measurements performed. The condition of the stone is rarely analyzed further. This leads to a situation where the conservator–restorer has to solve delicate conservation problems on-site; the decision often being based on tactile/visual inspection and experience. Pre-investigations of stone materials and conditions with a view to establishing suitable types of conservation materials and methods are therefore rare. The conservator–restorers have to rely on generally accepted methods, especially when it comes to dealing with Gotland sandstone. Such "solve the problem as it occurs" conservations are very hard to evaluate afterwards since data relating to both the condition and materials is lacking. The conservation reports are furthermore not sufficiently detailed. The conservator–restorer seldom maps the conservation treatments in detail and often omits important information, such as climatic conditions during treatment. The chosen methods and materials are thus not explained in detail and the treatments are not mapped on drawings. This is crucial if the results are to be interpreted correctly.

Tabasso's idea of creating a "zero point" using NDT methods is necessary to an efficient evaluation of stone conservations as the chosen areas can easily be followed up. The NHB is currently striving to implement a "standard conservation process" for stone and mural painting conservation (the methodology can be used for other materials in architectural conservation as well), that is intended to improve the situation. There is moreover a need for the NHB to support conservator–restorers with clear methodology and access to the necessary instruments. In other words, the use of NDT methods is seen as a natural part of the conservation process and thus something to be actively promoted and supported.

All this has led to the conclusion that so far it has been hard to find sufficient information to formulate any conclusions about previous conservation of stone in Sweden. Even though there has been an increased emphasis on and significant improvements in the conservation documentation, there is still a lack of detailed information. In addition, previous evaluations have not been able to reach any definite conclusions.

Even though NDT methods have many advantages, several problems have been encountered when using them in the field. One problem relates to knowledge about the moisture content in the stone. This is important since it influences the results of several of the instruments. The electrical principles on which most of the portable NDT instruments are based are disturbed by the presence of salts and moreover only measure a few millimetres into the material. Both the UPV and the influence of the presence of salt have not yet been sufficiently evaluated, and contradictory results have been recorded when it comes to water content and UPV on Gotland sandstone. The granular disintegration test also needs further testing, particularly in the laboratory tests.

In summary form, some of the main problems to be solved include:

1 How to analyze the salt situation and properly relate it to moisture and UPV measurements
2 How to measure the moisture content correctly with NDT methods. Improved methods are necessary
3 How to adjust the conservation process to include NDT methods
4 How some expensive instruments can become easier to access for the conservator–restorer, such as the UPV and Spectrophotometer
5 Further development of the granular disintegration test, or similar tests such as rubbing tests, is necessary
6 Further correlations between the methods are needed, which includes laboratory testing
7 Weathering characteristics of Gotland sandstone and NDT methods have to be analyzed further in the laboratory.

Despite these problems, however, it is clear that NDT methods will continue to be developed and used by scientific conservators and conservator–restorers all over the world. It is envisaged that this will lead to better and more efficient conservations. But on a daily basis it is still difficult for the conservator–restorer to gain access to the instruments, which

is why in this project we have tried to choose instruments that can be used in the field and are relatively easy to find. It is hoped that this project will provide one more step on the way to a more consistent use of the methods.

In her PhD work, Malin Myrin has proved that NDT methods are necessary to an understanding of the condition of the stone – especially the UPV method. She found, for example, that the surface may demonstrate deterioration by sanding while the interior might be in good shape, and vice versa. It is therefore necessary to understand how much the stone has deteriorated by using different NDT methods. [50]

9.2 Further Research

- Test of NDT methods that measure the moisture content without being disturbed by salts (for example, the portable microwave instrument and the neutron instrument)
- Test of the UPV and artificially weathered Gotland sandstone in the laboratory (with and without salts)
- Test of the correlation between the UPV and Karsten pipes, as well as the age and UPV in the laboratory on deteriorated Gotland sandstone (where the age is known)
- Determination of a classification index of weathered Gotland sandstone and UPV in the laboratory (similar to the Köhler system). The tests should be based on an empirically derived correlated function between the UPV and the V_p (the velocity of the P-waves) and the porosity and compressive strength of the stone
- Further statistical analysis of correlations can be undertaken from the data contained in this study. Examples include correlations between the colour and Karsten pipes.
- Further testing of the granular disintegration test on weathered stone in the laboratory. This might include the use of larger labels. Correlations between the method, the UPV and Karsten measurements are also advisable
- Rubbing tests and profilometric methods on deteriorated stone can also be tested in the laboratory and analyzed
- Further analysis of the w- and B-value of Gotland sandstone depending on deterioration and conservation treatment.

10. Notes

1. The feld tests were conducted by Dr. Katarina Malaga, SP, conservator Hélène Svahn, conservator Ragnhild Claesson, conservator Misa Asp and Dr. Runo Löfvendahl, the National Heritage Board (NHB).
2. The first test was undertaken by Dr. Katarina Malaga at SP in Borås and the second and third by the Conservators Hélène Svahn and Ragnhild Claesson, assisted by Dr. Runo Löfvendahl at the National Heritage Board's (NHB) stone atelier in Stockholm.
3. A preliminary report from Katarina Malaga is included within this report as Appendix 10. The report discusses the result of the UPV field tests, including an attempt to compare the UPV versus the Karsten measurements.
4. According to ECCO and ICOM-CC, professional conservationists are referred to as the conservator–restorer. This description has also been chosen for this study, since it is widely accepted. ICOM-CC: The activity of the Conservator–Restorer. The activity of the conservator–restorer (conservation) consists of technical examination, preservation, and conservation–restoration of cultural property: Examination is the preliminary procedure taken to determine the documentary significance of an artifact, original structure and materials, the extent of its deterioration, alteration, and loss and the documentation of these findings. Preservation is action taken to retard or prevent deterioration of or damage to cultural properties by control of their environment and/or treatment of their structure in order to maintain them as nearly as possible in an unchanging state. Restoration is action taken to make a deteriorated or damaged artefact understandable, with minimal sacrifice of aesthetic and historic integrity. http://icom.cc.icom.museum/About/DefinitionOfProfession/
5. Gotland sandstone was chosen because the stone is Sweden's major sculptural stone. In the last 20 years it has also been the most frequently conserved stone in Sweden. Quality stone extracted from the upper sections of the Valar quarry in Gotland has been chosen.
6. People that have been consulted are: Dr. Rolf Snethlage and Dr. Mathias Kocher, Conservation Scientists at Centrallabor at Bayerisches Landesamt für Denkmalpflege, München, Germany, Dr. Stefan Brüggerhoff, Conservation Scientist at Preservation of Cultural Heritage / Material Science, Deutsches Bergbau-Museum, Bochum, Germany, Dr. Stefan Simon, Conservation Scientist at Rathgen-Forschungslabor at Staatlische museum zu Berlin, Germany (he has recently worked at Getty's Conservation Institute, Los Angeles, USA), Dr. George Wheeler, Professor, Stone Conservator and Conservation Scientist at Columbia University, New York, USA, Dr. Marisa Laurenzi Tabasso, Private Consultant and Conservation Scientist specializing in Stone Conservation, Rome, Italy, Dr. Piero Tiano and Dr. Susanna Bracci, both Conservation Scientists at ICVBC-CNR, Florence, Italy, Dr. Susan Bradley, Conservation Scientist at the British Museum, London, Great Britain, Dr. Jadwiga Lukaszewicz, Professor and Conservation Scientist at Nicolaus Copernicus University, Torun, Poland, Dr. Daniel Kwiatowski, Conservation Scientist and Stone Conservator and Dr. Malin Myrin at Stenkonservatorn Skanska, Sweden, Stone Conservator Jarema Bielawski, JWB ARK & ART, Sweden, Stone Conservator Svante Nilsson, Prolithos Stone Conservation, Sweden, PhD candidate Jenny Hällström, Lund Institute of Technology, Lund University, Department of Architectural Conservation & Restoration, Dr. Anders Bodare, Royal Institute of Technology Stockholm, Sweden, Dr. Klaus Rapp, Munich, Germany.
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56. The southern portal has been subjected to different treatments. It was heavily restored by the artist Per Wallentin in 1911. For example, the figure "Faith" was replaced by a copy. The next restoration of the southern portal was conducted in 1929 under the surveillance of the architect Lejonhufvud. The stone was

cleaned with water and brushes and conserved with warm Ceresin and Tetra Cole Chloride applied to the dry stone. New restoration and mending with different mortars and oil paint was conducted in 1940. In 1970–1972 oil paint on the southern portal was removed with paint stripper by the sculptor Sibbern and conservator Barkman. This time the sculptures on the upper part of the portal were sent to a stone company based in Norsborg to make casts for copies. Today the figures on the upper part of the portal are of newly cast stone.

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Appendices

Appendix 1

Manual for Evaluation of Stone Conservation Treatments in the Field

This instruction manual is intended to help the conservator-restorer to evaluate conservations of highly significant stone objects using NDT methods. The manual provides an overall structure for how to plan the evaluation process before, during and after conservation. The complete methodology of each instrument is not explained here, however, most of this information can be found elsewhere in this report or in Report I. The choice of NDT methods in each project depends on the object and the planned conservation treatments. In general it is vital for the evaluations that quantitative data is gathered before and after conservation and that the data can be followed up in a precise area. Obviously this quantitative data has to be complemented with tactile and visual inspections. All the gathered information must be mapped on drawings or photographs in a scale between 1:5 to 1:10. Moreover, it is important to leave an untreated reference area.

Step 1. Before Conservation

1 Choose the NDT methods to be used; the minimum being moisture, salt content analysis and water absorption measurements with Karsten pipes.
2 Choose the location/locations, the "zero point", and where the measurements are going to be made. The location must be representative and possible to access. Mark the position of the untreated reference area.
3 Locate the investigation areas on drawings or photographs.
4 Inspect the investigation areas, identify the stone, look for the bedding planes and consider how the measurements are to be made. Decide on the exact measurement areas and mark them on the stone with a pencil in such a way that it will be possible to return to exactly the same spot.
5 If salts are present, analyse the quantity using the Löfvendahl or Borelli methods (see Report I). Present the conductivity in µS/cm². The result has to be followed up with a qualitative analysis of the salts if the conductivity is above 100–300 µS/cm².

Step 2. On the Investigation Day Before and After Conservation

Methods That Are Always Necessary

1 Measure the air temperature, the RH and note the climatic conditions.
2 Measure the moisture content in the stone with a portable instrument. If the instrument is based on the electrical principle it is important to know that the results are only relative. Other NDT methods for measuring moisture content are mentioned in Report I, although these methods have not yet been tested by the NHB. Another possibility is to take core samples and evaluate the actual moisture content. This is a destructive method and cannot always be used.
3 Measure the water absorption with the Karsten pipe. The water absorption measurement should be made in the course of one hour. Use a small pipe if it is possible (4 ml). If the absorption is too rapid for the small pipe, use the larger pipes instead (10 ml). Present the data on a graph or in w- and B-values (see Reports I and II).
4 If salt was present at the beginning, measure the salt content with the Löfvendahl or Borelli methods after conservation (see Report I).

Optional Methods

5 Measure the UPV – both direct and indirect. Present the results in m/s or km/s.
6 If you need to follow up colour change after a treatment (such as a hydrophobic or consolidation treatment) or if you wish to follow up a cleaning operation to see how quickly the material is re-soiled, measure the colour with a Spectrophotomer. Present the data in tables. This method depends on a variety of circumstances, such as the presence of biological growth, and is therefore the least reliable.

Potential Methods That Have Not Yet Been Sufficiently Analysed

7 The granular disintegration test needs to be further analysed if it is to become "standard". Other methods might also be tested, such as the profilometric method or a rub-

bing test. These methods have not yet been tested by the NHB.

Step 3. Evaluation of the Treatment

After a period of two years the conservation can be evaluated by measuring the exact area again with the chosen methods. The measurement is thereafter followed up according to a prefixed plan depending on the object and the treatment, for example, every second or third year.

Appendix 2

Result of the TRAMEX Moisture Measurement

Slottsbacken 6

Measurement	K1	K2
August 2005	3.7	4.5
October 2005	3.9	5
May 2006	2.8	4

Strandvägen 45

Measurement	K1	K2
August 2005	2.3	2.3
October 2005	3.9	2.5
May 2006	1	1.5

Skeppargatan 82

Measurement	K1	K2
August 2005	3.2	3.2
October 2005	4	4.2
May 2006	2	2.2

Engelbrektsgatan 21

Measurement	K1	K2
August 2005	2.8	3.2
October 2005	3.5	3.7
May 2006	1	1

The Karolin Chapel

Measurement	K1	K2
August 2005	1	1.5
October 2005	1.8	2.4
May 2006	0.5	1

The Bernadotte Chapel

Measurement	K1	K2
August 2005	2.4	4
October 2005	3.2	4.4
May 2006	1	2.5

Skeppsbron 21/Brunnsgränd 1

Measurement	K1	K2
August 2005	2.1	2.6
October 2005	2.5	2.6
May 2006	X	X

The German Church

Measurement	K1	K2
August 2005	3.7	4.5
October 2005	3.9	5
May 2006	2.8	4

Narvavägen 30

Measurement	K1	K2
August 2005	2.9	2.9
October 2005	3.2	3.4
May 2006	1	1.5

The House of Generals

Measurement	K1	K2
August 2005	3.4	3.5
October 2005	3.8	3.9
May 2006	2.2	2.2

Strandvägen 7C

Measurement	K1	K2
August 2005	3.5	3.6
October 2005	3.2	4
May 2006	1	2

The Gustavian Chapel

Measurement	K1	K2
August 2005	4	4.7
October 2005	5.3	5.2
May 2006	4	3.5

Lilla Nygatan 2

Measurement	K1	K2
August 2005	3.5	4
October 2005	4	3.6
May 2006	1.8	2.5

Slottsbacken 6

Measurement	K1	K2
August 2005	4	4
October 2005	4.1	4.3
May 2006	2.5	2.5

Bollhusgränd 3A

Measurement	K1	K2
August 2005	above scale	above scale
October 2005	above scale	above scale
May 2006	3.5	3.4

Svartmangatan 6

Measurement	K1	K2
August 2005	above scale	above scale
October 2005	above scale	above scale
May 2006	4	4

Stortorget 5

Measurement	K1	K2
August 2005	4.4	5
October 2005	4	5.7
May 2006	2	3

Appendix 3

Result of Karsten Pipe Measurements

The tables demonstrate the measurement of time in minutes and the water absorption in ml/cm² obtained with the Karsten pipe on three occasions: August 25, 2005, October 12, 2005 and May 17, 2006. Both large and small pipes were used and the absorption was recalculated into ml/cm². The graphs demonstrate the water absorption in ml/cm² versus the time in minutes for all three occasions.

The German Church

August 2005

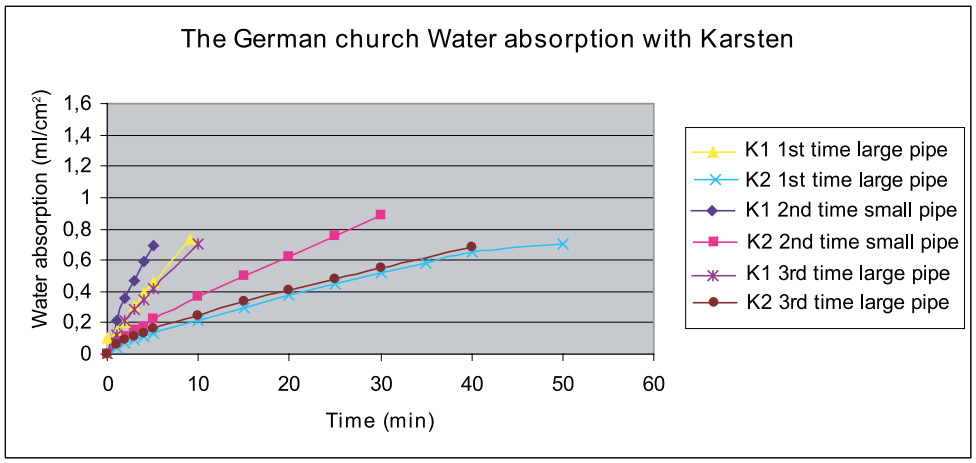
Karsten pipe measurement			
K1 large pipe		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.1	0	0
1	0.14	1	0.04
2	0.20	2	0.07
3	0.31	3	0.09
4	0.38	4	0.12
5	0.45	5	0.13
9.1	0.73	10	0.22
		15	0.30
		20	0.38
		25	0.45
		30	0.52
		35	0.58
		40	0.65
		50	0.71

October 2005

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0.21	1	0.07
2	0.35	2	0.11
3	0.46	3	0.15
4	0.59	4	0.18
5	0.70	5	0.22
10		10	0.36
		15	0.50
		20	0.62
		25	0.75
		30	0.88

May 2006

Karsten pipe measurement			
K1 large tube		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0.12	1	0.058
2	0.21	2	0.087
3	0.28	3	0.12
4	0.35	4	0.14
5	0.42	5	0.16
10	0.71	10	0.25
		15	0.33
		20	0.40
		25	0.48
		30	0.55
		40	0.69



Strandvägen 45

August 2005

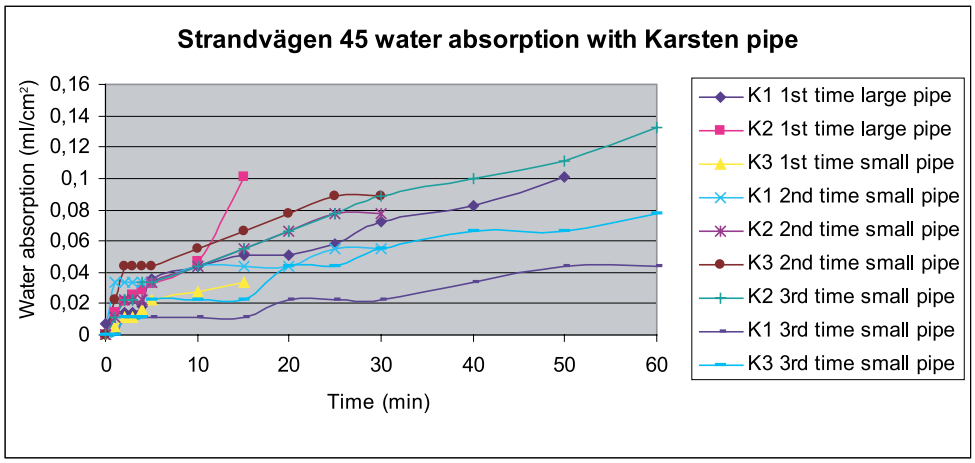
Karsten pipe measurement					
K1 large pipe		K2 large pipe		K3 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.5	0	0,2	0	0
1	0.01	1	0.01	1	0.01
2	0.01	2	0.02	2	0.01
3	0.01	3	0.03	3	0.01
4	0.01	4	0.03	4	0.02
5	0.02	5	0.03	5	0.02
10	0.04	10	0.05	10	0.03
15	0.04	15	0.10	15	0.03
20	0.05	20	leaking tube		
25	0.05	25			
30	0.06	30			
40	0.07	40			
50	0.08	50			
60	0.10	60			

October 2005

Karsten pipe measurement			Only small tubes		
K1 small pipe		K2 small pipe		K3 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.05	0	0	0	0
1	0.03	1	0.01	1	0.02
2	0.03	2	0.02	2	0.04
3	0.03	3	0.02	3	0.04
4	0.03	4	0.02	4	0.04
5	0.03	5	0.03	5	0.04
10	0.04	10	0.04	10	0.05
15	0.04	15	0.05	15	0.07
20	0.04	20	0.06	20	0.08
25	0.05	25	0.08	25	0.09
30	0.06	30	0.08	30	0.09

May 2006

Karsten pipe measurement					
K2 small pipe		K1 small pipe		K3 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0	0	0
1	0.01	1	0	1	0
2	0.02	2	0.01	2	0.01
3	0.02	3	0.01	3	0.01
4	0.03	4	0.01	4	0.01
5	0.03	5	0.01	5	0.02
10	0.04	10	0.01	10	0.02
15	0.06	15	0.01	15	0.02
20	0.07	20	0.02	20	0.04
25	0.08	25	0.02	25	0.04
30	0.09	30	0.02	30	0.06
40	0.10	40	0.03	40	0.07
50	0.11	50	0.04	50	0.07
60	0.13	60	0.04	60	0.08



Narvavägen 30

August 2005

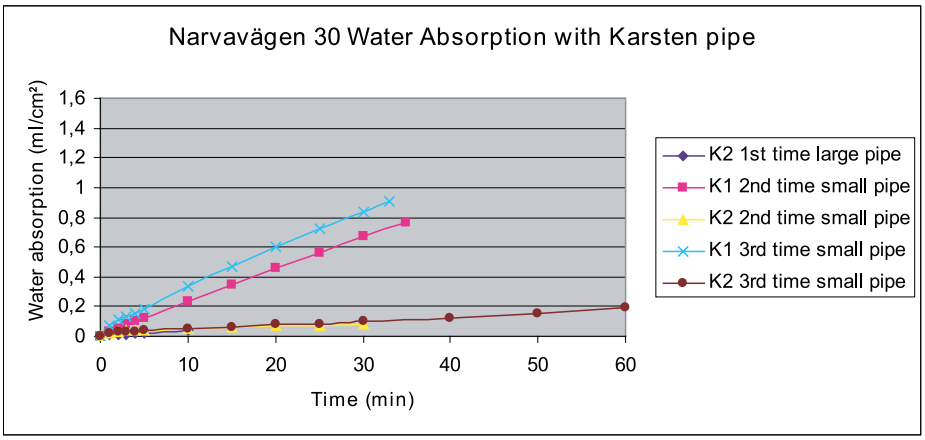
Karsten pipe measurement		
K2 large pipe		K1
Time (min)	Water absorption (ml/cm²)	Time (min)
0	-0.1	did not work
1	0.01	
2	001	
3	0.01	
4	0.02	
5	0.02	
10	0.04	
15		

October 2005

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	-0.05	0	0
1	0.03	1	0.02
2	0.06	2	0.03
3	0.08	3	0.04
4	0.10	4	0.04
5	0.13	5	0.04
10	0.24	10	0.05
15	0.35	15	0.06
20	0.45	20	0.07
25	0.56	25	0.07
30	0.65	30	0.08
35	0.77		

May 2006

Karsten pipe measurement			
K1 small pipe		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.1	0	0.15
1	0.07	1	0.02
2	0.11	2	0.03
3	0.13	3	0.03
4	0.15	4	0.03
5	0.19	5	0.04
10	0.31	10	0.05
15	0.46	15	0.06
20	0.60	20	0.08
25	0.72	25	0.09
30	0.84	30	0.10
33	0.91	40	0.13
40		50	0.15
50		60	0.19
60			



Skeppargatan 82

August 2005

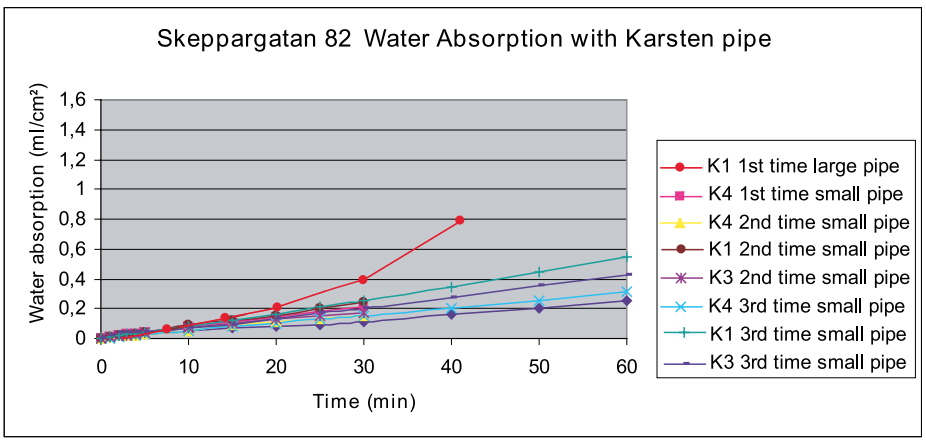
Karsten pipe measurement							
K1 large pipe		K2 large pipe		K3 large pipe		K4 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.2	0	0.5	0	0.3	0	0.35
1	0.01	1	0.01	1	0.01	1	0.01
2	0.01	2	0.02	2	0.02	2	0.02
3	0.02	3	0.04	3	0.02	3	0.03
4	0.02	4	0.05	4	0.02	4	0.03
5	0,03	5	0.065	5	0.03	5	0.04
10	0.09			10	0.05	10	0.08
15	0.15			15	0.07	15	0.11
20	0.28			20	0.08	20	0.14
25	0.46			25	0.09	25	0.18
30	0.58			30	0.12	30	0.21
40	0.77			40	0.16		
50				50	0.20		
60				60	0.25		

October 2005

K1 small pipe		K3 small pipe		K4 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0	0	0
1	0.01	1	0.01	1	0.01
2	0.02	2	0.02	2	0.02
3	0.02	3	0.02	3	0.02
4	0.03	4	0.03	4	0.02
5	0.04	5	0.04	5	0.03
10	0.09	10	0.07	10	0.05
15	0.12	15	0.10	15	0.09
20	0.15	20	0.13	20	0.11
25	0.20	25	0.15	25	0.13
30	0.24	30	0.18	30	0.15

