**Science and Art: A Future for Stone**

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# SCIENCE and ART: A Future for Stone

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# SURFACE HARDNESS TESTING FOR THE EVALUATION OF CONSOLIDATION OF POROUS STONES

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## Abstract

In the present study a commercial hardness tester was used to evaluate the effectiveness of consolidation on two monumental tombs composed of different sandstones. Furthermore different stone types were also repeatedly treated in a stepwise fashion and retested. The main goal was to determine whether it would be possible to detect even a small increase of consolidation by reloaded treatments. The results of the surface hardness tests on the stone samples correlated to their compressive strength. Tests were also conducted to determine whether a correlation between the increase of hardening of the surface in relation to the increase of the uniaxial compressive strength and ultrasonic velocity measurements exist. In an applied case study the consolidation effect has been verified after the consolidation of sandy stone parts with the same consolidant.

**Keywords**: consolidation, surface hardness, ultrasonic velocity, porosity

## 1. Introduction

To evaluate the state of weathering and the effectiveness of consolidation on-site only a few methods are available. The most common non- or low destructive technique is the ultrasonic wave measurement and the drilling resistance test, which has been applied for around 20 years in the field of stone conservation. The drilling resistance test is a useful method for detecting scales and exfoliations especially in sandstones (Cnudde *et al.* 2009, Siedel *et al.* 2010). However, the test cannot differentiate exactly between consolidated and untreated areas (Lotzmann and Sasse 1999). Using results from different sources a comparison between drilling resistances and uniaxial compressive strength could be derived (Fratini *et al.* 2006, Pamplona *et al.* 2007). However, the investigations in this study show that there is a clear positive correlation between the surface hardness and the compressive strength (Fig. 1). Testing stone objects with a low impact affect can be performed by using a Schmidt hammer. The method is a well-known portable field test. The testing tool applies an impact force and the rebound of the hammer applying the force is measured. Different

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types of hammers are in use, but the testing tool in general was developed for the testing of cement and not for weak and soft materials such as weathered building stones. In some cases the hammer will damage the material tested. The rebound hammer used in this study is comparable with a micro-rebound hammer with a low impact force. An overview on surface hardness measurements in geomorphology and heritage science can be found in Viles *et al.* 2010. Booth *et al.* (2012) show that the device used in this study could be used to detect the effect of different consolidation materials on stone.

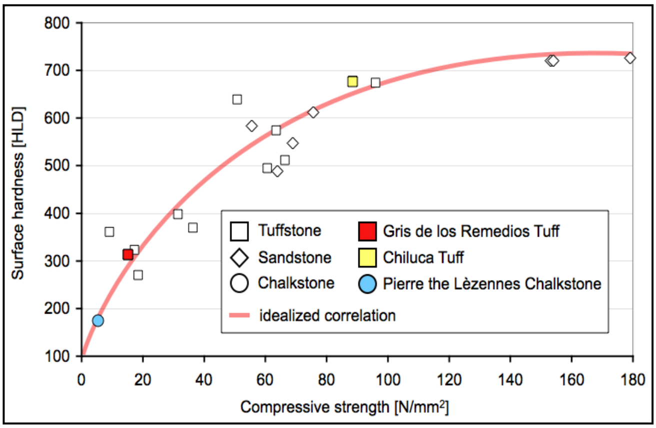


*Fig. 1: Surface hardness versus compressive strength for different stone types and the three stone samples investigated in this study.*

## 2. Testing material and case studies

The testing material included two tuffstones (Fig. 2b and Fig. 2c) and one poorly cemented limestone (Fig. 2a). These stone types show different petrophysical properties. Two of them (the chalkstone and the Remedios tuff) can be classified as low or weakly bound building stones. The object tested and treated in this study are two monumental pillar tombs in the historical Bartholomew Cemetery of Goettingen, Germany (Fig. 2d and Fig. 2e). The tested object is constructed from two different types of sandstone. They show different types of weathering as well as different forms of crusts and deposits.

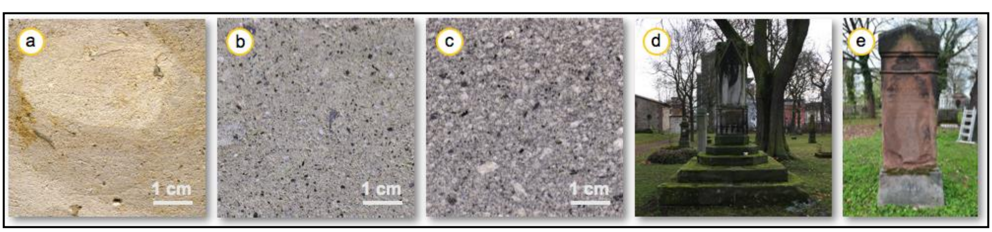


*Fig. 2: a) Pierre the Lèzennes Chalkstone; b) The Gris de los Remedios tuff; c) The Chiluca andesitic tuff; d) The Pickardt tomb monument and e) the Schneider pillar tomb.*

## 2.1. Stone material

### 2.1.1. Pierre the Lèzennes Chalkstone

The chalkstone investigated in this study is a glauconitic, granular calcareous chalk of the Maisières Chalk Formation. The rock is an important building stone and is known in France as "Verts", "Gris des mineurs" (Mons), “Pierre the Lézennes” (Lille), “Craie grise du Cambrésis” or "Bonne Pierre de Valenciennes". This chalk was worked in underground quarries for use as a building stone. The stone contains basal beds yielding phosphate grains or pebbles. Many fossil-like bivalves can be found in the highly porous matrix. The porosity of the stone reaches nearly 43 % and the compressive strength only 5 $N/mm^2$.

### 2.1.2. Gris de los Remedios Tuff

The volcanic rock of Remedios is a lapilli tuff, supported by an ash matrix. The color of this tuff is gray to light gray (Fig. 2c). The ash matrix is more or less gray. Within the matrix, dark spots occur that can be traced back to mafic minerals. The mafic minerals often show prismatic crystal shapes and represent mostly idiomorphic developed hornblende crystals. The white lapilli fragments are dominated by pumice. Microscopic examinations revealed the presence of minerals such as crystobalite, clays, sodium plagioclase and hornblende. The porosity of the Gris de los Remedios ranges from 24.5 to 31.5%, whereas their bulk density is around 1.78–1.92 $g/cm^3$. The Remedios variety has an average compressive strength of 17.3 $N/mm^2$ and a Youngs modulus of 8.29 $kN/mm^2$ (Wedekind *et al.* 2011). The investigated material originates from the quarries of Los Remedios located in the mountains northwest of Mexico City.

### 2.1.3. Chiluca Tuff

The Chiluca tuff is a pyroxene ash tuff with a high proportion of fragmented feldspar single crystals, giving the rock a porphyritic appearance. The tuff is gray in color with dark inclusions of mafic minerals (Fig. 2b). Feldspar single crystals occur in a fine-grained matrix. The Chiluca variety shows a porosity of 8% and a density of 2.58 $g/cm^3$ and a compressive strength of 90.5 $kN/mm^2$ (Wedekind *et al.* 2011). Historical quarries of the Chiluca tuff can be found on some islands of the former Lake Texcocco, now modern day Mexico City.

## 2.2. Case Studies

### 2.2.1. Tombs of Schneider and Pickardt

The tombs of Schneider and Pickardt are located in the historical Bartholomew Cemetery in Goettingen, Germany (Fig. 2d and Fig. 2e). The construction material predominately used for the tombs is the highly porous Buntsandstein. Here, the rocks of the Solling Formation of the Middle Buntsandstein are especially significant (Kracke *et al.* 2007). The Pickardt tomb is a neo-gothic pillar tomb (1857) made from the light coloured local Reinsberg variety. The Schneider tomb (1850) is a classical pillar tomb made from the Arenshausen variety (Kracke *et al.* 2008).

# 3. Methods

## *3.1. Porosity*

In order to acquire the matrix and bulk density as well as the porosity, hydrostatic weighing was carried out. Stone samples were measured using hydrostatic weighting (DIN 52 102) for determining the open (effective) porosity as well as the density. The water-saturated mass, the buoyancy mass of the samples measured after water saturation under vacuum, and the dry sample mass were used to calculate the porosity.

## *3.2. Compressive strength*

For the compressive strength tests, standard cylindrical specimens of 50 mm in diameter and 50 mm in length with co-planar end-faces were used. The uniaxial compressive strength in this study was only measured in Z-direction 10 times. The compressive load was applied by a servo-hydraulic testing machine with a very stiff testing frame (3000 $kN/mm^2$) and a class 1 load range up to 300 kN. The load was applied to the end-faces of the specimen with a strain rate of $10^{-5}$ $s^{-1}$ until failure. The maximum load is defined as the uniaxial compressive strength.