May 2006

Karsten pipe measurement					
K1 small pipe		K3 small pipe		K4 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.05	0	0.5	0	0.3
1	0.01	1	0.02	1	0
2	0.02	2	0.04	2	0.01
3	0.03	3	0.04	3	0.02
4	0.03	4	0.04	4	0.02
5	0.04	5	0.04	5	0.03
10	0.08	10	0.07	10	0.05
15	0.12	15	0.09	15	0.08
20	0.16	20	0.13	20	0.10
25	0.21	25	0.18	25	0.13
30	0.25	30	0.20	30	0.15
40	0.34	40	0.28	40	0.20
50	0.44	50	0.36	50	0.25
60	0.54	60	0.42	60	0.31



The House of Generals

August 2005

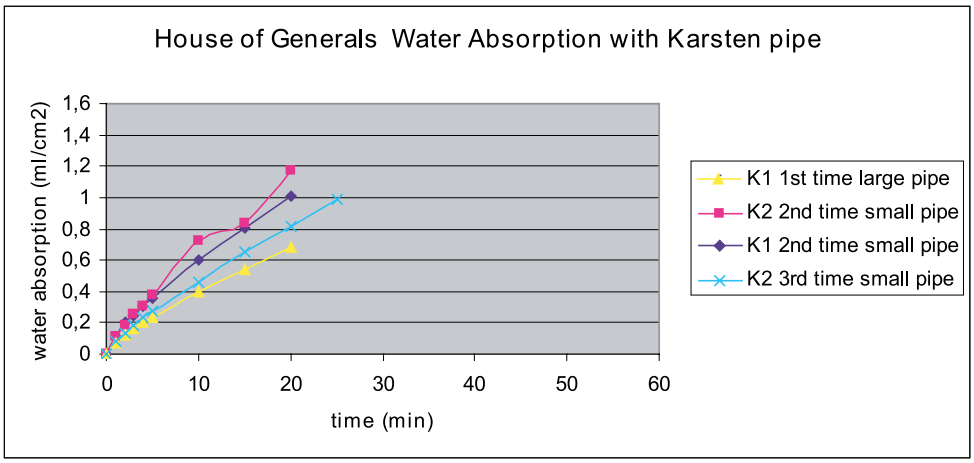
Karsten pipe measurement			
K1 large pipe		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	-0.2	0	did not work
1	0.07	1	
2	0.12	2	
3	0.17	3	
4	0.20	4	
5	0.24	5	
10	0.40	10	
15	0.54	15	
20	0.68	20	
		25	
		30	
		40	
		50	

October 2005

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.3	0	0.3
0	0	0	0
1	0.11	1	0.11
2	0.20	2	0.19
3	0.24	3	0.23
4	0.29	4	0.31
5	0.36	5	0.38
10	0.53	10	0.70
15	0.81	15	0.84
20	1.01	20	1.17
25		25	
30		30	
35		35	

May 2006

Karsten pipe measurement			
K1 large pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	did not work 0	0	0.25
1		1	0.08
2		2	0.13
3		3	0.19
4		4	0.23
5		5	0.28
10		10	0.45
15		15	0.65
20		20	0.82
25		25	0.98
30		30	
40		40	
50		50	
60		60	



Engelbrektsgatan 21

August 2005

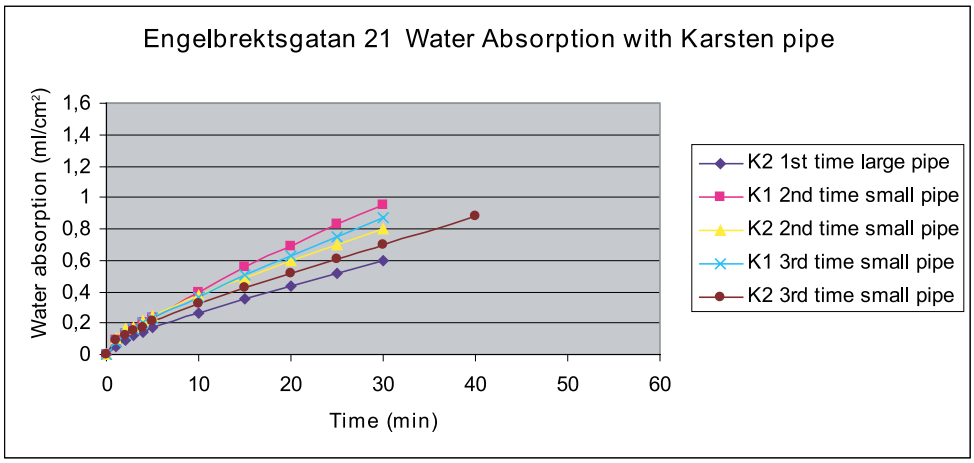
Karsten pipe measurement			
K1 large pipe		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	did not work	0	-0.1
1		1	0.05
2		2	0.09
3		3	0.12
4		4	0.14
5		5	0.17
10		10	0,27
15		15	0.35
20		20	0.44
25		25	0.52
30		30	0.60
40		40	
50		50	

October 2005

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.1	0	-0.1
0	0	0	0
1	0.09	1	0.10
2	0.13	2	0.17
3	0.17	3	0.18
4	0.20	4	0.21
5	0.23	5	0.24
10	0.40	10	0.38
15	0.55	15	0.49
20	0.69	20	0.60
25	0.83	25	0.70
30	0.95	30	0.80

May 2006

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0.08	1	0.09
2	0.13	2	0.12
3	0.16	3	0.15
4	0.20	4	0.18
5	0.23	5	0.21
10	0.36	10	0.32
15	0.51	15	0.42
20	0.63	20	0.52
25	0.75	25	0.61
30	0.87	30	0.70
40		40	0.90
50		50	
60		60	



Strandvägen 7C

August 2005

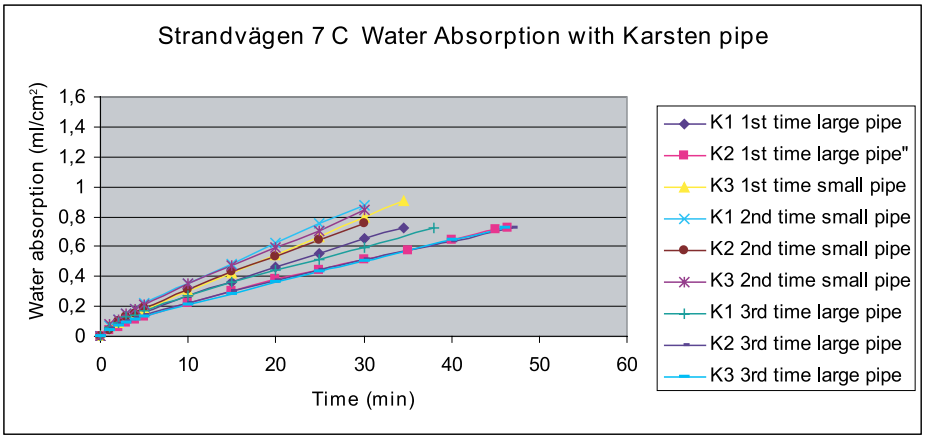
Karsten pipe measurement					
K1 large pipe		K2 large pipe		K3 small tube	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.1	0	0.1	0	0.1
1	0.05	1	0.04	1	0.07
2	0.08	2	0.06	2	0.09
3	0.11	3	0.09	3	X
4	0.13	4	0.11	4	0.15
5	0.16	5	0.13	5	0.18
10	0.27	10	0.22	10	0.30
15	0.36	15	0.30	15	0.42
20	0.46	20	0.38	20	0.54
25	0.56	25	0.44	25	0.66
30	0.65	30	0.51	30	0.80
34.5	0.73	35	0.58	34.5	0.91
		40	0.65		
		45	0.71		
		46.5	0.73		

October 2005

Karsten pipe measurement					
K1 small pipe		K2 small pipe		K3 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0	0	0
1	0.07	1	0.04	1	0.08
2	0.11	2	0.10	2	0.11
3	0.15	3	0.13	3	0.15
4	0.18	4	0.15	4	0.18
5	0.22	5	0.19	5	0.21
10	0.36	10	0.31	10	0.36
15	0.49	15	0.43	15	0.48
20	0.62	20	0.53	20	0.60
25	0.75	25	0.64	25	0.71
30	0.87	30	0.75	30	0.84

May 2006

Karsten pipe measurement					
K1 large pipe		K2 large pipe		K3 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0	0	0
1	0.06	1	0.05	1	0.04
2	0.09	2	0.08	2	0.07
3	0.13	3	0.10	3	0.09
4	0.14	4	0.12	4	0.11
5	0.17	5	0.14	5	0.13
10	0.27	10	0.22	10	0.21
15	0.36	15	0.30	15	0.28
20	0.44	20	0.37	20	0.36
25	0.52	25	0.44	25	0.43
30	0.60	30	0.51	30	0.50
38	0.72	40	0.64	40	0.64
50		47	0.72	46	0.72
60		60		60	



Riddarholm's Church: The Karolin Chapel

August 2005

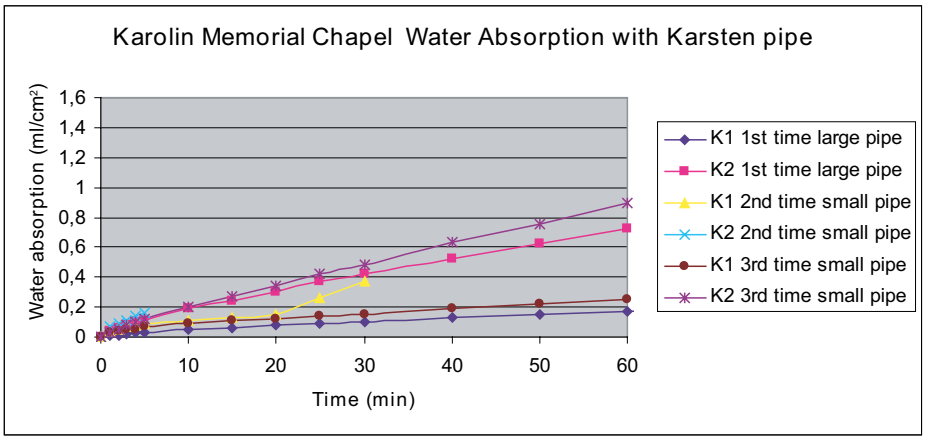
Karsten pipe measurement			
K1 large pipe		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.4	0	-0.2
1	0.01	1	0.04
2	0.01	2	0.06
3	0.02	3	0.08
4	0.03	4	0.10
5	0.03	5	0.11
10	0.05	10	0.19
15	0.06	15	0.25
20	0.08	20	0.30
25	0.09	25	0.37
30	0.10	30	0.42
40	0.13	40	0.53
50	0.15	50	0.62
60	0.17	60	0.72
70	0.19		

October 2005

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	-0.2	0	0.2
1	0.04	1	0.07
2	0.06	2	0.09
3	0.07	3	0.11
4	0.08	4	0.14
5	0.09	5	0.16
10	0.11	10	fell off
15	0.13	15	
20	0.15	20	
25	0.26	25	
30	0.38	30	

May 2006

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0.1
1	0.03	1	0.03
2	0.04	2	0.05
3	0.05	3	0.08
4	0.05	4	0.10
5	0.07	5	0.12
10	0.09	10	0.20
15	0.11	15	0.28
20	0.12	20	0.34
25	0.14	25	0.42
30	0.15	30	0.49
40	0.19	40	0.63
50	0.22	50	0.75
60	0.25	60	0.90



Riddarholm's Church: The Gustavian Chapel

August 2005

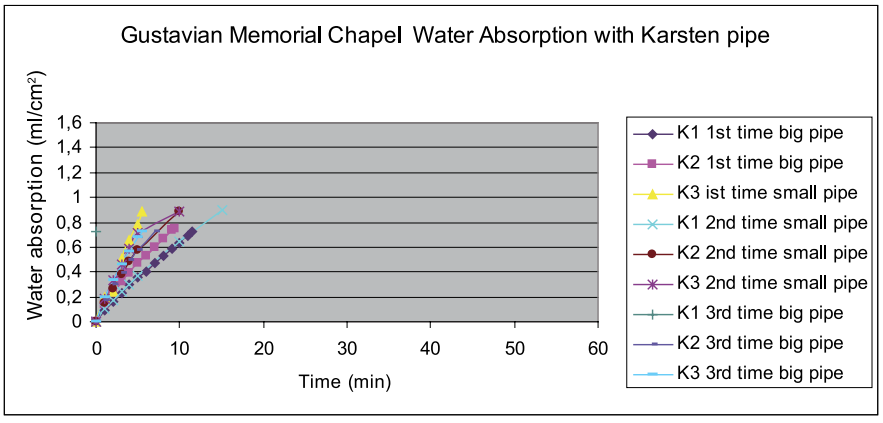
Karsten pipe measurement					
K1 large pipe		K2 large pipe		K3 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0.4	0	0
1	0.09	1	0.14	1	0.20
2	0.16	2	0.23	2	0.24
3	0.23	3	0.32	3	0.51
4	0.30	4	0.40	4	0.65
5	0.36	5	0.47	5	0.78
6	0.40	6	0.53	5,46	0.88
7	0.47	7	0.60		
8	0.53	8	0.67		
9	0.58	9	0.74		
10	0.63	9.5	0.75		
11	0.69				
11,45	0.72				

October 2005

Karsten pipe measurement					
K1small pipe		K2 small pipe		K3 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0	0	0
1	0.10	1	0.15	1	0.19
2	0.17	2	0.26	2	0.33
3	0.24	3	0.38	3	0.46
4	0.30	4	0.49	4	0.59
5	0.36	5	0.57	5	0.71
10	0.64	10	0.88	10	0.88
15	0.90	15		15	
20		20		20	
25		25		25	
30		30		30	

May 2006

Karsten pipe measurement					
K1 large pipe		K2 large pipe		K3 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0	0	0
1	0.19	1	0.17	1	0.20
2	0.32	2	0.30	2	0.34
3	0.44	3	0.40	3	0.45
4	0.55	4	0.50	4	0.56
5	0.65	5	0.57	5	0.68
5.47	0.72	10	0.72	10	0.72
15		15		15	
20		20		20	
25		25		25	
30		30		30	



Riddarholm's Church: The Bernadotte Chapel

August 2005

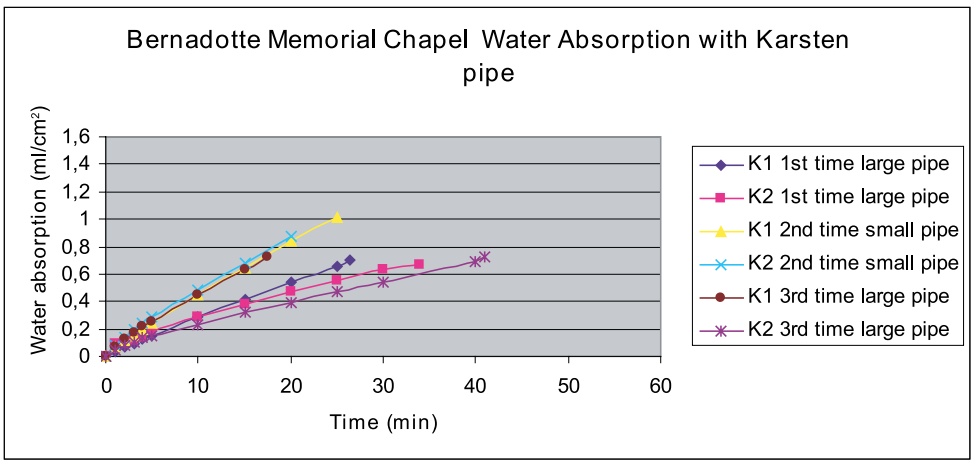
Karsten pipe measurement			
K1 large pipe		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.2	0	-0.3
1	0.03	1	0.09
2	0.07	2	0.10
3	0.10	3	0.12
4	0.12	4	0.14
5	0.15	5	0.18
10	0.29	10	0.29
15	0.42	15	0.38
20	0.54	20	0.47
25	0.66	25	0.55
26.4	0.70	30	0.63
40		34	0.67
50		35	
60		60	

October 2005

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.3	0	-0.3
1	0.07	1	0.08
2	0.11	2	0.14
3	0.15	3	0.20
4	0.20	4	0.24
5	0.24	5	0.29
10	0.45	10	0.49
15	0.64	15	0.68
20	0.84	20	0.87
25	1.02	25	
30		30	
40		40	
50		50	
60		60	

May 2006

Karsten pipe measurement			
K1 large pipe		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0.07	1	0.04
2	0.12	2	0.08
3	0.17	3	0.10
4	0.21	4	0.14
5	0.26	5	0.15
10	0.45	10	0.23
15	0.63	15	0.32
17.5	0.72	20	0.40
25		25	0.47
30		30	0.54
40		40	0.69
50		41	0.72
60		60	



Lilla Nygatan 2

August 2005

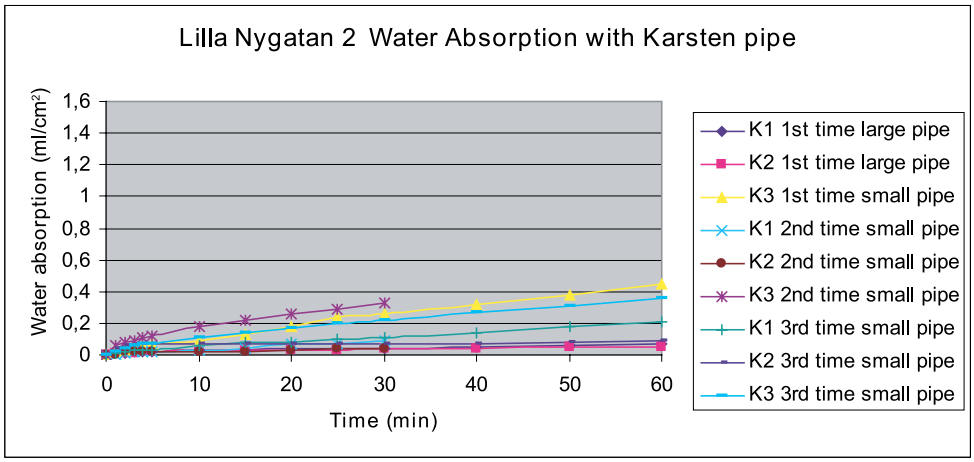
Karsten pipe measurement					
Tube K1		Tube K2		K3 small tube	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.3	0	0.3	0	0.3
1	0.01	1	0.01	1	0.02
2	0.01	2	0.01	2	0.03
3	0.02	3	0.01	3	0.04
4	0.02	4	0.02	4	0.05
5	0.02	5	0.02	5	0.07
10	0.03	10	0.03	10	0.09
15	0.03	15	0.03	15	0.13
20	0.04	20	0.03	20	0.18
25	0.04	25	0.03	25	0.24
30	0.04	30	0.04	30	0.25
40	0.05	40	0.04	40	0.32
50	0.06	50	0.04	50	0.38
60	0.06	60	0.05	60	0.44

October 2005

Karsten pipe measurement					
Tube K1		Tube K2		Tube K3	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0	0	0
1	0	1	0	1	0.05
2	0.01	2	0.02	2	0.07
3	0.02	3	0.02	3	0.08
4	0.02	4	0.02	4	0.11
5	0.02	5	0.02	5	0.12
10	0.03	10	0.02	10	0.18
15	0.04	15	0.02	15	0.22
20	0.07	20	0.03	20	0.25
25	0.07	25	0.04	25	0.29
30	0.09	30	0.04	30	0.33

May 2006

Karsten pipe measurement					
K1 small pipe		K2 small pipe		K3 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0	0	0
1	0.01	1	0.04	1	0.02
2	0.02	2	0.05	2	0.04
3	0.03	3	0.05	3	0.05
4	0.03	4	0.07	4	0.07
5	0.03	5	0.07	5	0.07
10	0.05	10	0.07	10	0.11
15	0.08	15	0.07	15	0.14
20	0.08	20	0.07	20	0.16
25	0.10	25	0.07	25	0.20
30	0.11	30	0.07	30	0.22
40	0.14	40	0.07	40	0.26
50	0.18	50	0.08	50	0.31
60	0.21	60	0.09	60	0.36



Skeppsbron 20/Brunnsgränd 1

August 2005

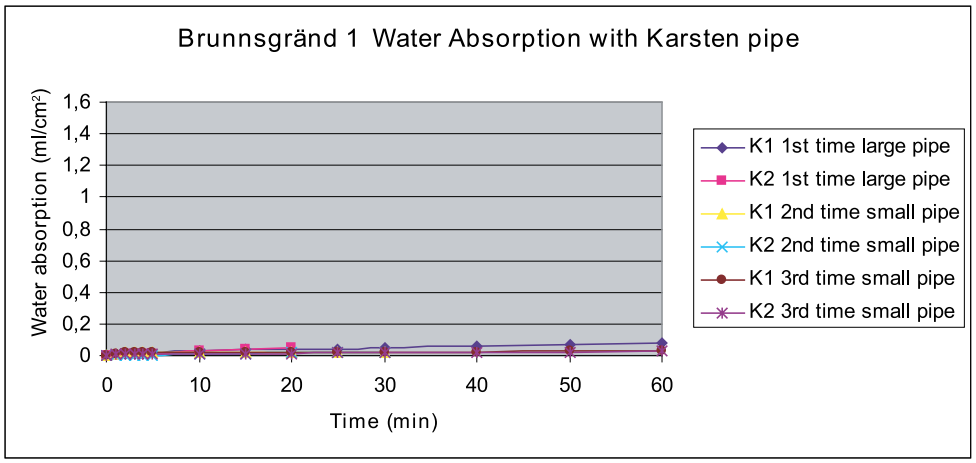
Karsten pipe measurement			
K1 large pipe		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.4	0	0.4
1	0.01	1	0.01
2	0.01	2	0.01
3	0.01	3	0.01
4	0.01	4	0.01
5	0.02	5	0.01
10	0.02	10	0.03
15	0.04	15	0.04
20	0.04	20	0.05
25	0.04	25	
30	0.05	30	
40	0.06	40	
50	0.07	50	
60	0.8	60	

October 2005

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.1	0	0.1
1	0.01	1	0
2	0.02	2	0
3	0.02	3	0
4	0.02	4	0
5	0.02	5	0.01
10	0.02	10	0.01
15	0.02	15	0.01
20	0.02	20	0.02
25	0.02	25	0.02
30	0.02	30	0.02

May 2006

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.1	0	0.2
1	0.01	1	0.01
2	0.02	2	0.01
3	0.02	3	0.01
4	0.02	4	0.01
5	0.02	5	0.01
10	0.02	10	0.01
15	0.02	15	0.01
20	0.02	20	0.01
25	0.02	25	0.02
30	0.02	30	0.02
40	0.02	40	0.02
50	0.03	50	0.02
60	0.03	60	0.03



Slottsbacken 6

August 2005

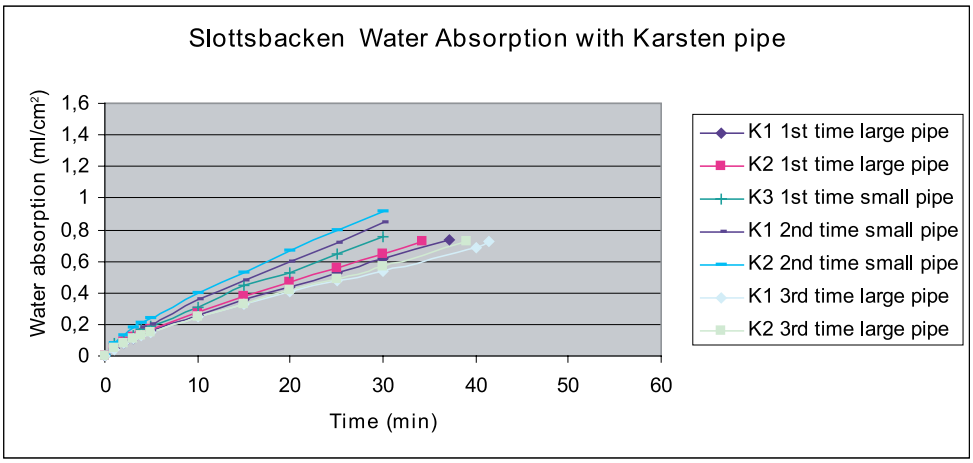
Karsten pipe measurement					
K1 large pipe		K2 large pipe		K3 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.2	0		0	0.15
1	0.05	1	0.05	1	0.08
2	0.08	2	0.09	2	0.10
3	0.11	3	0.11	3	0.13
4	0.14	4	0.14	4	0.17
5	0.16	5	0.17	5	0.19
10	0.26	10	0.27	10	0.31
15	0.35	15	0.37	15	0.44
20	0.44	20	0.47	20	0.53
25	0.53	25	0.56	25	0.64
30	0.61	30	0.64	30	0.75
37.1	0.74	34,2	0.72		
		50			