## *3.3. Surface hardness*

Surface hardness measurements were done in situ as well as on stone samples in the laboratory. The testing instrument works with the rebound method. Like the well-known Schmidt Hammer, it indirectly measures the loss of energy of a so-called impact body. D. Leep, the inventor of this method defined his own hardness value called the Leep hardness value: HL. For the measurements an Equotip 3 (proceq) portable testing device with an impact device D was used. Therefore, the final results are given as HLD. The instrument offers extended capabilities such as measurements on almost all parts with different geometries, with a high accuracy of ± 4 HL (0.5% at 800 HL) and automatic correction for impact direction. For each investigated area 10 individual measurements were done and the average value calculated. In the laboratory the measurements were done on dry and water-saturated samples. To optimise the testing results the tested surface of the cylindrical specimens were polished to reduce the roughness of the material. The specimens were consolidated by total saturation within a commercial silicic acid ester with a gel deposit rate of 10 % (KSE 100). In total 30 specimens of each stone type were treated: 10 samples one time, 10 samples two times and 10 samples three times.

## *3.4. Ultrasonic velocity*

Ultrasonic velocity measurements were carried out the cylindrical specimens. Transient times of ultrasonic pulses (piezoceramic transducers, resonant frequency 1 MHz) were measured in the Z-orthogonal direction using the pulse transmission technique (Birch 1960, 1961).

# 4. Results

## *4.1. Laboratory studies*

In general, the three different stone types show very different initial values and an increase in strength and hardness after consolidation treatment (Fig. 3).

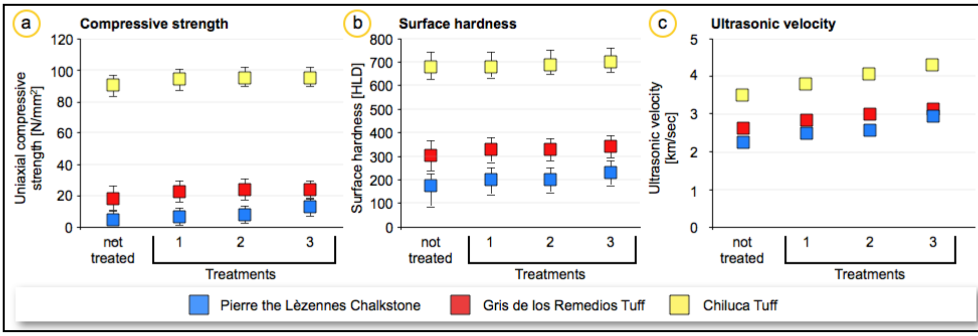


*Fig. 3: Results of the different petrophysical measurements before and after stepwise consolidation treatment; a) Compressive strength; b) surface hardness; c) ultrasonic velocity.*

### *4.1.1. Uniaxial compressive strength and porosity*

The chalkstone shows the largest increase in compressive strength after consolidation. However, with only 5 N/mm$^2$ the sample was the one with the lowest strength and the highest porosity (42.5%). After the first treatment an increase of 34 % took place. After the second treatment the compressive strength reaches 10.7 N/mm$^2$ with an increase of 114% related to the untreated value. After the third treatment 13.2 N/mm$^2$ was reached, again a significant increase of another 50%. At the same time a decrease in porosity took place: from nearly 5% (1$^{st}$ treatment) to 16.5% (2$^{nd}$ treatment) and finally after the 3$^{rd}$ treatment to nearly 36% (Fig. 4a). The increase in surface hardness of the Remedios tuff only reaches around 30% comparable to the untreated samples. Between the second and third treatment the increase was quite low with a value of only 1.1%. In contrast, the decrease in porosity shows the highest values by reaching 40.5% (Fig. 4b). For the Chiluca tuff the effect of strength increase was the lowest. The stone shows the highest compressive strength with more than 90 N/mm$^2$, but only an increase of 6% after the third treatment (Fig. 4c). Also the porosity shows the lowest decrease from 7% to 10.5% and finally 21%.

### *4.1.2. Surface hardness*

The percentage increase of surface hardness shows the highest values for the chalkstone congruent to the uniaxial compressive strength. After the first treatment an increase of 15.4% took place, then another 9% after the second treatment and after the last treatment another 8% occurred. Surface hardness ranges between 175.9 to 233.75 HLD (Fig. 3b). Surface hardness of the Remedios tuff shows values between 308 to 342 HLD (Fig. 3b). After the first treatment the percentage increase of the Remedios tuff reaches 7.1% and after the second one only another 1.1% and finally another 3% is attained. In the case of the Chiluca tuff the surface hardness is the highest but the increase after treatment the lowest. The HLD values range between 680 and 701 (Fig. 3b), but the increase after the first treatment only reaches 0.14%, after the second 1.1% and finally another 1.7 %.