October 2005

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0.07	1	0.08
2	0.10	2	0.3
3	0.13	3	0.18
4	0.18	4	0.21
5	0.20	5	0.24
10	0.35	10	0.40
15	0.48	15	0.53
20	0.60	20	0.66
25	0.72	25	0.80
30	0.84	30	0.92

May 2006

Karsten pipe measurement			
K1 large pipe		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0.04	1	0.05
2	0.08	2	0.08
3	0.11	3	0.10
4	0.13	4	0.13
5	0.15	5	0.15
10	0.25	10	0.25
15	0.32	15	0.33
20	0.40	20	0.42
25	0.47	25	0.50
30	0.54	30	0.57
40	0.68	39	0.72
41,48	0.72		



Bollhusgränd 3A

August 2005

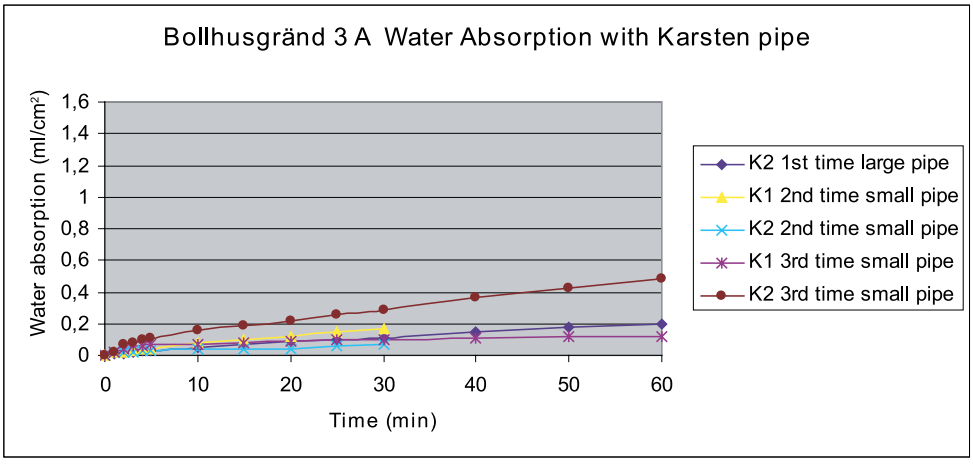
Karsten pipe measurement		
K2 large pipe		Tube K1
Time (min)	Water absorption (ml/cm²)	
0	-0.1	was not measured
1	0.01	
2	0.01	
3	0.02	
4	0.03	
5	0.03	
10	0.05	
15	0.07	
20	0.09	
25	0.10	
30	0.11	
40	0.14	
50	0.17	
60	0.20	

October 2005

Karsten pipe measurement			
K1 small pipe		K2 small pipe the water is dispersed irregularly on the surface.	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0.02	1	0.02
2	0.02	2	0.02
3	0.03	3	0.02
4	0.04	4	0.03
5	0.04	5	0.03
10	0.08	10	0.04
15	0.10	15	0.04
20	0.12	20	0.04
25	0.14	25	0.05
30	0.17	30	0.07

May 2006

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0.02	1	0.02
2	0.04	2	0.07
3	0.05	3	0.08
4	0.05	4	0.10
5	0.07	5	0.11
10	0.07	10	0.15
15	0.08	15	0.19
20	0.09	20	0.22
25	0.10	25	0.25
30	0.10	30	0.29
40	0.11	40	0.36
50	0.12	50	0.42
60	0.12	60	0.49



Stortorget 5

August 2005

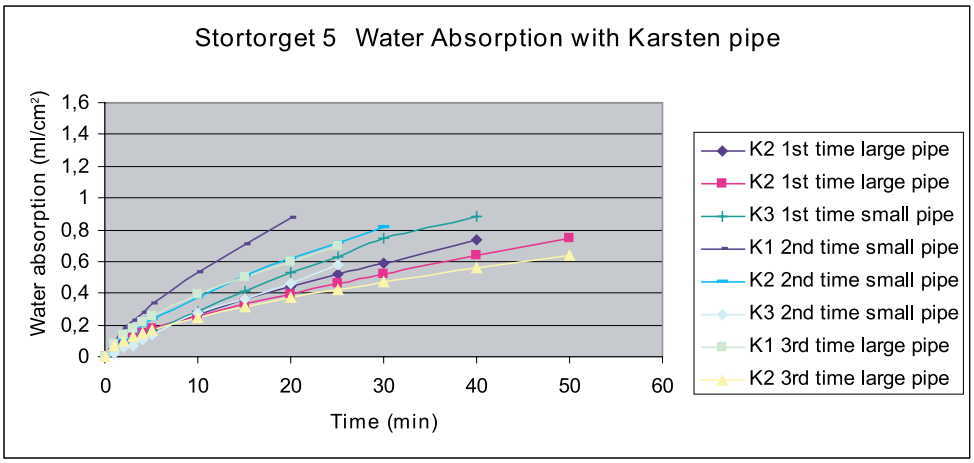
Karsten pipe measurement					
K1 large pipe		K2 large pipe		K3 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0.2	0	0.3	0	0
1	0.05	1	0.06	1	0.04
2	0.10	2	0.10	2	0.08
3	0.12	3	0.12	3	0.11
4	0.14	4	0.15	4	0.13
5	0.17	5	0.17	5	0.17
10	0.27	10	0.26	10	0.29
15	0.36	15	0.33	15	0.41
20	0.44	20	0.40	20	0.53
25	0.52	25	0.46	25	0.63
30	0.59	30	0.52	30	0.74
40	0.74	40	0.63	40	0.89
		50	0.74		

October 2005

Karsten pipe measurement					
K1 small pipe		K2 small pipe		K3 small pipe (moved 6 cm upwards after leaking)	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0	0	0
1	0.09	1	0.07	1	0.02
2	0.18	2	0.11	2	0.05
3	0.22	3	0.15	3	0.07
4	0.28	4	0.20	4	0.11
5	0.33	5	0.23	5	0.13
10	0.53	10	0.38	10	0.28
15	0.71	15	0.51	15	0.36
20	0,87	20	0,62	20	0,46
25		25	0,72	25	0,57
30		30	0,82	30	0,66

May 2006

Karsten pipe measurement			
K1 large pipe		K2 large pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0.08	1	0.06
2	0.14	2	0.10
3	0.18	3	0.13
4	0.22	4	0.14
5	0.25	5	0.17
10	0.40	10	0.25
15	0.51	15	0.31
20	0.60	20	0.38
25	0.69	25	0.43
30		30	0.47
40		40	0.56
50		50	0.64
60		60	0.71



Svartmangatan 6

August 2005

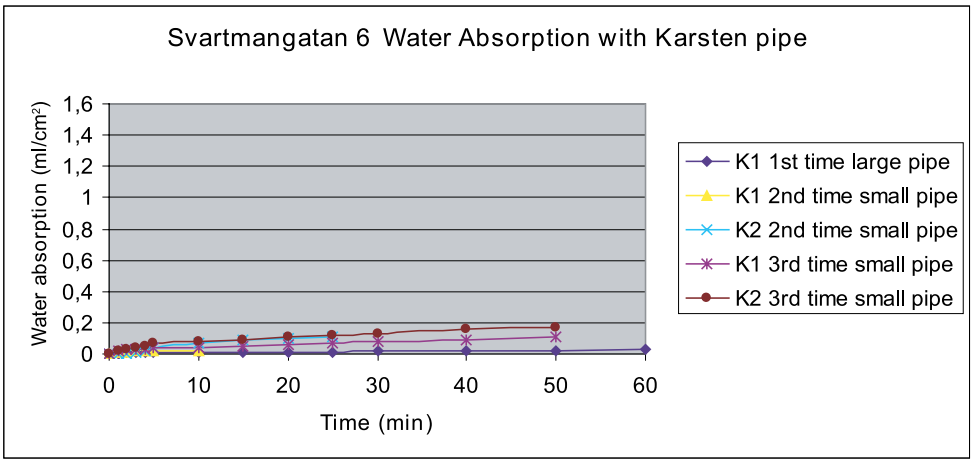
August 2005	K1 large pipe
Time (min)	Water absorption (ml/cm²)
0	-0.05
1	0.01
2	0.01
3	0.01
4	0.01
5	0.01
10	0.01
15	0.01
20	0.01
25	0.01
30	0.02
40	0.02
50	0.02
60	0.03

October 2005

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0	1	0
2	0.01	2	0
3	0.01	3	0
4	0.02	4	0.01
5	0.02	5	0.02
10	0.02	10	0.04
15	0.02	15	0.07
20		20	0.09
25		25	0.10
30		30	0.11

May 2006

Karsten pipe measurement			
K1 small pipe		K2 small pipe	
Time (min)	Water absorption (ml/cm²)	Time (min)	Water absorption (ml/cm²)
0	0	0	0
1	0	1	0
2	0.02	2	0.02
3	0.03	3	0.03
4	0.03	4	0.04
5	0.03	5	0.05
10	0.04	10	0.07
15	0.04	15	0.08
20	0.05	20	0.09
25	0.06	25	0.11
30	0.07	30	0.12
40	0.08	40	0.13
50	0.09	50	0.15
60	0.11	60	0.17



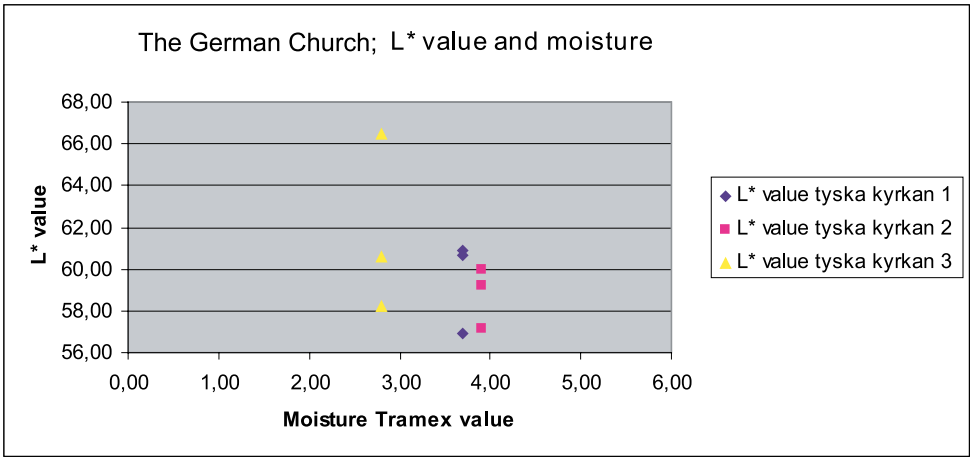
Appendix 4

Result of Colour Measurements in the Field

The measurements were taken on the same spots with a Minolta Spectrophotometer, a *Minolta CM-508i*, on three occasions over the period of a year. The tables demonstrate the values and the graphs plot the L* value against the moisture measurements with the Tramex moisture device. The moisture value in the graphs has been averaged for each measured occasion. The L* value was expected to be high when the moisture measurements were low and vice versa. This was not evident from the results and the reason for this has not yet been understood.

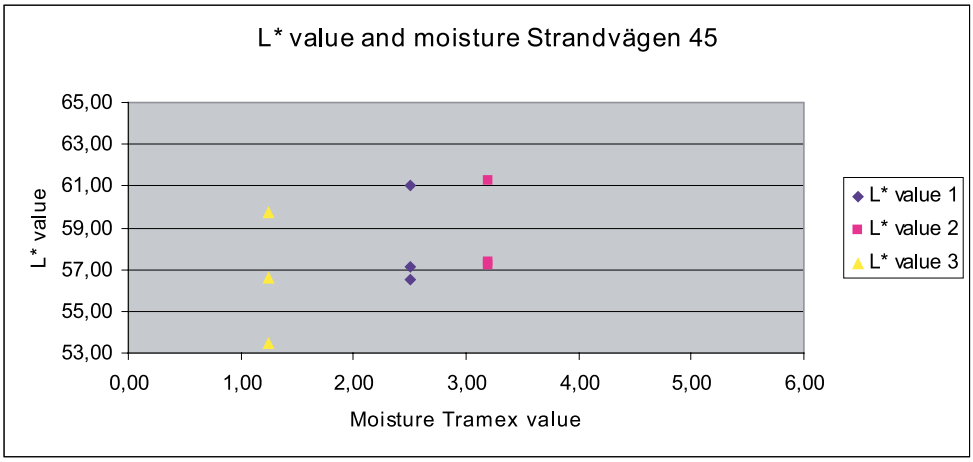
The German Church

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	devia-tion	L*	a*	b*	devia-tion	L*	a*	b*	devia-tion	L*	a*	b*
T 75/T 162/Sample 333	Right side of the chosen stone, grey colour in "good" condition.	0,4	60,86	1,83	13,96	1,01	59,24	1,87	14,3	0,86	60,58	1,79	14,17
T 76/T 149/Sample 332	Stone in "weathered" condition, sanding, grey with yellow iron marks.	0,53	56,95	4,54	21,42	0,33	57,14	4,7	21,9	0,29	58,2	4,53	21,77
T 78/T 150/Sample 335	Badly weathered stone, grey whitish.	0,89	60,64	-0,77	8,11	1,02	59,95	-0,69	8,81	0,99	66,44	-1,68	7,84



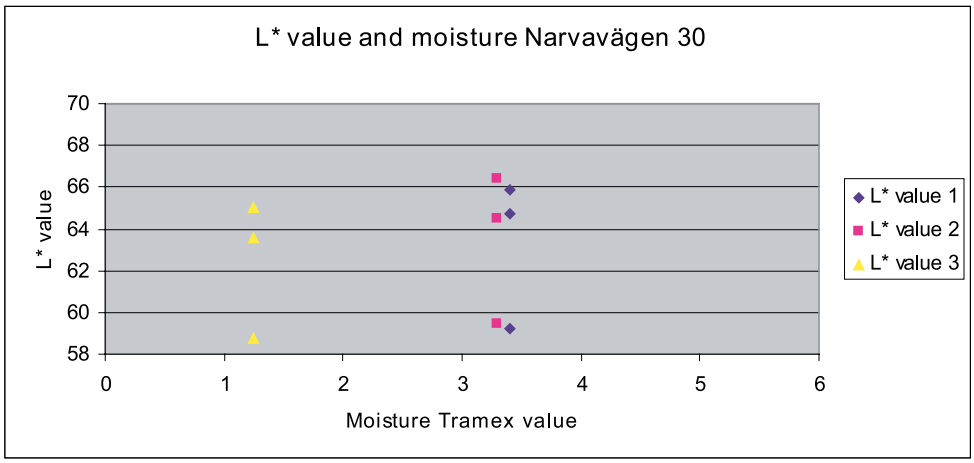
Strandvägen 45

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 26/99/Sample 284	Grey stone in good condition	2,89	56,75	2,7	15,54	0,68	58,05	2,83	16,09	X	X	X	X
T 27/T 100/Sample 283	Grey stone in good condition	1,74	56,55	2,7	15,52	1,63	57,17	2,79	15,95	0,7	56,6	2,73	16,07
T 28/T 101/Sample 284	Grey stone in good condition	0,45	57,13	3,02	14,32	0,13	57,36	3,02	14,36	0,57	53,49	2,92	13,95
T 29/T102/Sample 285	Grey stone in good condition	0,46	61,03	1,59	15,16	0,05	61,29	1,64	15,42	0,19	59,76	1,53	15,31



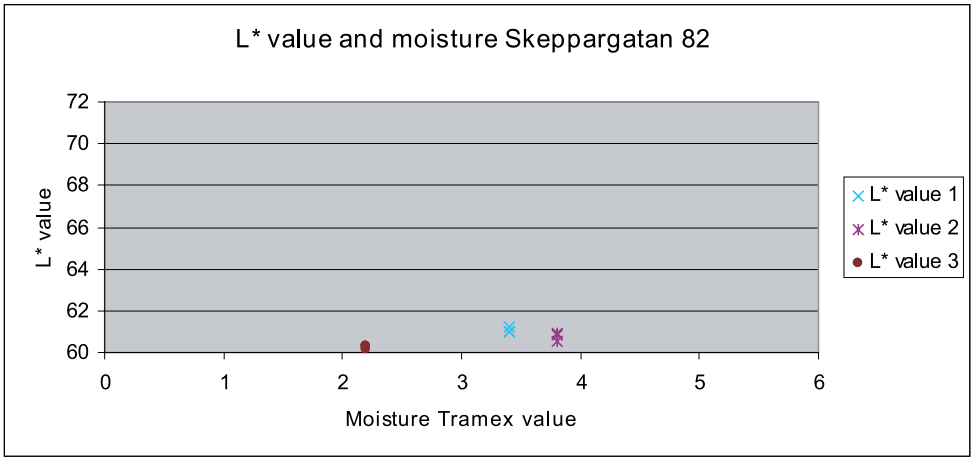
Narvavägen 30

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 30/T 104/Sample 286	Grey Gotland sandstone. Signs of deterioration: sanding and exfoliation. There are some shells and "fossils" in the stone.	0,21	64,69	2,06	16,55	0,06	64,51	2,03	16,63	0,42	63,57	2,05	16,45
T 31/T 105/Sample 287	Grey Gotland sandstone. Signs of deterioration: sanding and exfoliation.	0,73	65,9	1,72	15,35	0,56	66,41	1,74	15,31	0,15	65,07	1,69	15,09
T 32/T 106/Sample 288	Light grey Gotland sandstone. Signs of deterioration: sanding and exfoliation.	0,08	59,2	1,83	15,53	0,08	59,45	1,84	15,65	0,14	58,78	1,78	15,2



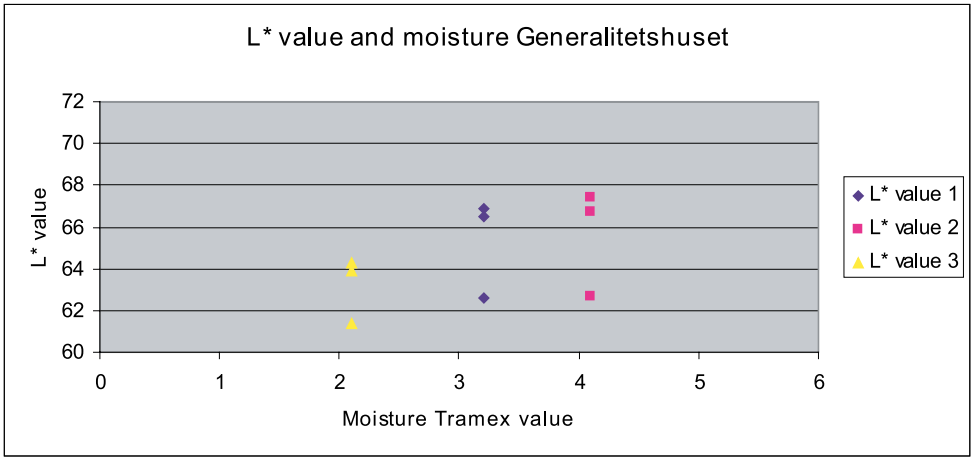
Skeppargatan 82

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 33/T 107/Sample 289	Grey Gotland sandstone	0,06	61	1,56	13,33	0,08	60,93	1,58	13,4	0,17	60,31	1,6	13,56
T 34/T 108/Sample 290	Grey Gotland sandstone	0,25	61,21	1,11	11,88	0,04	60,56	1,12	11,97	0,11	60,27	1,11	11,92
T 35/T 109/Sample 291	Grey Gotland sandstone	0,26	61	1,45	13,37	0,32	60,85	1,49	13,34	0,69	60,17	1,44	13,57



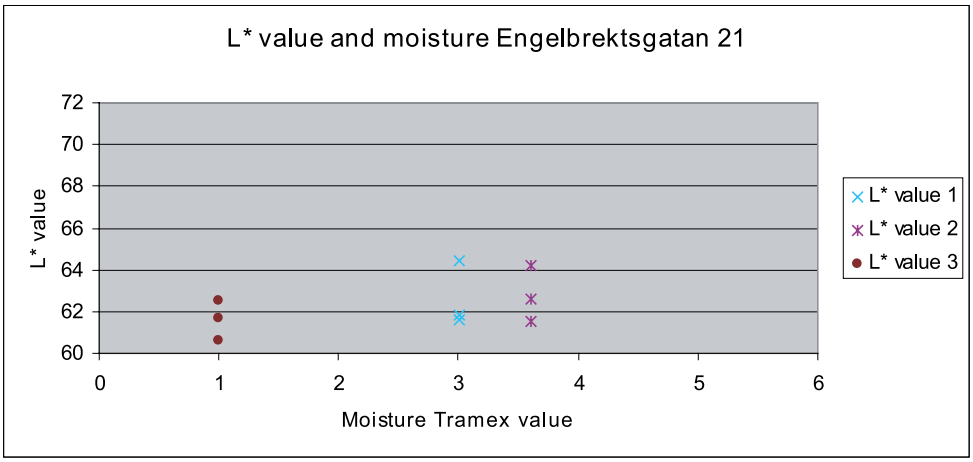
The House of Generals

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 36/T 110/Sample 292	Grey Gotland sandstone	0,39	62,59	3,26	19,38	0,36	62,66	3,14	19,43	0,57	61,34	3,23	19,43
T 37/T 111/Sample 293	Grey Gotland sandstone	1,13	66,5	2,9	19,36	2,71	67,42	2,27	18,47	0,28	63,92	2,96	19,69
T 38/T 112/Sample 294	Grey Gotland sandstone	0,35	66,85	3,05	17,35	1,2	66,75	2,29	17,21	0,53	64,25	2,28	17,51



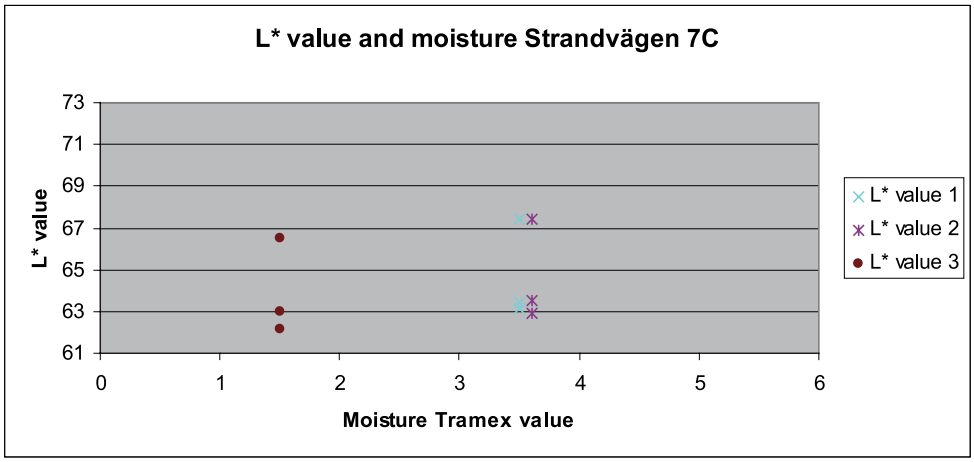
Engelbrektsgatan 21

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 39/T 113/Sample 295	Grey Gotland sandstone	0,27	61,57	2,52	13,87	0,17	61,52	2,4	13,85	0,38	60,63	2,56	13,85
T 40/T 114/Sample 296	Grey Gotland sandstone	0,06	64,4	2,5	14,78	0,09	64,17	2,44	14,82	2,36	62,49	2,46	14,63
T 41/T 115/Sample 297	Grey Gotland sandstone	0,33	61,83	2,54	16,3	0,07	62,58	2,42	16,43	0,15	61,67	2,46	16,21



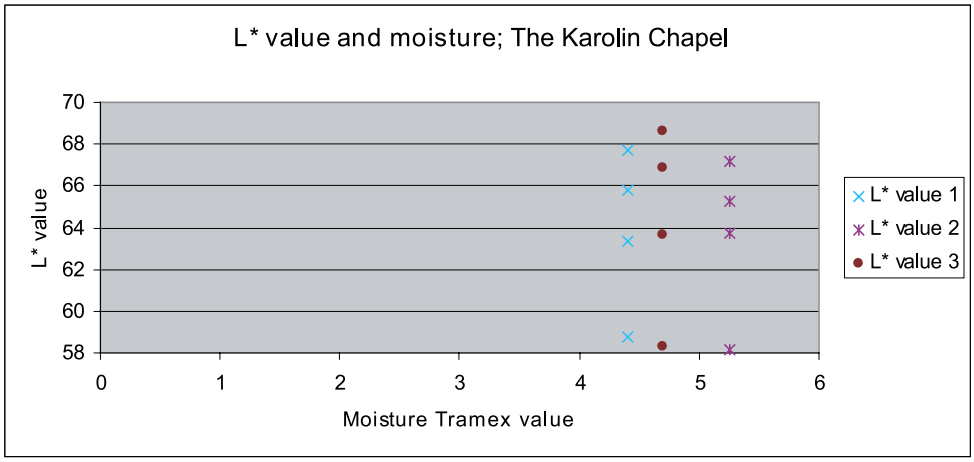
Strandvägen 7C

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 42/T 116/Sample 298	Grey Gotland Sandstone	0,1	67,44	0,02	8,76	0,29	67,39	0,02	8,95	0,31	66,54	0,03	8,87
T 43/T 117/Sample 299	Grey Gotland Sandstone	0,06	63,17	1,08	13	0,21	62,91	1,15	13,61	0,19	62,18	1,07	13,18
T 44/T 118/Sample 300	Grey Gotland Sandstone	0,15	63,45	0,58	11,02	0,08	63,53	0,56	11,21	0,13	63	0,55	11,17



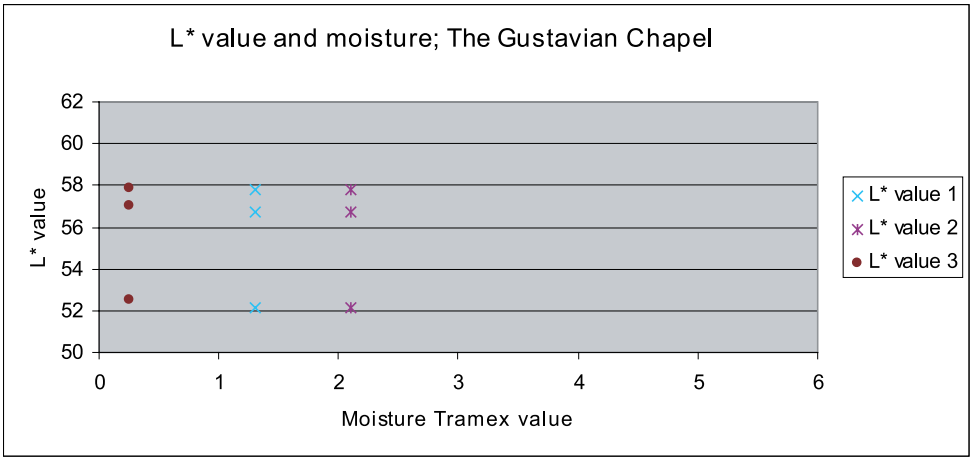
Riddarholm's Church: The Karolin Chapel

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/sample No	Stone description	devia-tion	L*	a*	b*	devia-tion	L*	a*	b*	devia-tion	L*	a*	b*
T 45/T119/Sample 302	New grey Gotland sandstone	0,13	63,38	-0,63	5,06	0,34	63,73	-0,64	4,99	0,39	63,65	-0,71	4,84
T 46/T 120/Sample 303	Old greyish Gotland sandstone	0,53	65,78	0,19	8,67	0,25	65,25	0,33	9,34	1,27	66,89	-0,01	8,12
T 47/T 121/Sample 304	Old greyish Gotland sandstone	0,3	67,67	0,57	9,14	1,3	67,19	0,63	9,44	0,21	68,64	0,53	9,02
T 48/T 122/Sample 305	New grey Gotland sandstone	0,22	58,77	1,7	12,85	0,18	58,17	1,71	12,94	0,16	58,32	1,55	12,33



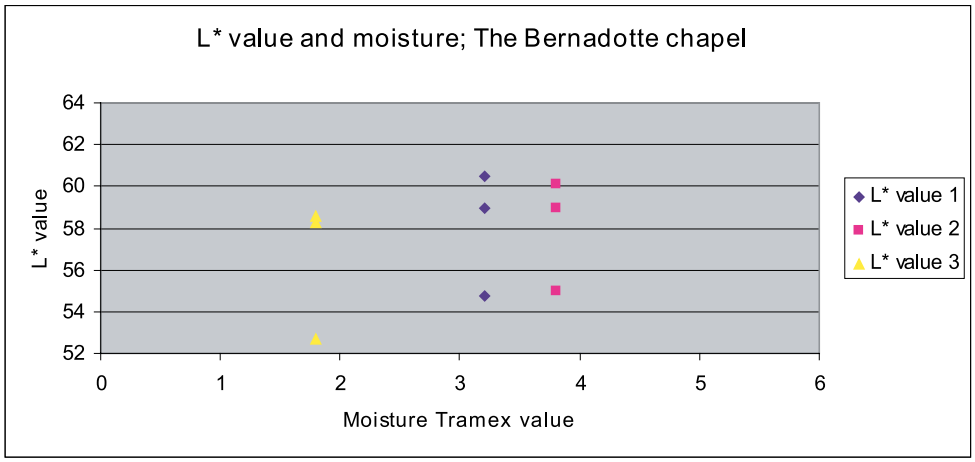
Riddarholm's Church: The Gustavian Chapel

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	devia-tion	L*	a*	b*	devia-tion	L*	a*	b*	devia-tion	L*	a*	b*
T 49/123/Sample 310	Grey deteriorated Gotland Sandstone	0,21	58,21	2,77	13,11	0,32	57,82	3,02	13,26	0,29	57,87	2,85	13,26
T 50/124/Sample 311	Grey deteriorated Gotland Sandstone	0,14	56,81	3,07	13,25	0,19	56,73	3,06	13,26	0,61	57,06	3,15	13,41
T 51/T 125/Sample 312	Grey deteriorated Gotland Sandstone	0,19	53,93	4,05	15,77	1,12	52,17	3,7	15,36	0,07	52,5	4,08	15,6



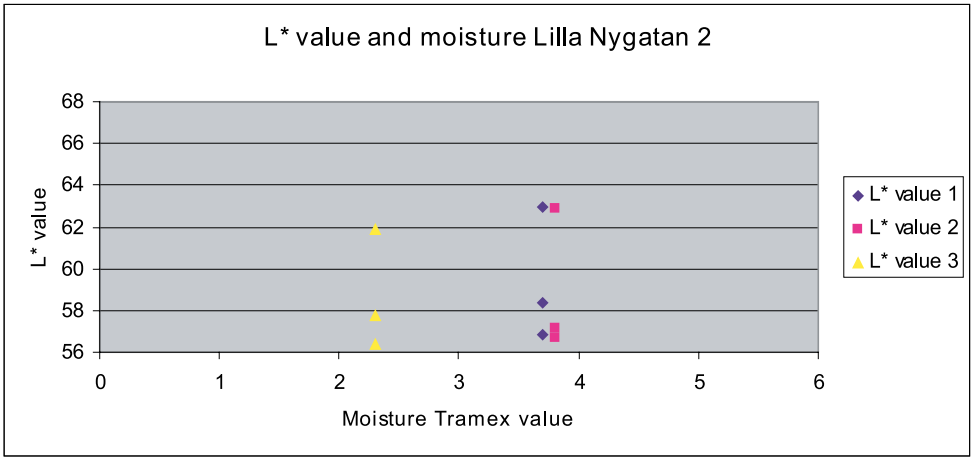
Riddarholm's Church: The Bernadotte Chapel

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 52/T 126/Sample 306	Grey Gotland sandstone	0,2	58,94	1,9	14,16	0,2	58,95	1,78	14,17	0,14	58,56	1,93	13,84
T 53/T 127/sample 307	Grey Gotland sandstone	0,73	60,46	1,26	13,94	1,13	60,1	1,3	14,53	0,72	58,26	1,5	14,17
T 54/T 128/sample 308	Grey Gotland sandstone	0,37	54,77	3,82	15,26	0,49	55	4,02	15,83	0,74	52,65	3,45	13,73



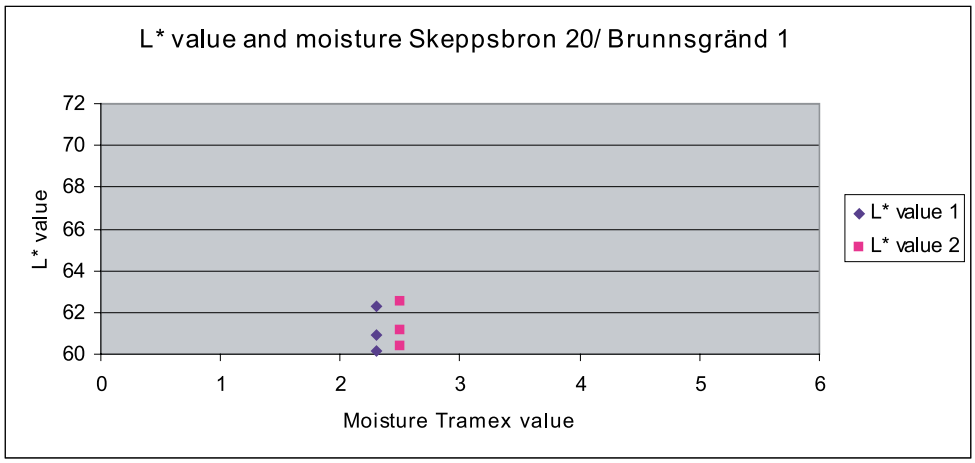
Lilla Nygatan 2

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 55/T 129/Sample 312	Grey Gotland sandstone	0,38	62,94	0,24	9,22	0,16	62,85	0,27	9,52	0,46	61,92	0,35	9,42
T 56/T 130/Sample 313	Grey Gotland sandstone	0,17	58,35	1,54	12,49	0,53	57,11	1,26	12,18	0,39	57,72	1,39	12,35
T 57/T 131/Sample 314	Grey Gotland sandstone	0,07	56,86	1,18	10,62	0,09	56,68	1,2	10,79	0,19	56,42	1,13	10,63



Skeppsbron 20/Brunnsgränd 1

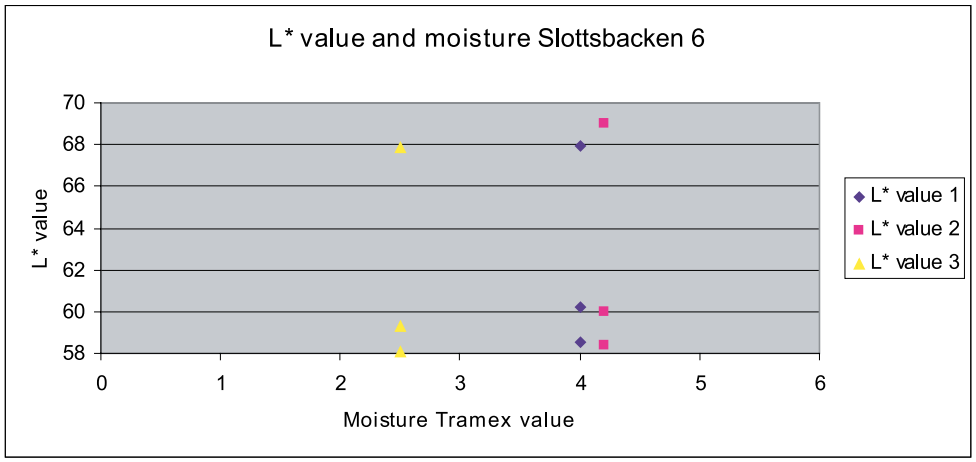
		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 58/T 132/Sample 316	Grey Gotland sandstone	0,4	60,19	1,22	10,22	0,18	60,37	1,2	10,41	0,32	58,78	1,15	10,09
T 59/T 133/Sample 317	Grey Gotland sandstone	0,15	60,94	1,09	11,28	0,31	61,14	1,05	11,17	0,05	60,82	1,05	11,25
T 60/T 134/Sample 318	Grey Gotland sandstone	0,08	62,32	1,18	11,95	0,04	62,49	1,15	11,17	0,18	61,63	1,1	11,74



Moisture value of the third measurement is missing.

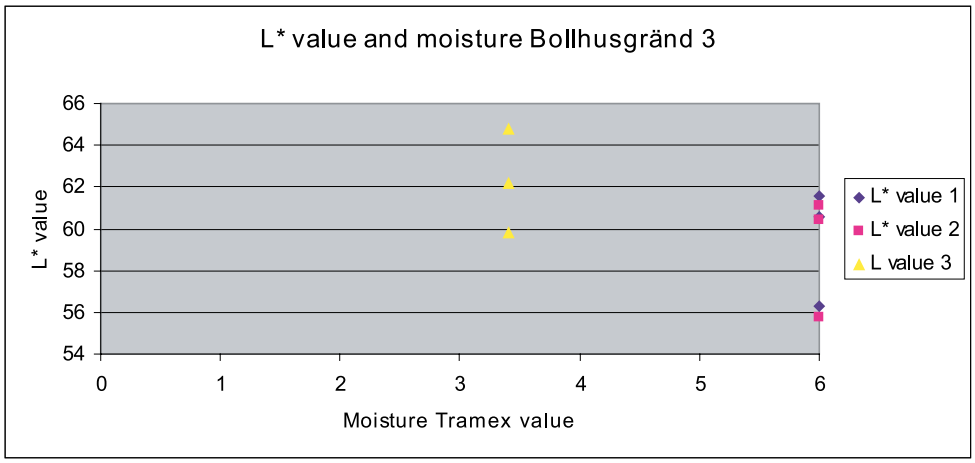
Slottsbacken 6

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 61/T 135/Sample 319	The stone is dirty	0,33	67,9	1,55	14,16	0,3	69	1,46	14,29	0,06	67,83	1,53	14,25
T 62/T 136/Sample 320	The stone is grey and dirty	0,16	58,52	3,1	17,14	0,63	58,36	3,12	17,18	0,54	58,05	3,25	17,55
T 63/T 137/Sample 321	The stone is grey and dirty	0,29	60,22	2,82	18,55	0,21	60,01	2,68	18,61	0,77	59,32	2,67	18,86



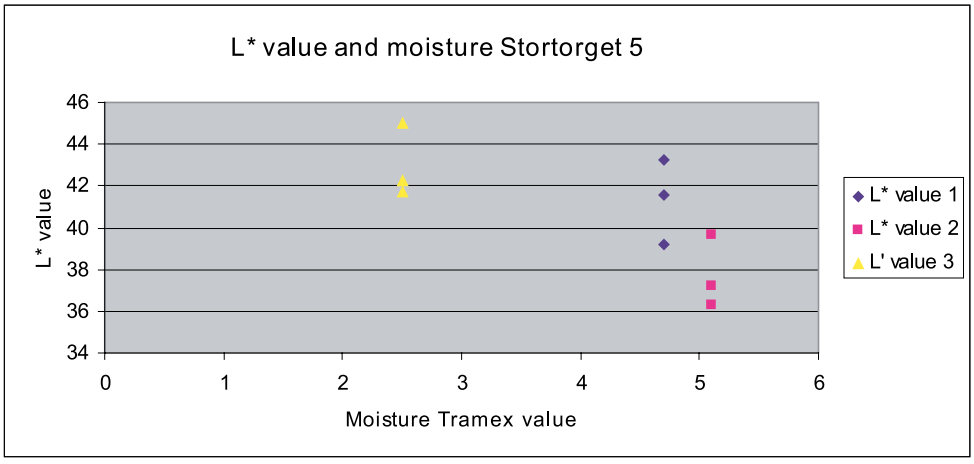
Bollhusgränd 3A

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 64/T 138/Sample 322	Light grey Gotland sandstone	0,34	61,54	-0,27	8,18	0,19	61,13	-0,28	8,41	0,97	64,81	-0,62	7,22
T 65/T 139/Sample 323	Light grey Gotland sandstone	0,16	60,56	-0,32	8,14	0,12	60,4	-0,3	8,15	0,29	62,16	-0,48	7,39
T 66/T 140/Sample 324	Light grey Gotland sandstone	0,31	56,29	-0,58	8,1	0,24	55,78	-0,59	8,44	0,4	59,83	-0,65	7,28



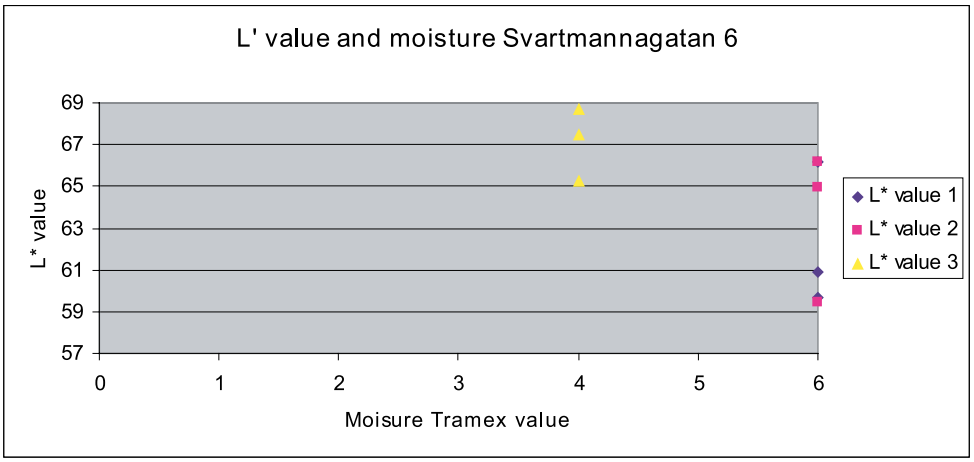
Stortorget 5

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	deviation	L*	a*	b*	deviation	L*	a*	b*	deviation	L*	a*	b*
T 67/T 142	Black stained Gotland sandstone	0,56	41,54	2,01	9,9	0,36	36,31	2,37	9,69	0,99	42,29	1,68	8,89
T 68/T 143	Black stained Gotland sandstone	0,52	39,2	2,35	10,42	1,48	37,18	2,57	11,34	0,11	41,69	2,05	10,33
T 69/	Black stained Gotland sandstone	1,5	42,36	2,75	13,58	X	X	X	X	X	X	X	X
T 70/T 144/Sample 327	Black stained Gotland sandstone	0,66	43,25	2,79	13,84	0,46	39,67	2,78	13,16	1,14	44,97	2,3	13,07



Svartmangatan 6

		August 2005 (1)				October 2005 (2)				May 2006 (3)			
Target/Sample No	Stone description	devia-tion	L*	a*	b*	devia-tion	L*	a*	b*	devia-tion	L*	a*	b*
T 71/T 145/Sample 331	The Gotland sandstone is light grey	0,2	66,18	0,3	8,71	0,13	64,95	0,32	8,84	0,37	68,68	0,08	7,66
T 72/T 146/	The Gotland sandstone is light grey	1,2	60,75	0,53	9,85	wrong	X	X	X	X	X	X	X
T 73/T 147/Sample 330	The Gotland sandstone is light grey	0,17	60,86	0,53	10,09	0,27	66,21	0,54	10,2	0,75	67,48	0,39	9,11
T 74/T 148/Sample 329	The Gotland sandstone is light grey	0,17	59,68	0,28	10,6	0,15	59,45	0,07	10,44	0,21	65,24	-0,26	8,71



Appendix 5

Result of the Granular Disintegration Test

The test was performed on three occasions: August 2005, October 2005 and May 2006. The Herma labels were weighed in the laboratory (see the chapter on the granular disintegration test).

	Svartmangatan 6	Stortorget 5	Bollhusgränd 3	Slottsbacken 6	Brunnsgränd 1	Bernadotte Chapel Riddarholm's Church
	sample 1	sample 1	sample 1	sample 1	sample 1	sample 1
Weight (g)	0,119	0,117	0,118	0,121	0,121	0,122
Weight (g)	0,119	0,117	0,117	0,119	0,117	0,120
Weight (g)	0,117	0,114	0,116	0,118	0,115	0,120
Average weight (g)	0,118	0,116	0,117	0,119	0,117	0,120

	Gustavian Chapel Riddarholm's Church	Karolin Chapel	Riddarholm's Church	Standvägen 7C	Engelbrektsgatan 21	
	sample 1	sample 1	sample 1	sample 1	sample 1	sample 1
Weight (g)	0,122	0,118	0,120	0,120	0,117	0,117
Weight (g)	0,116	0,115	0,116	0,120	0,117	0,119
Weight (g)	0,118	0,115	0,116		0,116	0,118
Average weight (g)	0,118	0,116	0,117	0,120	0,116	0,118

	House of Generals	Skeppargatan 82	Narvavägen 30		Lilla Nygatan 2	The German Church	
	sample 1	sample 1	sample 1	sample 1	sample 1	sample 1	sample 2
Weight (g)	0,125	0,119	0,123	0,12	0,118	0,122	0,157
Weight (g)	0,137	0,119	0,121	0,117	0,117	0,121	0,135
Weight (g)	0,134	0,118	0,119	0,114	0,115	0,121	0,159
Average weight (g)	0,132	0,118	0,121	0,117	0,116	0,121	0,150

Range 0,116–0,151	Severely weathered/dirty	Medium weathered/dirty	Good condition/clean
	>0,120 g	0,118–0,200 g	0,114–0,117g

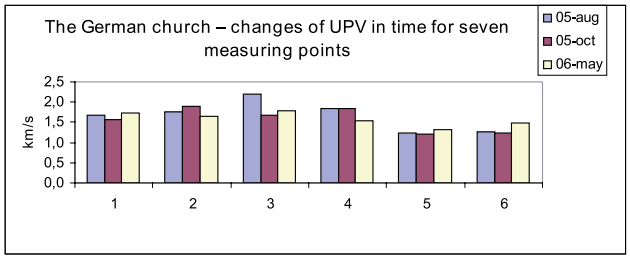
Appendix 6

Result of the Ultrasonic Pulse Velocity Measurements

The measurements were taken on three occasions: August 2005, October 2005 and May 2006 on the same areas and with a portable ultrasonic tester *AU 2000 Ultrasonic tester from CEBTP*.

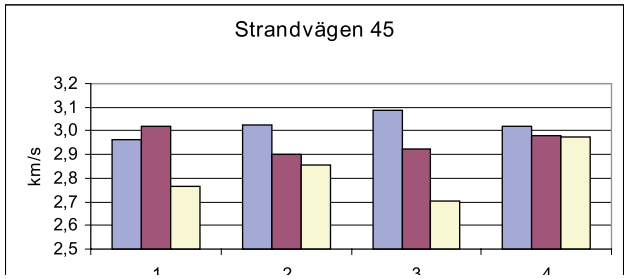
The German Church

No	Direct/indirect measurement	1st measurement	2nd measurement	3rd measurement
		km/s	km/s	km/s
T German 1	Indirect	1,7	1,6	1,7
T German 2	Indirect	1,75	1,9	1,7
T German 3	Indirect	2,2	1,7	1,8
T German 4	Indirect	1,8	1,8	1,6
T German 5	Indirect	1,2	1,2	1,3
T German 6	Indirect	1,3	1,2	1,5
T German 7	Indirect	1,9	2,3	2,4



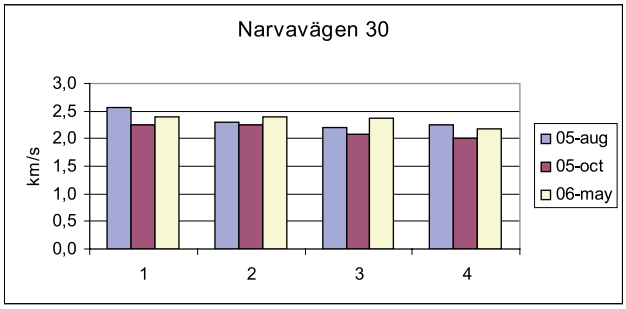
Strandvägen 45

No	Direct/indirect measurement	1st measurement	2nd measurement	3rd measurement
		km/s	km/s	km/s
T Strand 1	Indirect	2,9	3,0	2,8
T Strand 2	Indirect	3,0	2,9	2,9
T Strand 3	Indirect	3,1	2,9	2,7
T Strand 4	Indirect	3,0	3,0	3,0
T Strand 5	Direct	2,2		



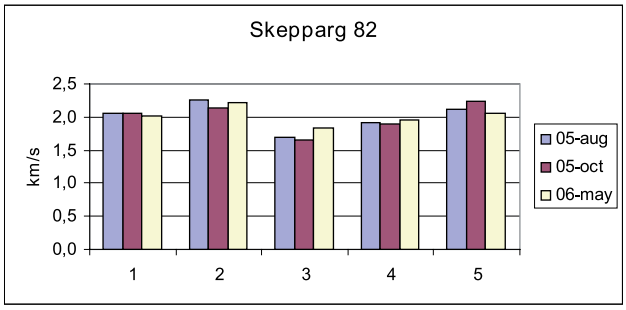
Narvavägen 30

No	Indirect/direct	1st measurement	2nd measurement	3rd measurement
		km/s	km/s	km/s
T narva 1	Direct	2,6	2,3	2,4
T narva 2	Direct	2,3	2,3	2,4
T narva 3	Direct	2,2	2,1	2,4
T narva 4	Direct	2,2	2,0	2,2
T narva 5	Indirect	1,2	1,3	1,4



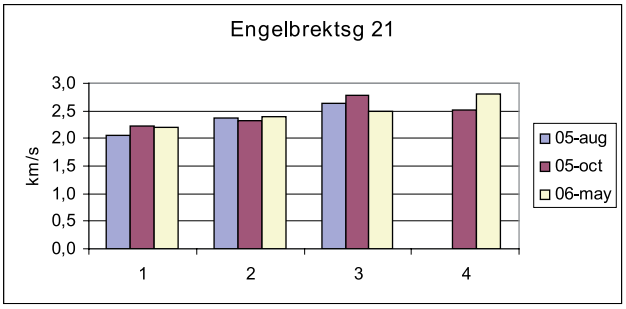
Skeppargatan 82

No	Indirect/direct	1st measurement	2nd measurement	3rd measurement
		km/s	km/s	km/s
T skeppar 1	Indirect	2,1	2,1	2,0
T skeppar 2	Indirect	2,3	2,1	2,2
T skeppar 3	Indirect	1,7	1,6	1,8
T skeppar 4	Indirect	1,9	1,9	2,0
T skeppar 5	Indirect	2,1	2,2	2,1



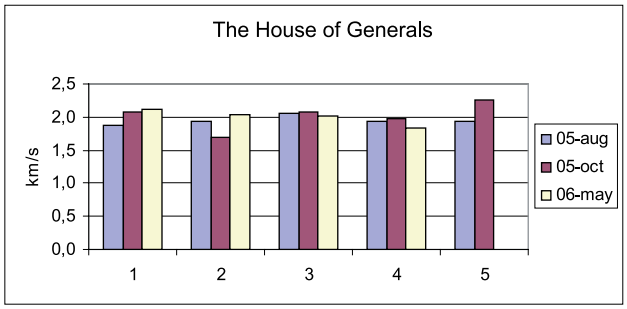
Engelbrektsgatan 21

No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T engel 1	Indirect	2,0	2,2	2,2
T engel 2	Indirect	2,4	2,3	2,4
T engel 3	Direct	2,6	2,8	2,5
T engel 4	Direct	x	2,5	2,8



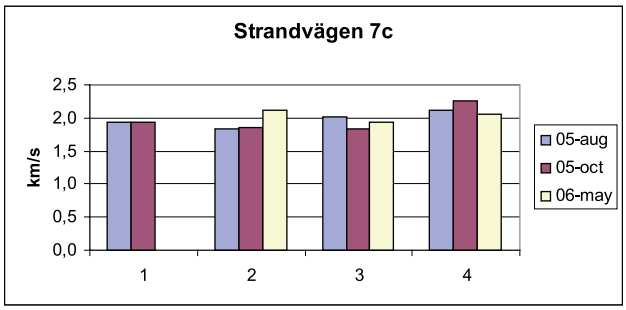
The House of Generals

No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T General 1	Indirect	1,9	2,1	2,1
T General 2	Indirect	1,9	1,7	2,0
T General 3	Indirect	2,1	2,1	2,0
T General 4	Indirect	1,9	2,0	1,8
T General 5	Indirect	1,9	2,3	



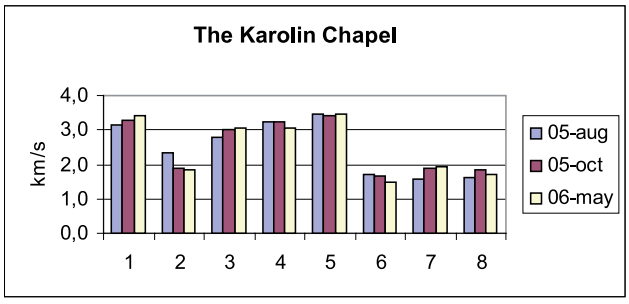
Strandvägen 7C

No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T diplomat 1	Indirect	1,9	1,9	1,9
T diplomat 2	Indirect	1,8	1,8	2,1
T diplomat 3	Indirect	2,0	1,8	1,9
T diplomat 4	Direct	2,1	2,3	2,1



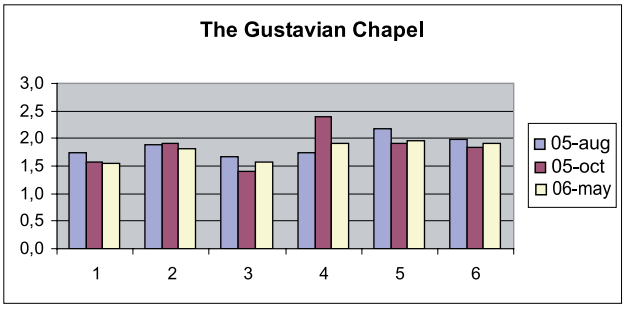
Riddarholm's Church: The Karolin Chapel

No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T karolinska 1,1	Direct	3,1	3,3	3,4
T karolinska 2,1	Indirect	2,3	1,9	1,9
T karolinska 3,1	Direct	2,8	3,0	3,0
T karolinska 4,1	Direct	3,2	3,2	3,1
T karolinska 5,1	Direct	3,4	3,4	3,5
T karolinska 6,1	Indirect	1,7	1,7	1,5
T karolinska 7,1	Indirect	1,6	1,9	1,9
T karolinska 8,1	Indirect	1,6	1,8	1,7



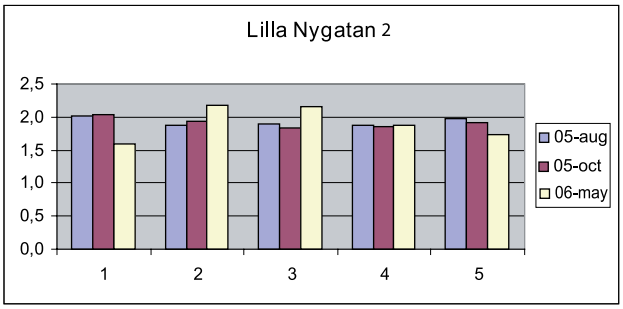
Riddarholm's Church: The Gustavian Chapel

No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T gustav 1,1	Indirect	1,75	1,6	1,6
T gustav 2,1	Indirect	1,9	1,9	1,8
T gustav 3,1	Indirect	1,7	1,4	1,6
T gustav 4,1	Indirect	1,7	2,4	1,9
T gustav 5,1	Indirect	2,2	1,9	1,9
T gustav 6,1	Indirect	2,0	1,81	1,9



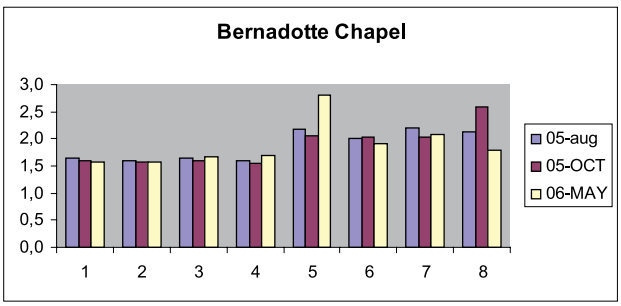
Lilla Nygatan 2

No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T Nygatan 1,1	Direct	2,0	2,0	1,6
T nygatan 2,1	Indirect	1,9	1,94	2,2
T nygatan 3,1	Indirect	1,9	1,8	2,2
T nygatan 4,1	Indirect	1,9	1,9	1,9
T nygatan 5,1	Indirect	2,0	1,9	1,7



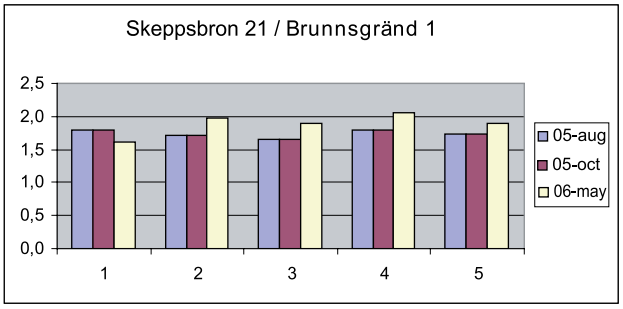
Riddarholm's Church: The Bernadotte Chapel

No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T bernadotte 1,1	Indirect	1,6	1,6	1,6
T bernadotte 2,1	Indirect	1,6	1,6	1,6
T bernadotte 3,1	Direct	1,7	1,6	1,7
T bernadotte 4,1	Direct	1,6	1,5	1,7
T bernadotte 5,1	Indirect	2,2	2,1	2,8
T bernadotte 6,1	Indirect	2,0	2,0	1,9
T bernadotte 7,1	Direct	2,2	2,0	2,1
T bernadotte 8,1	Direct	2,1	2,6	1,8



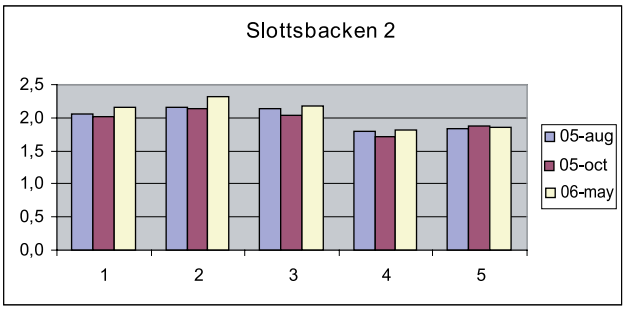
Skeppsbron 21 / Brunnsgränd 1

No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T brunn 1,1	Indirect	1,8	1,8	1,6
T brunn 2,1	Indirect	1,8	1,7	2,0
T brunn 3,1	Indirect	1,7	1,7	1,9
T brunn 4,1	Indirect	1,8	1,8	2,1
T brunn 5,1	Indirect	1,7	1,7	1,9



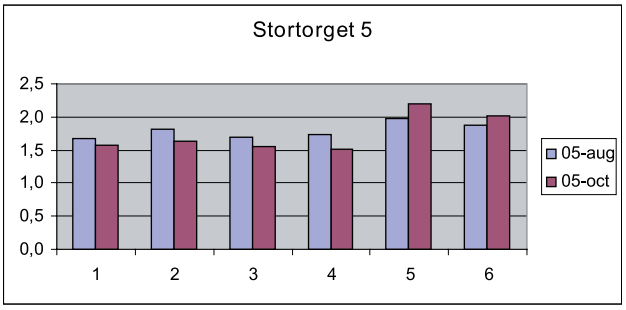
Slottsbacken 2

No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T slotts 1,1	Direct	2,1	2,0	2,2
T slotts 2,1	Direct	2,2	2,1	2,3
T slotts 3,1	Direct	2,1	2,0	2,2
T slotts 4,1	Indirect	1,8	1,7	1,8
T slotts 5,1	Indirect	1,8	1,9	1,9



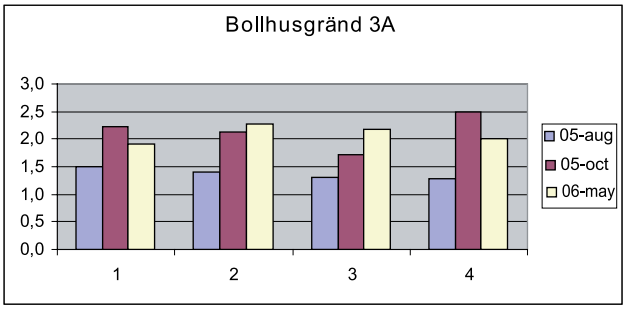
Stortorget 5

No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T stor 1,1	Indirect	1,7	1,6	
T stor 2,1	Indirect	1,8	1,6	
T stor 3,1	Indirect	1,7	1,5	
T stor 4,1	Indirect	1,7	1,5	
T stor 5,1	Indirect	2,0	2,2	
T stor 6,1	Indirect	1,9	2,0	



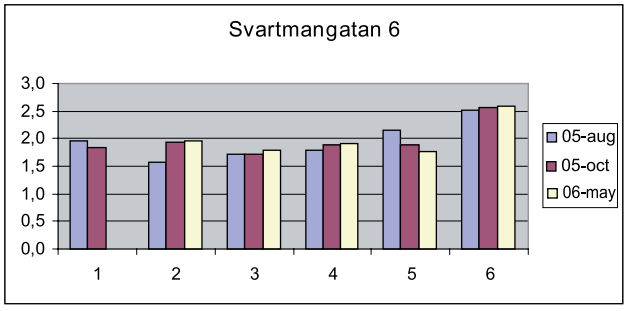
Bollhusgränd 3A

No	Indirect/di-rect	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T bollhus 1,1	Direct	1,5	2,2	1,9
T bollhus 2,1	Direct	1,4	2,1	2,3
T bollhus 3,1	Direct	1,3	1,7	2,2
T bollhus 4,1	Direct	1,3	2,5	2,3



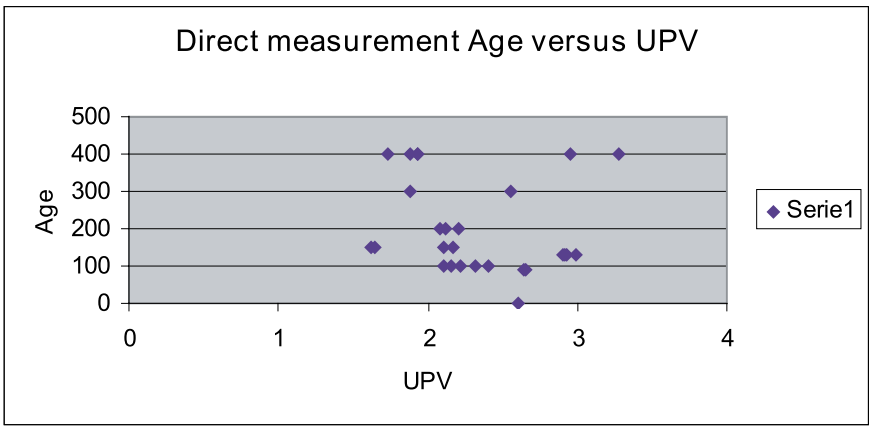
Svartmangatan 6

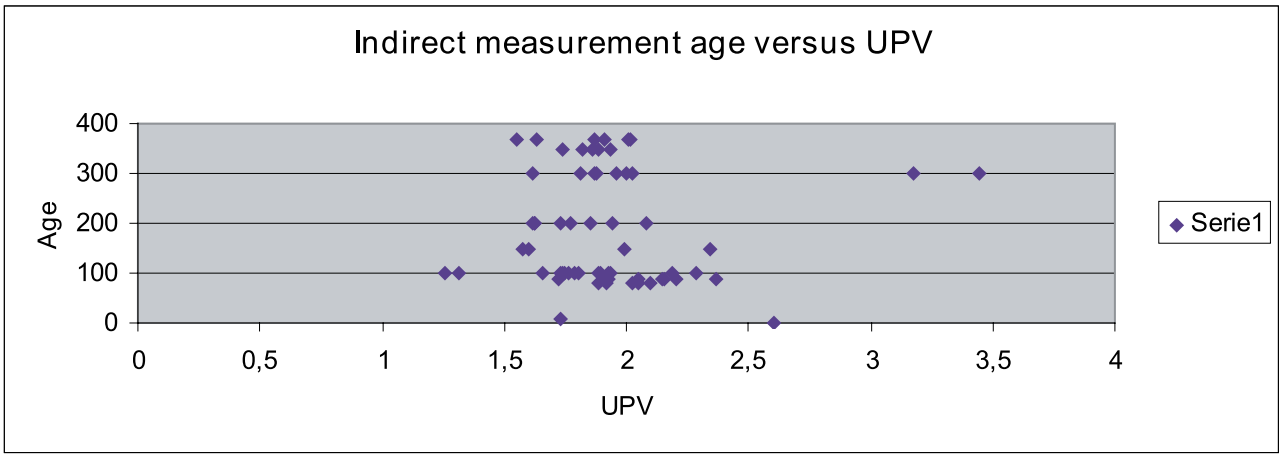
No	Indirect/ direct	1st measure-ment	2nd measure-ment	3rd measure-ment
		km/s	km/s	km/s
T svart 1,1	Indirect	1,9	1,8	
T svart 2,1	Indirect	1,6	1,9	2,0
T svart 3,1	Indirect	1,7	1,7	1,8
T svart 4,1	Indirect	1,8	1,9	1,9
T svart 5,1	Indirect	2,1	1,9	1,8
T svart 6,1	Direct	2,5	2,6	2,6



Measurement of UPV and the age of Gotland sandstone

It is hard to find a correspondence between the age of the stone and the UPV. This appears to depend on a number of facts, such as that some of the oldest stone has been consolidated.





Appendix 7

Variation of Ultrasound Pulse Velocity due to Changes in the Relative Humidity in Laboratory Conditions. Case Study for Gotland Sandstone

Report to NHB, by Katarina Malaga, SP

Introduction

Ultrasound pulse velocity (UPV) measurements represent a very suitable method for the quantification of stone deterioration and also for the detection of pre-imminent stone damage. This can be used as a complement to visual inspections and absorption tests. Research on the technique of UPV used in laboratory environments for the evaluation of stone properties is available, although there are no investigations of that type for objects of Gotland sandstone located in Sweden.

Several objects of different ages, such as porches, sculptured details and façade stones, were chosen for studies in the field. Hence, non-destructive testing by means of ultrasound pulse velocity measurements of Gotland sandstone objects exposed to outdoor conditions needs to be calibrated with those results obtained from simulated humid environments in controlled laboratory conditions.

The aim of this study was to analyse how the ultrasound pulse velocity varies with changes in relative humidity and to relate these results to observations and measurements taken in field. The samples selected for the analyses were freshly quarried and of two different dimensions. The measurements of UPV were taken in both a direct and indirect way. The relative humidity varied from 50 percent to total saturation.

Table 1: Description of the samples.

Sample dimensions [mm]	No of samples	Samples ID	RH
50x50x50	3	1–852–85 3–85	85
50x50x50	3	1–65 2–65 3–65	65
50x50x50	2	1–50 2–50	50
100x100x100	3	1–85 2–85 3–85	85
100x100x100	3	1–65 2–65 3–65	65
100x100x100	3	1–50 2–50 3–50	50
100x100x100	3	1R 2R 3R	Laboratory room
400x100x30	2	1–85 2–85	85
400x100x30	2	1–65 2–65	65
400x100x30	2	1–50 2–50	50

This study implies that ultrasound pulse velocity measurements are useful in practical conservation work for analysing changes in physical properties and, in combination with visual inspection for monitoring the state of the stone as well as for maintenance planning.

Samples and Climate Chambers

The samples used for testing UPV versus humidity are presented in Table 1.

Figure 1: Samples used for the UPV analyses. Markings on the samples indicate the relative humidity.

Controlled climatic chambers with different relative humidities were used:

- 50% RH
- 65% RH
- 85% RH

The temperature in these chambers was 20 °C and was constant.

Testing Procedure

Water absorption test EN 13755: 2002

A total of six samples were analysed in the water absorption test. The European standard method, Natural stone test method – Determination of water absorption at atmospheric pressure, was used. The samples were dried to a constant mass, weighed, and immersed in water at the atmospheric pressure for the specified period of time. The ratio of the mass of the water absorbed by each specimen was calculated when constant mass was reached. The totally immersed samples were also measured for UPV. These values were used as 100 percent RH results.

Compressive strength

The European standard method, Natural stone test method – Determination of compressive strength EN 1926:1999, was used for testing the 50 x 50 x 50 mm samples. The compressive strength was measured both parallel and perpendicular to the sandstone's lamination.

Ultrasound pulse velocity

Ultrasound pulse velocity measurements offer an accurate and repeatable non-destructive technique with the potential of detecting changes in the strength of a stone even when there are no visible signs of deterioration. On a comparison basis, density variations in a single piece or between similar parts can be detected. Ultrasonic measurements can be correlated to modulus of elasticity, modulus of rupture, and degradation of internal structure, such as the detection of cracks.

The wave frequency used was 60 kHz, the sampling frequency 10 MHz and the time resolution 0.1(s. All measurements were repeated several times and an average was calculated for each measured spot and occasion.

Results

Water absorption test

The mean value for the water absorption was ca 5 percent by weight. There were no significant differences between the two different dimensions of the samples. The density of the samples was calculated to ca 2210 kg/m3.

Table 2:

Samples	UPV dry parallel to the lamination mean value km/s	UPV saturated parallel to the lamination mean value km/s	UPV dry perpendicular to the lamination mean value km/s	UPV saturated perpendicular to the lamination mean value km/s
100x100x100 mm	2.5	2.1	2.7	2.2
50x50x50 mm	2.4	2.2	2.5	2.2
Difference	0.1	0.1	0.2	0

The results for the UPV measurements showed that the samples have a detectable lamination. The difference in UPV is about 0.2 km/s. The differences in UPV between the two measurements' dimensions are small, in the range 0 – 0.2 km/s and therefore could be treated as a normal variation of the samples' internal structure. However it is more important to see the difference in UPV between the totally dry and totally wet samples. The UPV decreases for both dimensions. For the 100x100x100 mm samples it decreases by 0.4–0.5 km/s. For the 50x50x50 mm samples the UPV decreases by 0.3–0.4 km/s. This indicates that the measure-

Figure 2: Water absorption test.

Figure 3: Indirect measurement of UPV.

ments are less sensitive to wet/dry conditions for smaller dimensions of samples than for larger dimensions.

Compressive strength

The results for compressive strength showed that there is a lamination of the samples. The compressive strength taken parallel to the lamination was 61 MPa and perpendicular 84 MPa. These results showed that Gotland sandstone has a low compressive strength when compared to other natural stones. Typical Swedish limestone has a compressive strength of ca 160 MPa and typical Swedish granite of over 200 MPa.

Ultrasound pulse velocity

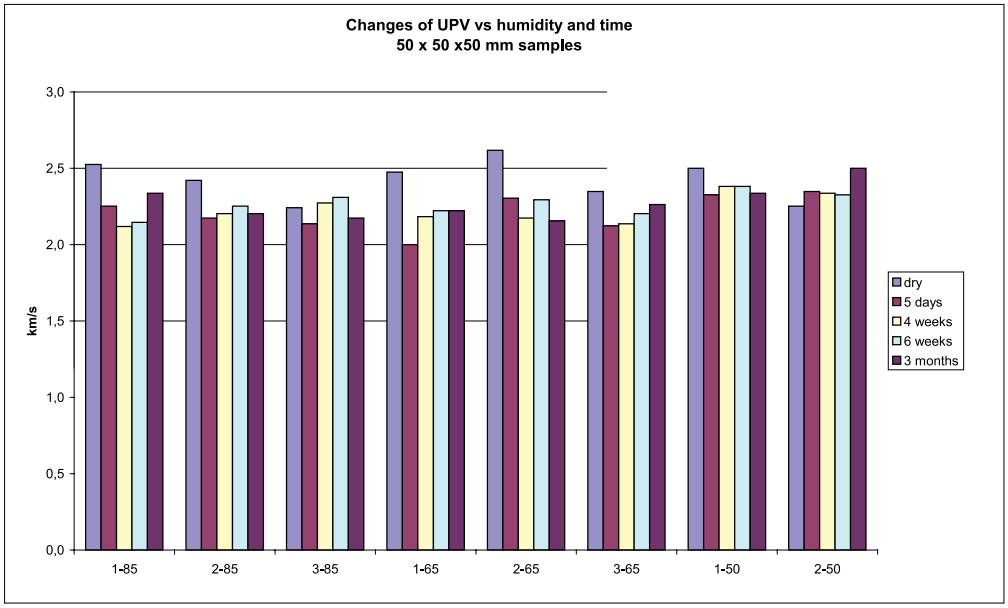


Figure 4: Changes of UPV from dry conditions (blue bars) to humid conditions. Samples 50x50x50 mm. The exposure time was 3 months and the measurements were taken 5 times, including the dry conditions.

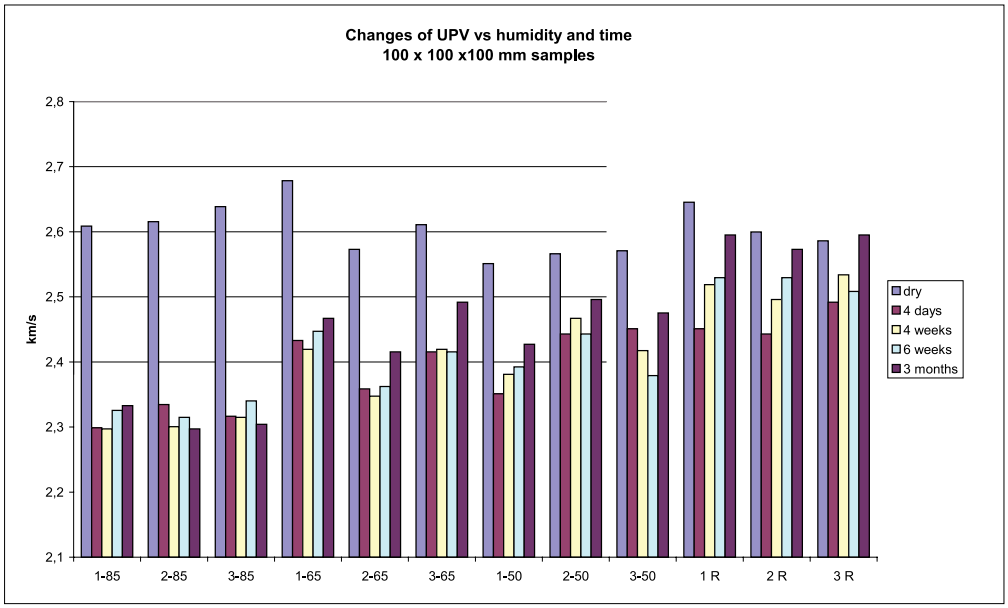


Figure 5: Changes of UPV from dry conditions (blue bars) to humid conditions. Samples 100x100x100 mm. The exposure time was 3 months and the measurements were taken 5 times, including the dry conditions.

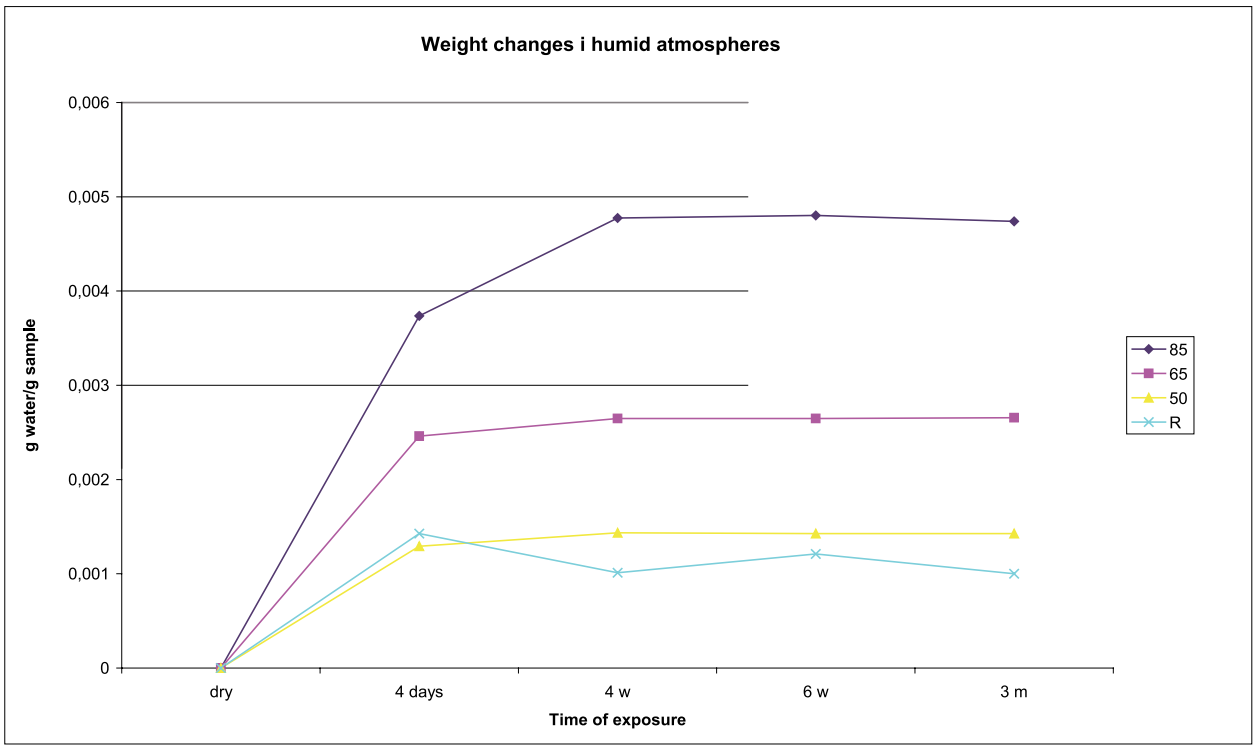


Figure 6: Weight increases for samples exposed to different relative humidities. The relative humidity varied from 0 to 85%. Time of exposure was 3 months.

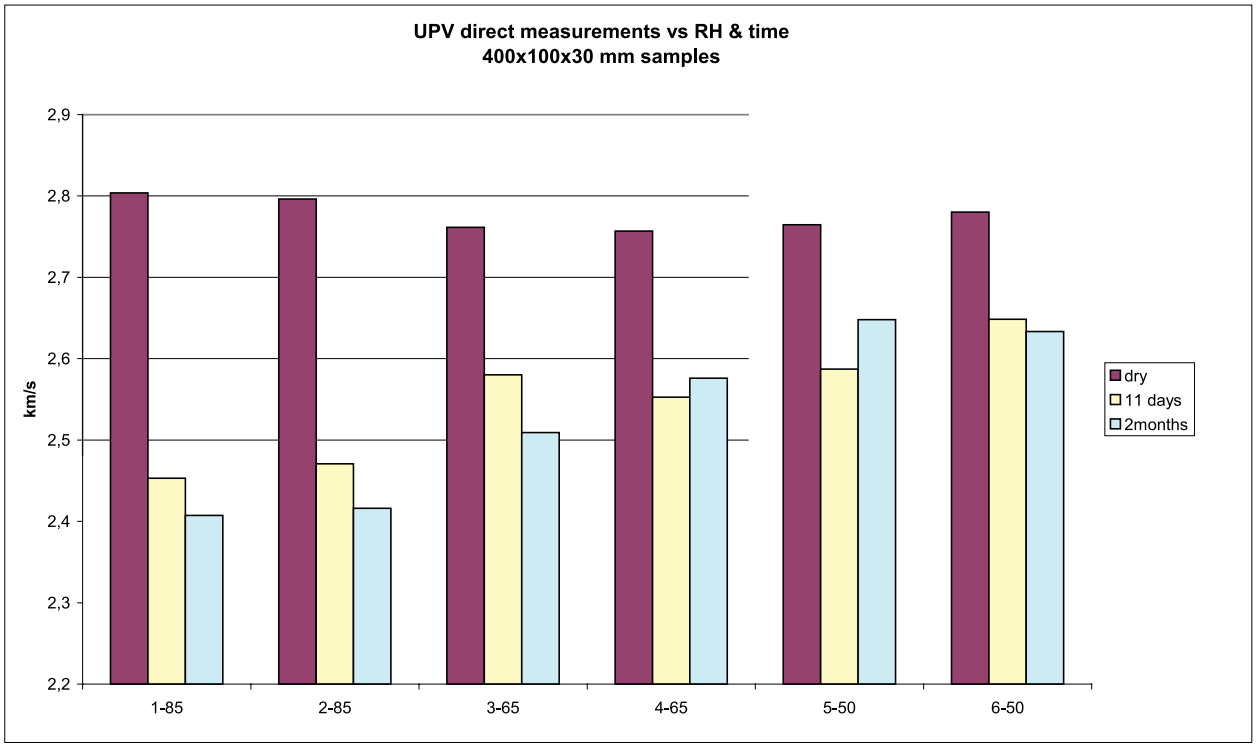


Figure 7: Direct measurements (the sensors placed on the opposite sides of the stone) of the UPV versus RH.

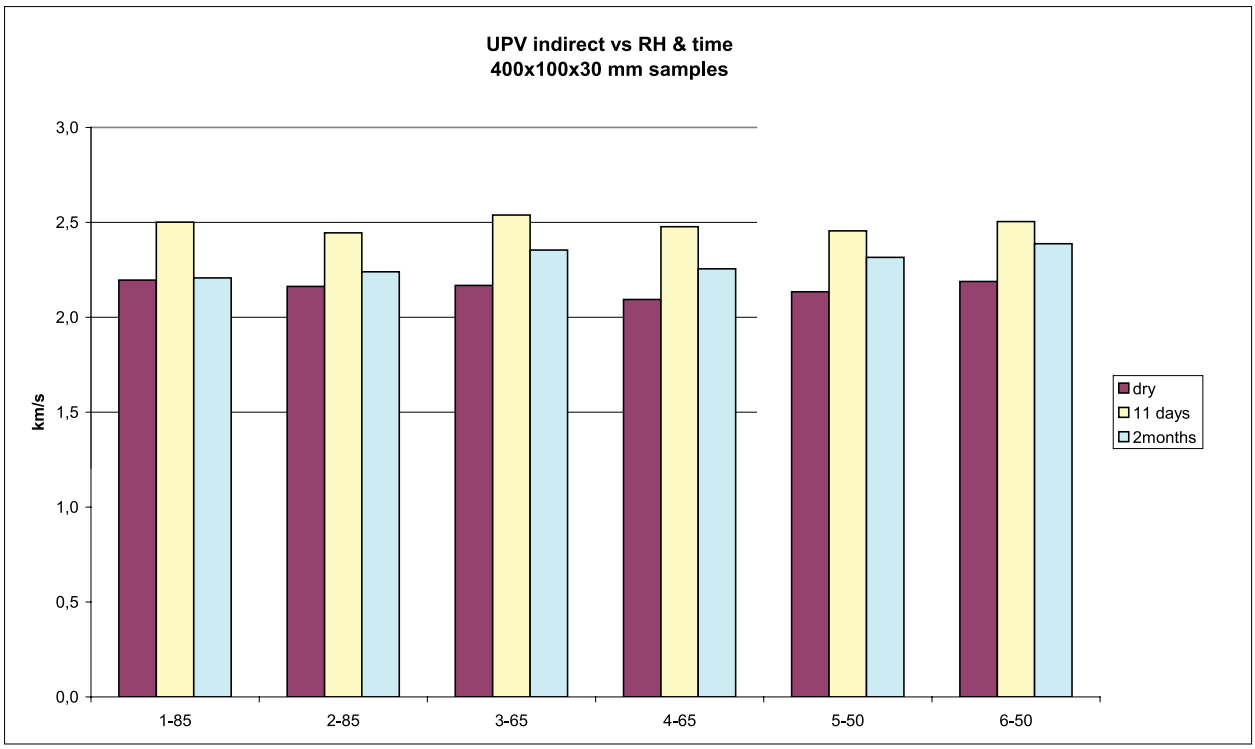


Figure 8: Indirect measurements (the sensors placed on the same side of the stone e.g. on the surface) of the UPV versus RH.

Appendix 8

Result From the Colorimetric Measurement in the Laboratory

Test Programme For the Minolta Spectrotometer in the Laboratory

The test was performed on three samples of Gotland sandstone extracted from the Burgsvik quarry: 10 x 10 x 10 cm.

1. Test Of The Influence Of Temperature

a. Dry the samples in the oven at 60 °C for three days.
b. Weigh the samples and measure the colour (the average of three measurements on all three stones) at ca 60 °C.
c. Leave the samples at room temperature and measure the surface temperature and the colour every half an hour until the temperature reaches room temperature (ca. 22 °C).
d. Freeze the samples until the temperature is ca. – 8 °C, and measure the colour.
e. Take the samples out of the freezer and measure the colour and temperature every 15 minutes.
f. Plot the results on a graph.

2. Test Of The Influence Of Water Content

a. Saturate the samples with water at room temperature (ca 22 °C).
b. Weigh the samples and calculate the percentage water content.
c. Leave the samples at room temperature and allow the water to evaporate. Measure the colour of the stones containing different water contents over the period of a day (by weighing the samples and measuring the colour and weight, for example every second hour for two days (during the night the samples should be put in sealed plastic bags).
d. The result is the plotted on a graph.

8.1 Measurement of colour on Gotland sandstone in the laboratory, depending on water content

The samples were put into a water container for 12 hours at room temperature.

STONE I

Original weight/Dry weight (g): 2104,4

DATE/TIME	Water weight	Moisture ratio	L*	a*	b*	Deviation	Protimeter	Moisture content (kg/m²)	Room Temperature	RH (%)
2006-02-16 10:06	139,9	6,65%	47,19	-1,18	5,28	0,1	10,5	140,26	18	34
2006-02-16 10:36	137	6,51%	49,13	-1,13	5,46	0,07	10,3	137,31		
2006-02-16 11:06	134,9	6,41%	49,99	-1,09	5,66	0,04	11,5	135,20		
2006-02-16 11:36	132,6	6,30%	50,28	-1,09	5,79	0,14	10,5	132,89		
2006-02-16 12:06	130,4	6,20%	50,6	-1,07	5,92	0,07	11	130,77		
2006-02-16 12:36	128,4	6,10%	50,68	-1,06	5,97	0,09	11	128,66		
2006-02-16 13:06	126,3	6,00%	50,91	-1,06	6,03	0,03	11	X		
2006-02-16 14:04	122,2	5,81%	51,27	-1,07	6,13	0,07	10	122,54		
2006-02-16 15:06	117,8	5,60%	51,51	-1,03	6,19	0,11	11	118,12		
2006-02-16 16:06	113,6	5,40%	51,78	-1,03	6,29	0,07	10	113,90		
2006-02-16 17:06	109,2	5,19%	51,9	-1,02	6,31	0,16	11	109,47		
2006-02-16 18:06	104,8	4,98%	52,03	-1,04	6,28	0,16	11	105,04		
2006-02-17 09:00	103,9	4,94%	52,32	-1	5,75	0,07	10	104,20	15,3	34
2006-02-17 09:58	99,4	4,72%	52,41	-1,01	5,95	0,07	11	99,55		
2006-02-17 11:00	94,7	4,50%	52,46	-1,02	5,99	0,08	11	94,91		
2006-02-17 12:00	90	4,28%	52,33	-1,01	6,05	0,1	10	90,27		
2006-02-17 13:00	85,8	4,08%	52,42	-1,02	6,1	0,1	11	86,06		
2006-02-17 14:00	81,7	3,88%	52,42	-1,02	6,21	0,1	10,5	81,84		
2006-02-17 15:00	77,7	3,69%	52,73	-0,99	6,38	0,06	10	77,83		
2006-02-17 16:00	73,4	3,49%	52,64	-0,97	6,32	0,07	10,5	73,61		
2006-02-17 17:00	69,1	3,28%	52,82	-0,98	6,44	0,07	10	69,18		
2006-02-17 18:00	63,3	3,01%	53,06	-0,96	6,42	0,16	10	63,49		
2006-02-20 08:15	64,6	3,07%	53,21	-0,92	5,84	0,28	10	64,75	17,4	36
2006-02-20 09:15	60,5	2,87%	53,57	-0,96	5,92	0,05	10	60,53		
2006-02-20 11:12	54,1	2,57%	54,07	-0,91	6,14	0,13	11	54,21		
2006-02-20 13:15	47,9	2,28%	56	-0,86	6,21	0,05	10	48,09		
2006-02-20 15:15	42,8	2,03%	59,67	-0,8	6,03	0,09	10	42,82		
2006-02-20 17:15	38,9	1,85%	64,27	-0,88	5,04	0,28	10	39,02		
2006-02-21 08:30	38,3	1,82%	57,86	-0,79	5,84	0,21	10	64,75	17,4	36
2006-02-21 12:30	30,8	1,46%	65,31	-0,9	5,92	0,09	9	60,53		
2006-02-21 14:33	28,2	1,34%	65,35	-0,88	6,14	0,16	8,5	54,21		
2006-02-21 16:30	26,2	1,25%	65,3	-0,88	6,21	0,08	8,5	48,09		
2006-02-21 17:30	25	1,19%	65,38	-0,89	6,03	0,04	8,5	42,82		
2006-02-22 08:55	24,7	1,17%	64,4	-0,81	5,04	0,05	10	39,02		
2006-02-22 12:18	21,3	1,01%	65,44	-0,88	5,08	0,08	9	38,39		34
2006-02-22 14:15	19,1	0,91%	65,7	-0,88	5,28	0,07	8	30,80		
2006-02-22 16:45	17,6	0,84%	65,54	-0,89	5,46	0,06	8	28,26		
2006-02-23 08:45	12,1	0,57%	65,59	-0,85	5,66	0,08	7	26,36		
2006-02-24 08:28	7,5	0,36%	65,67	-0,86	5,79	0,14	6	25,10		
2006-02-27 09:26	1,8	0,09%	65,7	-0,89	5,92	0,17	5	24,68	18,7	32
2006-02-28 09:01	1,1	0,05%	65,63	-0,86	5,97	0,08	4	21,31		
2006-03-01 10:04	0,7	0,03%	65,86	-0,86	6,03	0,08	4	19,19		
2006-03-02 09:32	0,4	0,02%	66,01	-0,86	6,13	0,08	4	17,72		
2006-03-03 08:47	0,4	0,02%	65,45	-0,85	6,19	0,13	4	3,61	17,9	35
2006-03-07 08:40	0,3	0,01%	65,4	-0,89	6,29	0,16	4	2,28	17,9	35
2006-03-09 09:00	0,3	0,01%	65,52	-0,87	6,31	0,13	4	0,57	18,1	32

STONE II

Original weight/Dry weight (g): 2093,9

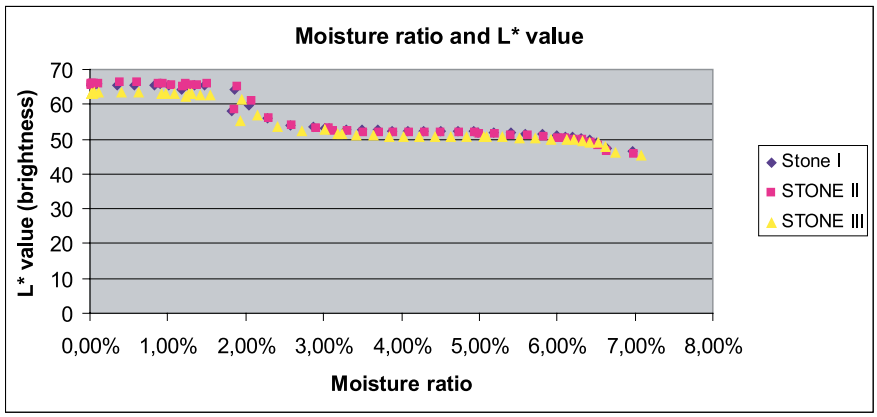
DATE/TIME	Water weight	Moisture ratio	L*	a*	b*	Deviation	Protimeter	Moisture content (kg/m²)	Room Temperature	RH (%)
2006-02-16 09:39	146,5	7,00%	45,53	-1,15	4,57	0,06	11	146,80	18	34
2006-02-16 10:08	138,9	6,63%	46,5	-1,14	4,81	0,03	10,5	140,26		
2006-02-16 10:38	136,7	6,53%	48,3	-1,05	5,03	0,1	11	137,31		
2006-02-16 11:08	134,6	6,43%	49,19	-1,05	5,28	0,07	11	135,20		
2006-02-16 11:36	132,4	6,32%	49,63	-1,03	5,39	0,06	10,5	132,88		
2006-02-16 12:08	130,1	6,21%	49,91	-1,03	5,44	0,08	10	130,78		
2006-02-16 12:38	127,9	6,11%	50,15	-1,02	5,5	0,07	11	128,66		
2006-02-16 13:08	125,9	6,01%	50,34	-1,02	5,52	0,13	11	126,55		
2006-02-16 14:05	122,2	5,84%	50,62	-1,01	5,59	0,08	9,5	122,54		
2006-02-16 15:07	117,8	5,63%	50,93	-0,98	5,66	0,05	11	118,11		
2006-02-16 16:06	113,4	5,42%	51,16	-1,01	5,67	0,1	10	113,90		
2006-02-16 17:06	109,1	5,21%	51,31	-0,98	5,74	0,03	10	109,47		
2006-02-16 18:07	104,7	5,00%	51,56	-0,99	5,79	0,2	10	105,04		
2006-02-17 09:00	103,6	4,95%	51,98	-0,97	5,32	0,07	10	104,19	15,3	34
2006-02-17 09:59	99,3	4,74%	51,9	-0,97	5,42	0,16	10	99,55		
2006-02-17 11:03	94,5	4,51%	51,96	-0,97	5,49	0,11	10,5	94,91		
2006-02-17 12:01	90,1	4,30%	51,81	-0,98	5,59	0,12	10	90,27		
2006-02-17 13:03	85,8	4,10%	51,79	-0,98	5,6	0,05	11	86,05		
2006-02-17 14:01	81,8	3,91%	51,75	-0,98	5,77	0,09	10	81,84		
2006-02-17 15:01	77,9	3,72%	51,8	-0,96	5,76	0,12	11	77,83		
2006-02-17 16:01	73,4	3,51%	51,86	-0,98	5,91	0,17	10	73,61		
2006-02-17 17:01	69,2	3,30%	52,16	-0,96	5,89	0,1	10	69,18		
2006-02-17 18:01	65,3	3,12%	52,5	-0,95	6,03	0,09	10	63,49		
2006-02-20 08:16	64,5	3,08%	53,19	-0,93	5,23	0,3	10	64,75	17,4	36
2006-02-20 09:16	60,7	2,90%	53,26	-0,94	5,48	0,19	10	60,53		
2006-02-20 11:14	54,4	2,60%	53,98	-0,93	5,47	0,05	10,5	54,21		
2006-02-20 13:17	48,3	2,31%	56,13	-0,91	5,43	0,28	10	48,09		
2006-02-20 15:16	43,4	2,07%	61,11	-0,83	4,68	0,35	9	42,82		
2006-02-20 17:16	39,6	1,89%	64,95	-0,93	4,06	0,41	9	39,02		
2006-02-21 08:30	38,9	1,86%	58,37	-0,84	4,69	0,32	10	38,39	17,9	34
2006-02-21 12:31	31,5	1,50%	65,77	-0,97	3,81	0,28	9	30,80		
2006-02-21 14:35	28,8	1,38%	65,38	-0,96	4,1	0,34	8,5	28,26		
2006-02-21 16:32	26,8	1,28%	65,63	-0,96	3,92	0,13	8	26,36		
2006-02-21 17:32	25,7	1,23%	65,76	-0,97	3,79	0,27	8,5	25,10		
2006-02-21 09:00	25	1,19%	64,9	-0,89	3,92	0,32	9,5	24,68	18,7	32
2006-02-21 12:19	21,9	1,05%	65,59	-0,91	3,93	0	8,5	21,30		
2006-02-21 14:16	19,8	0,95%	65,8	-0,95	3,85	0,34	8	19,19		
2006-02-21 16:46	18,3	0,87%	65,96	-0,95	3,75	0,47	8	17,72		
2006-02-23 08:50	12,8	0,61%	66,09	-0,91	3,73	0,16	6,5	12,02	17,9	35
2006-02-24 08:31	8,1	0,39%	66,18	-0,93	3,65	0,14	6	7,60	17,9	35
2006-02-27 09:28	2,2	0,11%	65,7	-0,89	3,9	0,3	5	1,90	18,1	32
2006-02-28 09:03	0,9	0,04%	65,99	-0,93	3,7	0,05	4,5	1,055	18,5	30
2006-03-01 10:05	0,9	0,04%	65,86	-0,95	3,61	0,19	4	0,63	18,5	30
2006-03-02 09:34	0,6	0,03%	66,01	-0,94	3,51	0,29	4	0,42	18,7	31
2006-03-07 08:50	0,6	0,03%	65,77	-0,91	3,66	0,13	4	0,42	18,1	30
2006-03-07 08:42	0,5	0,02%	65,35	-0,92	4,01	0,11	4	0,21	18,1	29
2006-03-09 09:02	0,4	0,02%	65,78	-0,92	3,72	0,21	4	0,21	17,8	29

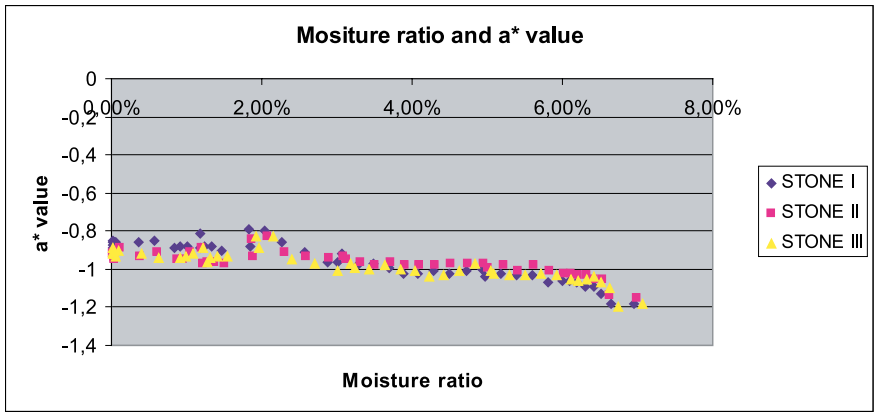
STONE III

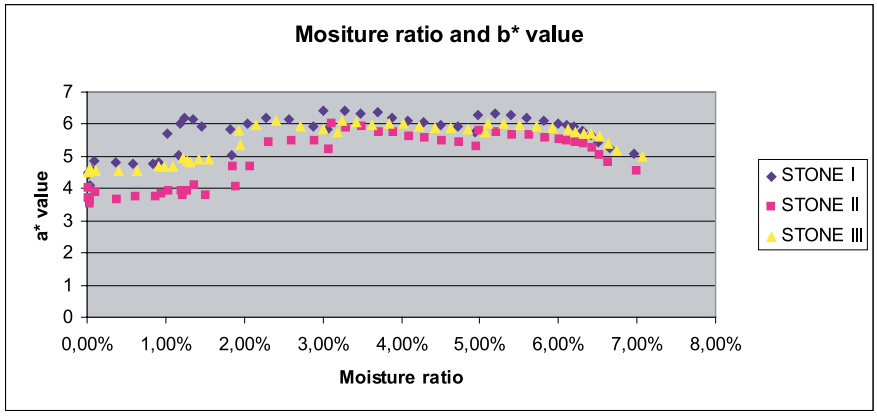
Original weight/Dry weight (g): 2129,7

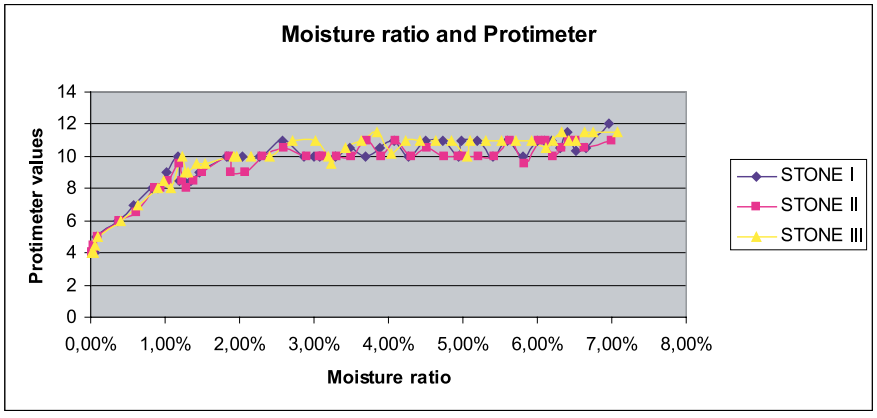
DATE/TIME	Water weight	Moisture ratio	L*	a*	b*	Deviation	Protimeter	Moisture content (kg/m^2)	Room Temperature	RH (%)
2006-02-16 09:41	150,6	7,07%	45,22	-1,18	5,01	0,01	11,5	146,80	18	34
2006-02-16 10:11	143,7	6,75%	45,99	-1,2	5,18	0,04	11,5	140,26		
2006-02-16 10:40	141,1	6,63%	47,85	-1,1	5,4	0,04	11,5	137,31		
2006-02-16 11:10	138,9	6,52%	48,82	-1,07	5,62	0,19	11	135,20		
2006-02-16 11:39	136,8	6,42%	49,02	-1,04	5,7	0,09	11	132,90		
2006-02-16 12:10	134,6	6,32%	49,36	-1,05	5,7	0,06	11,5	130,77		
2006-02-16 12:40	132,4	6,22%	49,62	-1,06	5,77	0,1	11	128,66		
2006-02-16 13:09	130,3	6,12%	49,7	-1,05	5,84	0,06	10,5	126,55		
2006-02-16 14:08	126,3	5,93%	49,98	-1,03	5,89	0,03	11	122,54		
2006-02-16 15:10	121,8	5,72%	50,26	-1,02	5,92	0,09	11	118,12		
1900-01-09 00:00	117,4	5,51%	50,4	-1,03	5,96	0,06	11	113,90		
2006-02-16 17:08	112,9	5,30%	50,62	-1,03	6,01	0,1	11	109,47		
2006-02-16 18:09	108,5	5,09%	50,62	-1,02	6,01	0,09	11	105,038		
2006-02-17 09:01	107,7	5,06%	50,68	-1,01	5,73	0,04	10	104,19	15,3	34
2006-02-17 10:00	103,2	4,85%	50,67	-0,97	5,83	0,05	11	99,55		
2006-02-17 11:06	98,7	4,63%	50,78	-1,01	5,89	0,08	11	94,91		
2006-02-17 12:04	94,3	4,43%	50,68	-1,03	5,9	0,04	11	90,27		
2006-02-17 13:07	89,9	4,22%	50,77	-1,04	5,91	0,29	11	86,05		
2006-02-17 14:02	85,9	4,03%	50,59	-1,01	6,03	0,08	10,2	81,84		
2006-02-17 15:02	82	3,85%	50,53	-1	6	0,04	11,5	77,83		
2006-02-17 16:02	77,4	3,63%	50,92	-0,98	5,99	0,27	11	73,61		
2006-02-17 17:02	73	3,43%	51	-1	6,06	0,08	10,5	69,18		
2006-02-17 18:02	68,9	3,24%	51,27	-0,99	6,09	0,12	9,5	63,49		
2006-02-20 08:17	67,8	3,18%	51,62	-0,97	5,75	0,18	10	64,75	17,4	36
2006-02-20 09:17	64,1	3,01%	52,72	-1,01	5,82	0,14	11	60,53		
2006-02-20 11:15	57,8	2,71%	52,19	-0,97	5,93	0,2	11	54,21		
2006-02-20 13:18	51,3	2,41%	53,43	-0,95	6,09	0,05	10	48,09		
2006-02-20 15:19	45,8	2,15%	56,97	-0,83	5,98	0,33	10	42,82		
2006-02-20 17:18	41,6	1,95%	61,43	-0,89	5,35	0,15	10	39,02		
2006-02-21 08:32	41	1,93%	55,24	-0,83	5,81	0,08	10	38,40	17,9	34
2006-02-21 12:32	32,9	1,54%	62,74	-0,93	4,92	0,04	9,5	30,80		
2006-02-21 14:36	30,2	1,42%	62,74	-0,93	4,92	0,03	9,5	28,26		
2006-02-21 16:33	28	1,31%	62,97	-0,94	4,83	0,15	9	26,36		
2006-02-21 17:33	27,1	1,27%	62,99	-0,96	4,87	0,15	9	25,10		
2006-02-21 09:00	26,1	1,23%	62,15	-0,89	4,94	0,08	10	24,68	18,7	32
2006-02-21 12:20	23,1	1,08%	63,07	-0,92	4,69	0,09	8	21,30		
2006-02-21 14:17	20,9	0,98%	63,18	-0,93	4,66	0,06	8,5	19,19		
2006-02-21 16:47	19,4	0,91%	63,19	-0,94	4,66	0,04	8	17,71		
2006-02-23 08:51	13,4	0,63%	63,54	-0,94	4,57	0,16	7	12,02	17,9	35
2006-02-24 08:32	8,5	0,40%	63,42	-0,92	4,57	0,09	6	7,59	17,9	35
2006-02-27 09:30	2,2	0,10%	63,28	-0,9	4,56	0,03	5	1,90	18,1	32
2006-02-28 09:04	1,3	0,06%	63,42	-0,93	4,54	0,14	4,5	1,05	18,5	30
2006-03-01 10:06	0,9	0,04%	63,08	-0,92	4,59	0,03	4	0,63	18,5	30
2006-03-02 09:36	0,7	0,03%	63,2	-0,92	4,55	0,03	4	0,42	18,7	31
2006-03-07 08:52	0,5	0,02%	63,06	-0,89	4,56	0,05	4	0,42	18,1	30
2006-03-07 08:45	0,5	0,02%	63,05	-0,92	4,53	0,06	4	0,21	18,1	29
2006-03-09 09:04	0,4	0,02%	63,14	-0,91	4,5	0,12	4	0,21	17,8	29

The stones were put in a plastic bag during the night and at the weekends.
This has provoked the ”zig-zag” pattern.


Moisture ratio and L* value
L* value (brightness)
70
60
50
40
30
20
10
0
0,00%
1,00%
2,00%
3,00%
4,00%
5,00%
6,00%
7,00%
8,00%
Moisture ratio
Stone I
STONE II
STONE III


Mositure ratio and a* value
a* value
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
0,00%
2,00%
4,00%
6,00%
8,00%
Moisture ratio
STONE I
STONE II
STONE III


Mositure ratio and b* value
a* value
7
6
5
4
3
2
1
0
0,00%
1,00%
2,00%
3,00%
4,00%
5,00%
6,00%
7,00%
8,00%
Moisture ratio
STONE I
STONE II
STONE III


Moisture ratio and Protimeter
Protimeter values
14
12
10
8
6
4
2
0
0,00%
1,00%
2,00%
3,00%
4,00%
5,00%
6,00%
7,00%
8,00%
Moisture ratio
STONE I
STONE II
STONE III

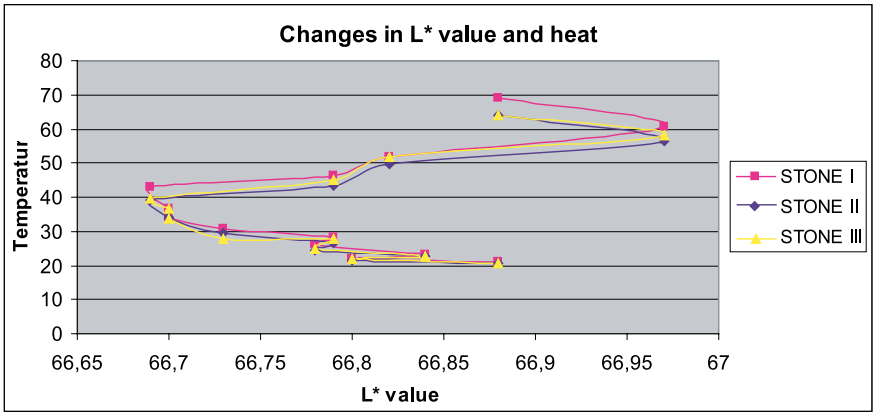
8.2 Measurement of colour on Gotland sandstone in the laboratory, depending on heat

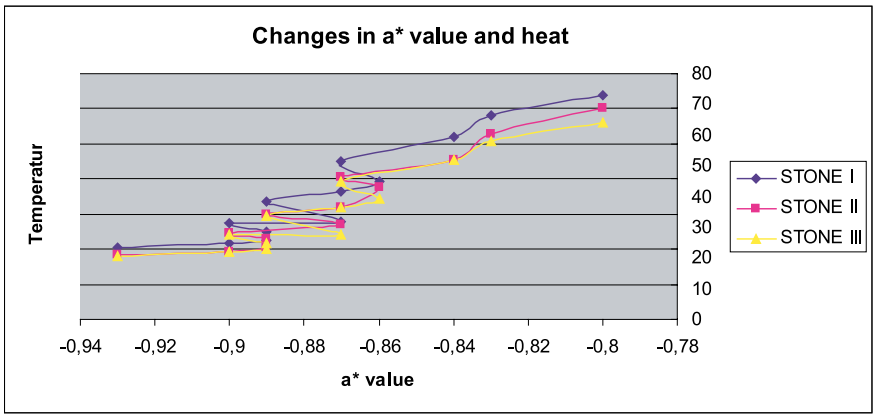
Room temperature; 19.5 °C
RH: 34 %
Date: 50214

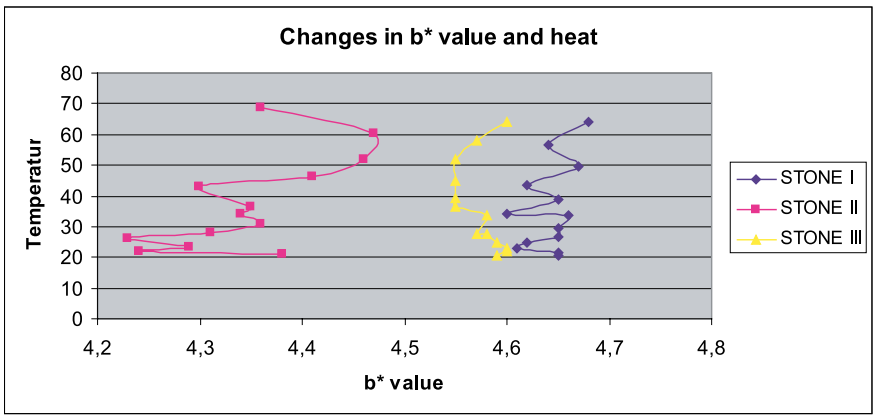
STONE I					
Time	**Tempera-ture**	**L***	**a***	**b***	**deviation**
14:05	64	66,88	-0,82	4,68	0,06
14:15	56,5	66,97	-0,8	4,64	0,02
14:25	49,5	66,82	-0,85	4,67	0,06
14:35	43,5	66,79	-0,85	4,62	0,14
14:45	39	66,69	-0,84	4,65	0,06
14:55	34	66,7	-0,84	4,6	0,1
15:05	33,5	66,7	-0,84	4,66	0,07
15:25	29,5	66,73	-0,83	4,65	0,1
15:45	26,7	66,79	-0,82	4,65	0,14
16:05	24,6	66,78	-0,84	4,62	0,12
16:47	22,7	66,84	-0,88	4,61	0,13
17:15	21,3	66,8	-0,89	4,65	0,03
17:57	20,5	66,88	-0,87	4,65	0,05

STONE II					
Time	**Tempera-ture**	**L***	**a***	**b***	**deviation**
14:07	69	65,82	-0,8	4,36	0,06
14:18	60,5	65,71	-0,79	4,47	0,03
14:25	52	65,74	-0,8	4,46	0,15
14:37	46,3	65,74	-0,82	4,41	0,03
14:47	43	65,67	-0,84	4,3	0,16
14:57	36,5	65,74	-0,83	4,35	0,07
15:08	34	65,6	-0,86	4,34	0,1
15:27	30,8	65,68	-0,84	4,36	0,2
15:47	28,2	65,75	-0,85	4,31	0,03
16:07	26,1	66,04	-0,86	4,23	0,16
16:47	23,3	65,91	-0,89	4,29	0,28
17:22	22	65,93	-0,88	4,24	0,17
17:58	21	65,87	-0,86	4,38	0,11

STONE III					
Time	**Tempera-ture**	**L***	**a***	**b***	**deviation**
14:10	64	65,1	-0,8	4,6	0,03
14:20	58	65,1	-0,83	4,57	0,83
14:30	52	65,03	-0,84	4,55	0,04
14:40	45	65,09	-0,87	4,55	0,09
14:50	39,5	65,08	-0,86	4,55	0,03
15:00	36,5	65,1	-0,87	4,55	0,08
15:10	33,5	65,1	-0,89	4,58	0,08
15:30	27,8	65,09	-0,87	4,57	0,02
15:50	27,6	65,09	-0,9	4,58	0,02
16:10	25	65,27	-0,89	4,59	0,08
16:50	22,7	65,23	-0,89	4,6	0,04
17:23	21,8	65,23	-0,9	4,6	0,04
18:00	20,6	65,34	-0,93	4,59	0,07


Changes in L* value and heat
Temperatur
80
70
60
50
40
30
20
10
0
66,65
66,7
66,75
66,8
66,85
66,9
66,95
67
L* value
STONE I
STONE II
STONE III


Changes in a* value and heat
Temperatur
80
70
60
50
40
30
20
10
0
-0,94
-0,92
-0,9
-0,88
-0,86
-0,84
-0,82
-0,8
-0,78
a* value
STONE I
STONE II
STONE III


Changes in b* value and heat
Temperatur
80
70
60
50
40
30
20
10
0
4,2
4,3
4,4
4,5
4,6
4,7
4,8
b* value
STONE I
STONE II
STONE III

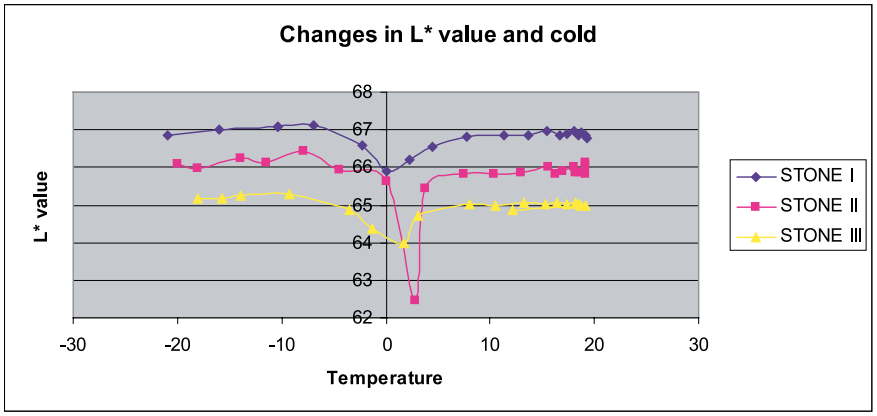
8.3 Measurement of colour on Gotland sandstone in the laboratory, depending on the cold

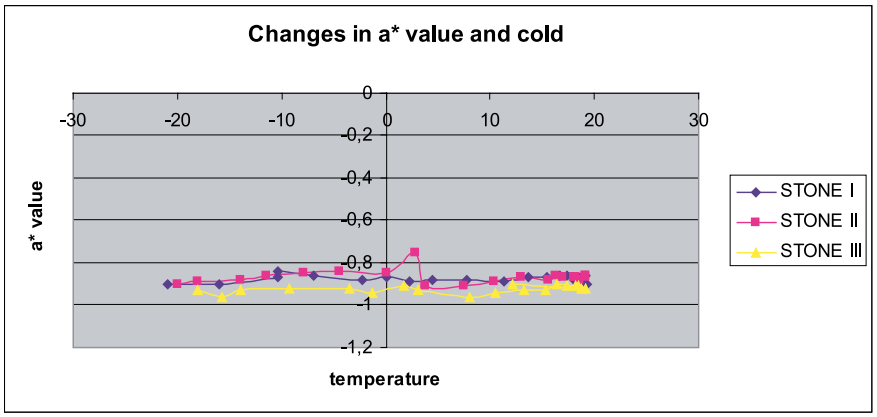
The stones had been in the freezer for 18 hours in plastic bags.
Date: 15/2/2005
Room temperature; 18 °C
RH: 34 %

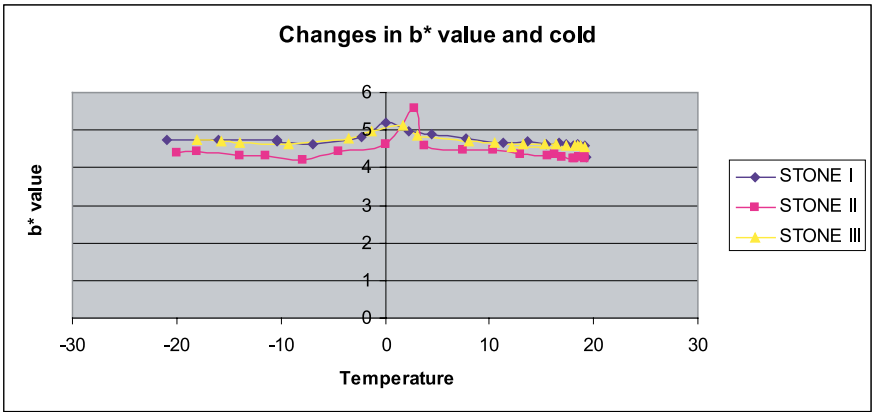
STONE I					
Time	**Tempera-ture**	**L***	**a***	**b***	**deviation**
10:41	-21	66,87	-0,9	4,75	0,1
10:45	-16	67	-0,9	4,75	0,05
10:51	-10,4	67,07	-0,87	4,73	0,03
10:54	-10,3	67,1	-0,84	4,7	0,09
10:59	-6,9	67,12	-0,86	4,62	0,14
11:09	-2,2	66,6	-0,88	4,81	0,07
11:13	0	65,88	-0,87	5,18	0,62
11:21	2,2	66,19	-0,89	4,97	0,07
11:27	4,5	66,56	-0,88	4,88	0,04
11:47	7,8	66,81	-0,88	4,77	0,03
12:07	11,3	66,86	-0,89	4,66	0,07
12:37	13,7	66,86	-0,87	4,7	0,03
13:07	15,5	66,95	-0,87	4,63	0,12
13:37	16,7	66,86	-0,86	4,68	0,06
14:07	17,4	66,9	-0,86	4,63	0,04
14:36	18,1	66,97	-0,88	4,58	0,06
15:07	18,5	66,86	-0,87	4,62	0,06
15:38	18,8	66,92	-0,88	4,57	0,04
16:07	19,2	66,87	-0,86	4,59	0,07
16:37	19,3	66,76	-0,9	4,28	0,05

STONE II					
Time	**Tempera-ture**	**L***	**a***	**b***	**deviation**
10:44	-20	66,08	-0,9	4,4	0,11
10:57	-18	65,97	-0,89	4,44	0,03
10:52	-13,9	66,26	-0,88	4,31	0,18
10:56	-11,5	66,12	-0,86	4,33	0,04
11:00	-7,9	66,42	-0,85	4,21	0,15
11:10	-4,4	65,94	-0,84	4,44	0,13
11:15	0	65,63	-0,85	4,63	0,22
11:23	2,8	62,46	-0,75	5,57	0,99
11:29	3,8	65,43	-0,91	4,59	0,14
11:49	7,5	65,82	-0,91	4,46	0,1
12:09	10,3	65,84	-0,89	4,46	0,08
12:39	13	65,87	-0,87	4,37	0,13
13:12	15,6	66,03	-0,88	4,32	0,2
13:38	16,3	65,82	-0,86	4,34	0,06
14:08	16,9	65,91	-0,87	4,29	0,15
14:37	18,1	66	-0,87	4,26	0,16
15:08	18,2	65,87	-0,87	4,26	0,1
15:40	18,6	65,86	-0,88	4,29	0,09
16:09	19,1	65,82	-0,87	4,31	0,05
16:40	19,1	66,14	-0,86	4,24	0,08
16:42	19,1	66,05	-0,86	4,28	0,02

STONE III					
Time	**Tempera-ture**	**L***	**a***	**b***	**deviation**
10:50	-18	65,17	-0,93	4,74	0,1
10:53	-15,7	65,16	-0,96	4,69	0,03
10:57	-14	65,23	-0,93	4,65	0,02
11:02	-9,3	65,29	-0,92	4,61	0,07
11:12	-3,5	64,88	-0,92	4,76	0,05
11:18	-1,3	64,37	-0,94	4,95	0,18
11:24	1,7	64	-0,91	5,11	0,1
11:31	3,1	64,72	-0,93	4,87	0,04
11:41	8	65,03	-0,96	4,71	0,04
12:09	10,5	64,98	-0,94	4,66	0,05
12:40	13,3	65,04	-0,93	4,64	0,03
13:11	15,3	65,01	-0,93	4,62	0,04
13:40	16,4	65,04	-0,9	4,62	0,05
14:10	17,3	65,01	-0,91	4,6	0,03
14:38	18,2	65,06	-0,91	4,58	0,07
15:09	18,4	65,03	-0,91	4,59	0,09
15:41	18,7	64,98	-0,92	4,57	0,04
16:10	19,2	64,99	-0,92	4,56	0,07
16:41	12,2	64,88	-0,9	4,56	0,04


Changes in L* value and cold
L* value
68
67
66
65
64
63
62
-30
-20
-10
0
10
20
30
Temperature
STONE I
STONE II
STONE III


Changes in a* value and cold
a* value
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-30
-20
-10
0
10
20
30
temperature
STONE I
STONE II
STONE III


Changes in b* value and cold
b* value
6
5
4
3
2
1
0
-30
-20
-10
0
10
20
30
Temperature
STONE I
STONE II
STONE III

Appendix 9

Capillary Water Absorption – Calculation of w- and B-values

Test 1									
Stone type: Gotland sandstone/Valar 1									
Samples: 1.7–1.9					Date: 2006-04-18				
Height [mm]: 160 Width [mm]: 40					Area [mm²]: 6400				
Mass [g]: 567,56					Climate [T /RH %)]: 40% RH 19,1 °C				
t [sec]	30	60	120	300	600	1200	1800	3600	*24h*
√t [sec]	5,48	7,75	10,95	17,32	24,49	34,64	42,43	60,00	*293,94*
m [g] Sample-No. 1,7: 578,85 g	579,78	580,22	580,60	581,28	581,88	582,78	583,52	584,99	*608,71*
m [g] Sample-No. 1,8; 580,00 g	580,95	581,43	581,84	582,49	583,15	584,14	584,88	586,41	*609,71*
m [g] Sample-No. 1,9; 543,83 g	544,42	544,62	544,82	545,07	545,43	545,94	546,33	547,23	*572,51*
m [g]	568,38	568,76	569,09	569,61	570,15	570,95	571,58	572,88	*610,79*
Δm_{H20} [g]	0,82	1,20	1,53	2,05	2,59	3,39	4,02	5,32	*29,42*
Δm_{H20} [kg/m²]	0,13	0,19	0,24	0,32	0,41	0,53	0,63	0,83	*4,60*
Height [mm] Sample-No. 1,7	1	1,1	1,2	1,4	1,85	2,45	2,8	3,6	
Height [mm] Sample-No. 1,8	0,9	1,1	1,3	1,5	1,85	2,4	2,85	3,6	
Height [mm] Sample-No. 1,9	0,9	1,05	1,15	1,3	1,45	1,75	1,9	2,35	
Height [mm]	9,33	10,83	12,17	14,00	17,17	22,00	25,17	31,83	
$w=m_{H20}$, A [kg/m²√h]	5,97				B = x(t)/√t [mm/vs]	0,42			
Total water absorption in % weight	5,18%				Total water absorption in % volume	11,49%			
Bulk Density (g/cm³)	2,22		True Density (g/cm³)	2,50	Porosity (Vol %)	11,49%			

Test 2									
Stone type: Gotland sandstone/Valar 2									
Samples: 2,1–2,5					Date: 2006-04-18				
Height [mm]: 160 Width [mm]: 40					Area [mm²]: 6400				
Mass [g]: 567,56					Climate [T /RH %)]: 40% RH 19,1 °C				
t [sec]	30	60	120	300	600	1200	1800	3600	*24h*
√t [sec]	5,48	7,75	10,95	17,32	24,49	34,64	42,43	60,00	*293,94*
m [g] Sample-No. 2.1: 578,85 g	581,3	581,58	581,97	582,66	583,41	584,43	585,22	586,93	*609,69*
m [g] Sample-No. 2.2; 580,00 g	564,12	564,42	564,81	565,38	566,04	566,98	567,67	569,35	*591,81*
m [g] Sample-No. 2.5; 543,83 g	583,22	583,58	584	584,7	585,44	586,33	587,14	588,72	*613,04*
m [g] ; 579,62 g	576,21	576,53	576,93	577,58	578,30	579,25	580,01	581,67	*604,85*
Δm_{H20} [g]	1,07	1,38	1,78	2,44	3,15	4,10	4,87	6,52	*29,70*
Δm_{H20} [kg/m²]	0,17	0,22	0,28	0,38	0,49	0,64	0,76	1,02	*4,64*
Height [mm] Sample-No. 2,1	1	1,1	1,3	1,6	1,8	2,3	2,6	3,5	
Height [mm] Sample-No. 2,2	0,9	1,05	1,2	1,4	1,75	2,3	2,75	3,6	
Height [mm] Sample-No. 2,5	1	1,1	1,2	1,45	1,7	2,15	3,4	3,4	
Height [mm]	9,67	10,83	12,33	14,834	17,50	22,50	29,17	35.00	
$w=m_{H20}$, A [kg/m²√h]	5,84				B = x(t)/√t [mm/√s]	0,48			
Total water absorption in % weight	5,16%				Total water absorption in % volume	11,60%			
Bulk Density (g/cm³)	2,25		True Density (g/cm³)	2,54	Porosity (Vol %)	11,60%			

Average w-value: 5.90 kg/m²√h
Average B-value: 0.45 mm/√s

Appendix 10

Results: Field Measurements of UPV in Stockholm for NHB

Report by Dr. Katarina Malaga, SP

Ultrasound pulse velocity (UPV) measurements offer an accurate and repeatable non-destructive technique with the potential of detecting changes in the strength of a stone even when there are no visible signs of deterioration. On a comparison basis, density variation within a single piece or between similar parts can be detected.

The wave frequency used was 60 kHz, the sampling frequency 10 MHz and the time resolution 0.1(s. All measurements were repeated several times and an average was calculated for each measured point and occasion. The measurements were direct (the two sensors placed on two opposite sides of the sample) and indirect (the two sensors placed on the same side of the sample – surface measurements).

The objective of the UPV was to analyse the condition of the measuring objects and to find a relation to other properties analysed on the stones.

Ultrasonic measurements can be correlated to modulus of elasticity, modulus of rupture, and degradation of internal structure, such as the detection of cracks. In this particular case an attempt to correlate water absorption by means of Karsten pipes was made. The assumption was made that if the UPV is relatively low, water absorption should be higher than for the fresh stone. This assumption was difficult to prove directly by performing calculations of the correlation of all objects, although the overall results are in agreement with this assumption.

Another type of correlation between UPV and age of the object was expected to give an indication of the deterioration of the object over a period of time. Objects of different ages were analysed both by direct and indirect measurements. The result does not give any straight line, although none was expected. In most cases the age of the object tallies with the age of the completion of the construction. The age of the measuring points of many of the objects might vary significantly as a result of unnoticed and undocumented exchanges of the material. Many of the objects had been treated with different chemical agents at some point. Age is only one of the factors influencing the deterioration of the object. The reason why the results are so widespread demonstrates that other factors also influence the results of the UPV and should be taken into account. Although the results are widespread there is a clear indication of deterioration over a period of time (see the straight lines inserted in the diagrams). The natural decrease in UPV for the object in outdoor conditions is assumed to be ca 0.3 km/s per 100 years. This should be confirmed and further investigated by measuring objects or samples located indoors that have a good documented history. All interventions made during the lifetime of any object can change the natural way of deterioration, and through this the expected UPV result, particularly in the observation and documentation of the natural weathering process. For the examination of the conditions of the investigated objects the result can be taken as being conclusive. However, all the influencing factors have to be recorded. A more detailed and object adjusted measurement of humidity in the object and in the nearest vicinity is required. Further studies of how older samples of Gotland sandstone behave in different humidities by analysing their sorption, water absorption and UPV would improve the interpretation of the overall results. A continuation of this investigation is therefore recommended. A detailed planning of future correlations between the UPV and Karsten pipe has to be performed in order to show reliable results. Not all the objects analysed in this study could be used for such correlations.

Correlations between the UPV and age of the object

In the following two diagrams (Figs 1 and 2), the results of the UPV (direct and indirect) are plotted against the construction age of the objects. This age might be misleading in several objects, due to intervention work that has not been documented. The curve in the diagrams is an assumption of the natural weathering process where a decreasing intergranular decohesion is expected leading to a loosening of the stones' structure and resulting in a higher porosity that gives lower values of the UPV.

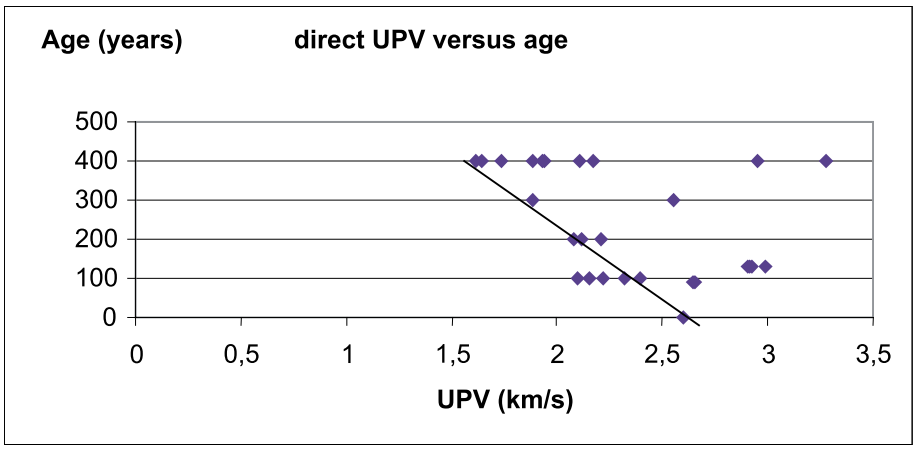


Fig 1. Correlation of the results of the direct UPV with the construction age of the measured objects.

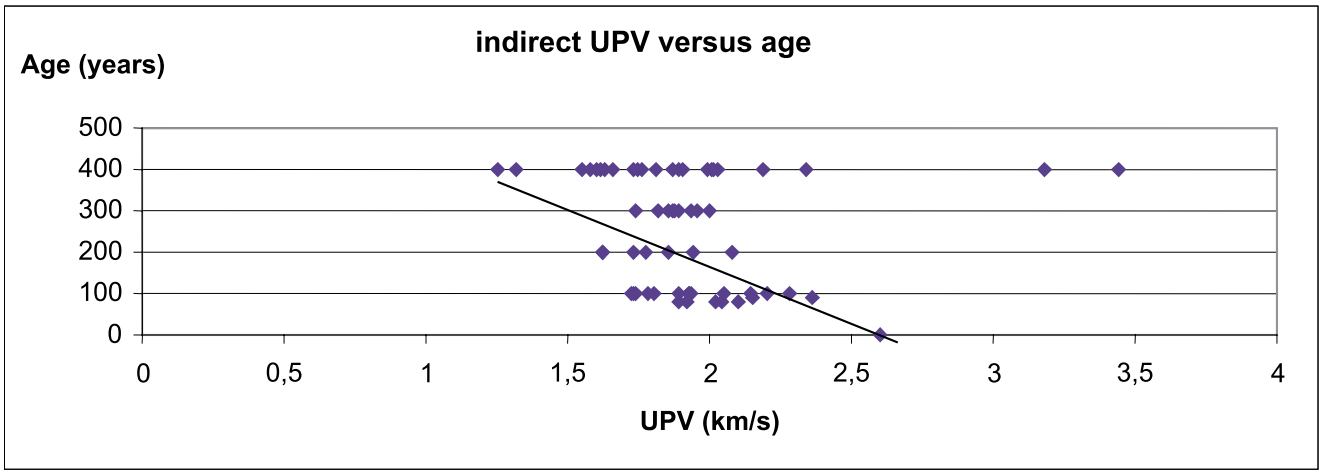


Fig 2. Correlation of the results of the indirect UPV with the construction age of the measured objects.

The German Church

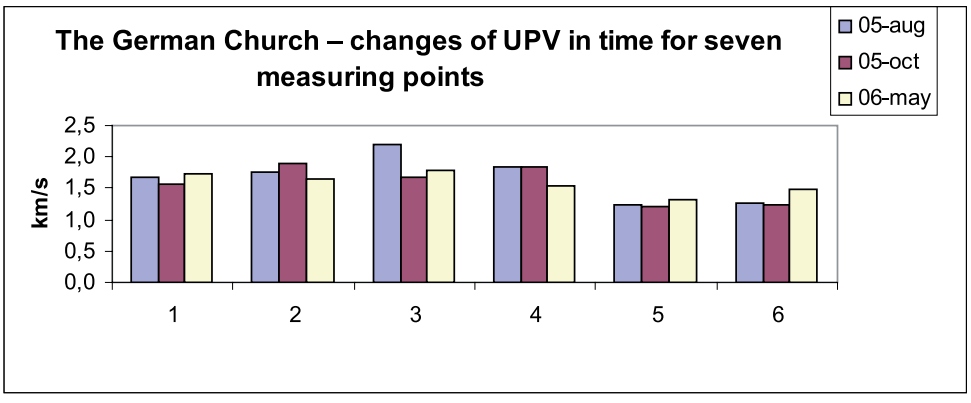


Fig 3. Indirect measurements of UPV for the German Church for the period 2005–2006.

The UPV was measured on three separate occasions (see the legend in Fig 3). The measurements show relatively stable values which demonstrates the good repeatability of the measuring method. No drastic changes of the UPV were expected. The UPV is humidity dependent and small variations in the results might be explained by the small variations of humidity between the measurement occasions. The mean value of all the UPV measurements at this place is low, 1.7 ± 0.1 km/s with the lowest values of 1.2 km/s, compared to fresh sandstone's UPV of ca 2.6–2.8 km/s. These measurements directly reflect the visual observations of the object. The worst weathered parts measured at the German Church had the lowest UPV values compared to all the measured objects. The object has severely deteriorated. The UPV of 1.2 km/s indicates at least 50 percent loss of the original strength (which means that sand grains are losing their cohesion and expressed by sanding) in the stone.

An attempt to compare the UPV with water absorption by means of Karsten pipes was made. The correlation between the two measurements is a difficult task to perform due to several uncertainties. Several aspects need to be included. The places are not the same for the two measurements despite the fact that the UPV measuring distance covers the Karsten pipe area (Fig 4). The result shows that

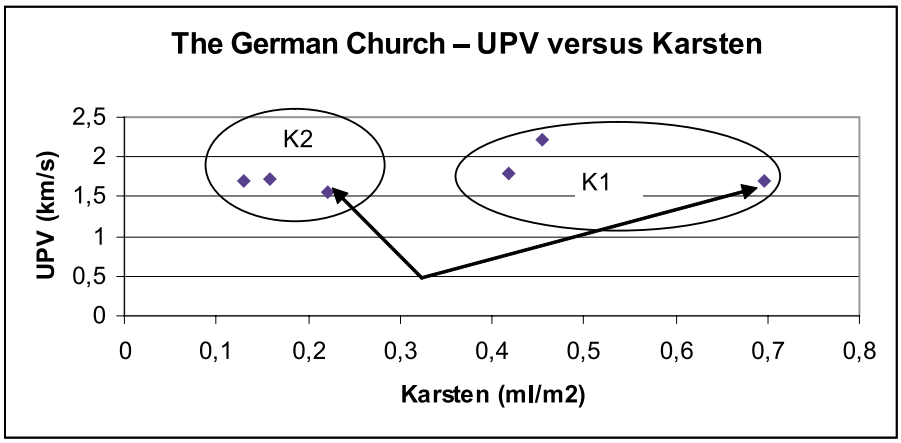


Fig 4. Correlation between UPV and Karsten pipe (K1 and K2 – two measuring points) water absorption for the German Church for the period 2005–2006.

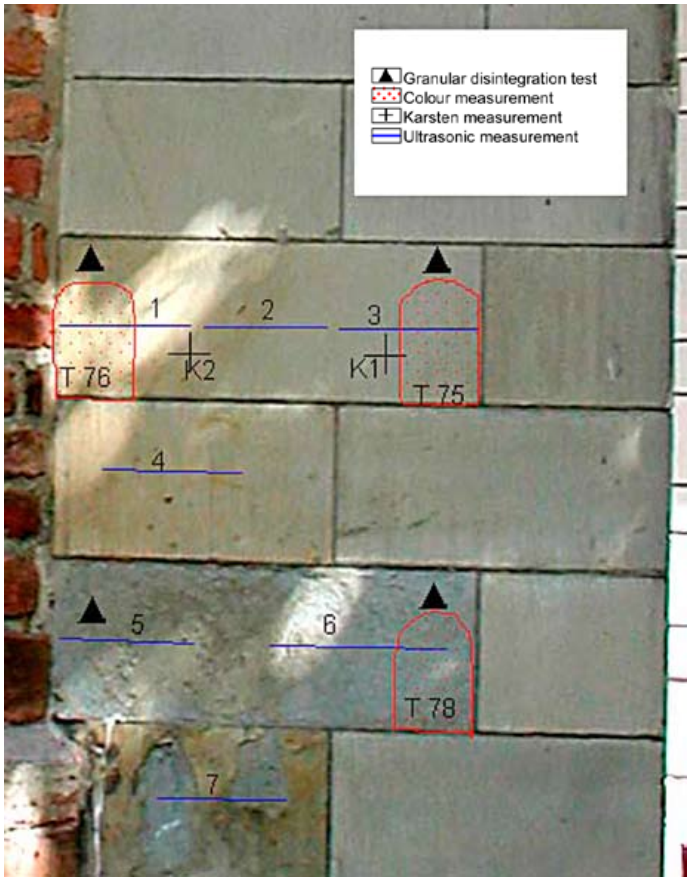


Fig 5. The German Church – location of the measuring points. Blue lines correspond to UPV distances and K1 and K2 for Karsten pipe areas.

the two measured areas have higher variations of water absorption than the variation in UPV. The most damaged areas were not possible to use for Karsten pipe measurement (not possible to attach the pipe to the surface) although the UPV could be measured. The marked areas for K1 and K2 demonstrate two different measurements points, so the absorption was expected to be different. In both cases the absorption was higher on the third occasion, which may be explained by the drier air conditions.

The following four diagrams show the results of the UPV measurements. The results were relatively stable during the measurement sessions. Small variations in UPV reflect the humidity changes rather than any deterioration. This also points out that deterioration is a relatively slow process and that in order to detect changes, the UPV should be measured once a year, preferably in similar same atmospheric conditions (humidity and insolation).

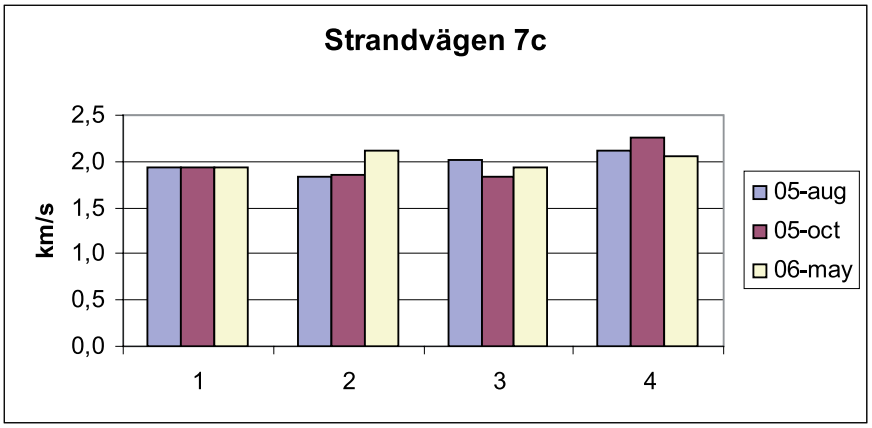


Fig 6. Results of indirect measurements of UPV.

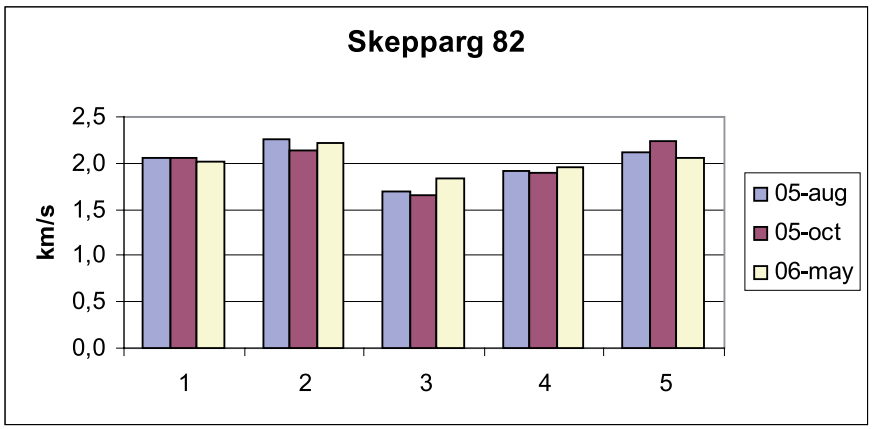


Fig 7. Results of indirect UPV.

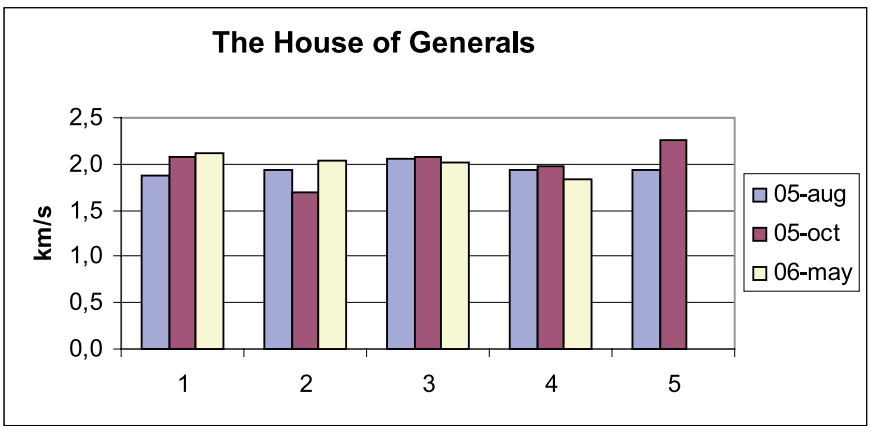


Fig 8. Results of direct UPV.

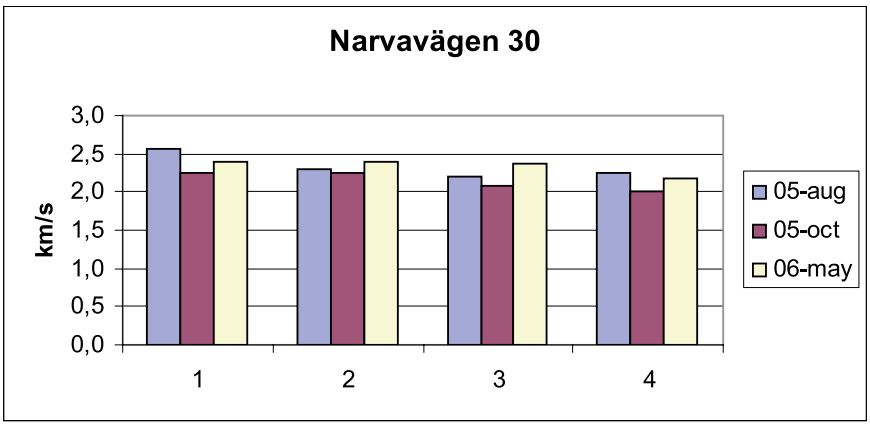


Fig 9. Results of direct UPV.

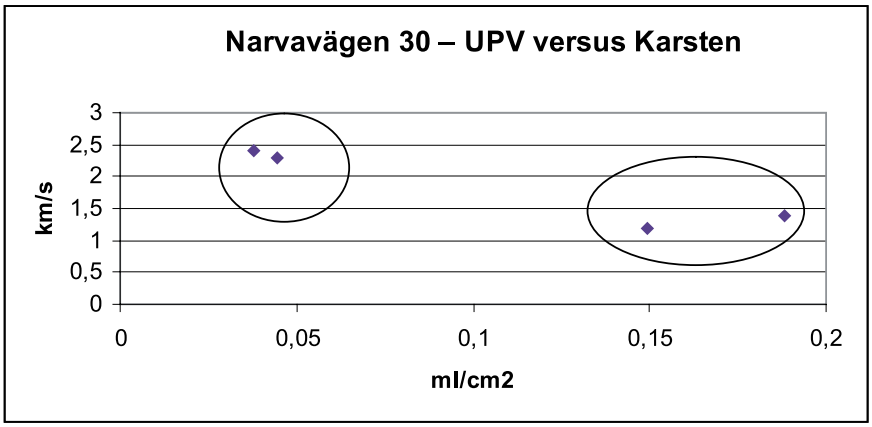


Fig 10. Correlation between UPV and water absorption by means of Karsten pipe.

High UPV values (ca 2.5 km/s) correspond to much lower water absorption (at least 3 times lower) than for the second absorption area where the UPV was low (ca 1.4 km/s). In this case the correlation between UPV and water absorption is good. Water absorption decreases with increased UPV (in this case probably more dense stone). However, it should be pointed out that the investigated areas for the two measuring methods are not the same.

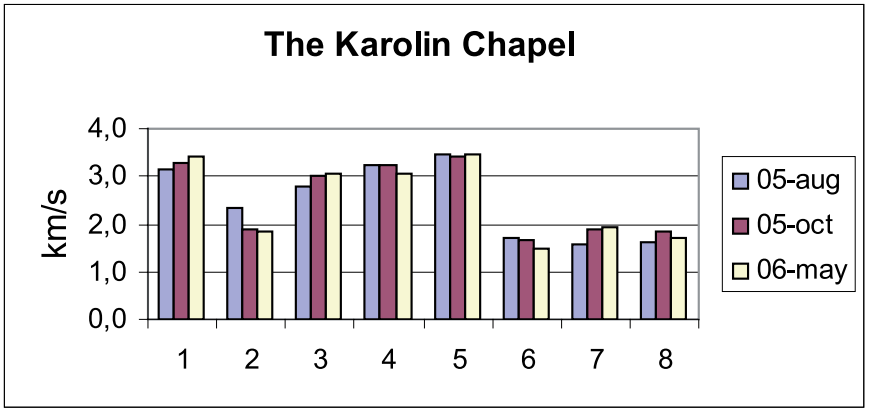


Fig 11. Results of direct and indirect measurements. This diagram shows a clear diversity of weathering conditions in that the same object could also be observed by visual examination.

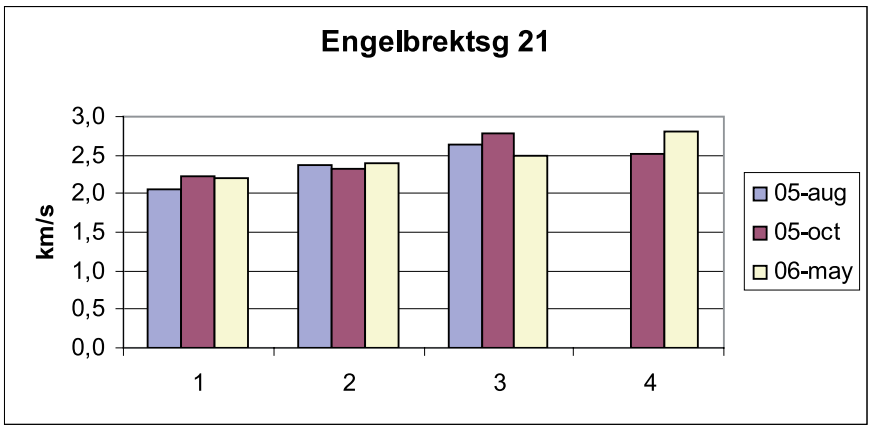


Fig 12. Results of indirect (1 and 2) and direct (3 and 4) UPV measurements. In most cases the direct measurements give higher values of UPV.

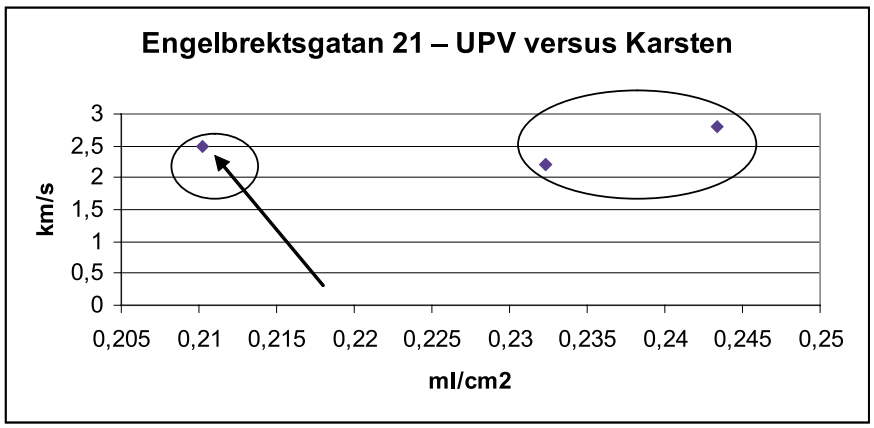


Fig 13. Relation between UPV and water absorption. The arrow shows two identical absorption values.