### *4.1.3. Ultrasonic velocity*

In general, the highest initial value of ultrasonic velocity is shown by the Chiluca tuff (3.516 km/sec), the second highest is the Remedios tuff (2.65 km/sec) and the lowest is the chalkstone with a value of 2.26 km/sec. The values of ultrasonic velocity of the different samples show closer values of percentage increase after treatment than the destructive mechanical testing procedures. After the first treatment the chalkstone shows an increase of nearly 10% followed by another 4.4% and finally a significant step of 16.8% (Fig. 4a). The Remedios tuff has a comparable increase of 7.1% after the first treatment and a stepwise further increase of another 5.7% followed by another 4.5% after the last treatment (Fig. 5b). The values of the Chiluca tuff range between the ones of the chalkstone and the Remedios tuff. In the first step of consolidation an increase of 8.5% was established. After the second treatment another 7.5% was attained, which is nearly doubled and finally again an increase of 7.2% could be measured (Fig. 4c).

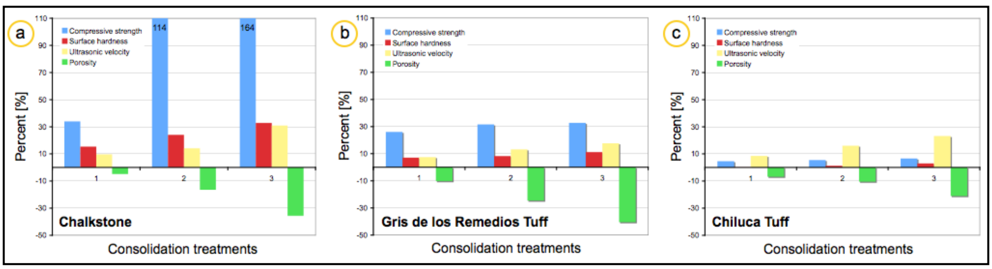


*Fig. 4: Percentage increase of the compressive strength, the surface hardness, the ultrasonic velocity and the decrease after stepwise treatments. a) For the chalkstone, b) the Gris de los Remedios tuff and c) the Chiluca tuff.*

## ***4.2. Case Studies***

During 2014 and 2015 a scientific consolidation treatment project was done on the tomb monuments presented in this study. The weathered areas show sanding and are located mostly in those areas where no water runs down during a rainfall and are visible by dark deposits and microbiology (Fig. 5a and Fig. 5b). Where decorative areas of the Pickardt tomb and the Schneider tomb are exposed to rain, only low weathering or none could be observed. At these areas the surface hardness averaged 481 HLD for the Pickardt tomb and 479 HLD for the Schneider tomb (Fig. 5c). Surface hardness for the pedestal of the Schneider tomb averaged only 331 HLD but is made from another sandstone variety than the pillar. The areas affected by weathering show an average value of 355 HLD for the Pickardt tomb (Fig. 5d) and 332 HLD for the Schneider tomb (Fig. 6d). Some areas of the Schneider tomb that were highly affected by weathering and sanding were not measurable by the equotip device (Fig. 6d). After consolidation of the weathered areas (Fig. 5b, red areas by silicic acid ester (KSE 100)), the surface hardness could be increased to around 445 HLD for the Pickardt tomb and 400 HLD for the Schneider tomb (Fig. 5e and Fig. 6e).

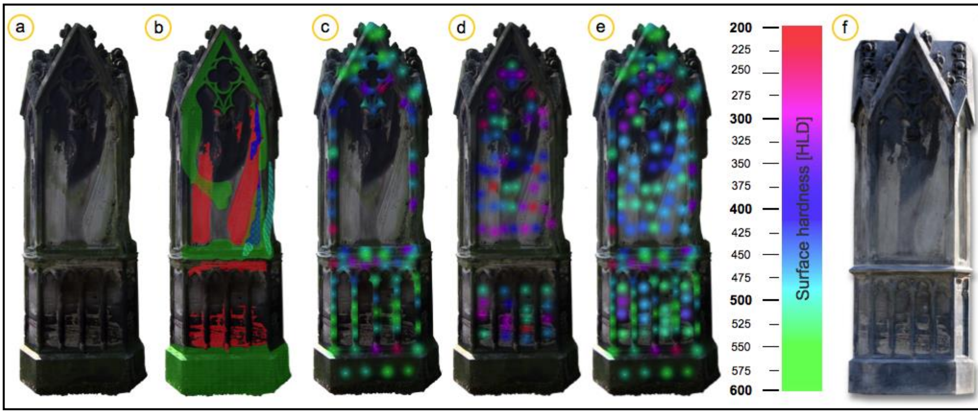


*Fig. 5: a) The Pickardt tomb before consolidation and restoration. b) Damage mapping of the monument with indications of microbiology (green), sanding areas (red), gypsum crusts (blue) and delamination (light blue). c) Surface hardness of the exposed decorative parts of the monument. d) Surface hardness of the backside of the monument. e) Surface hardness after the consolidation treatment. f) The monument after conservation and restoration.*

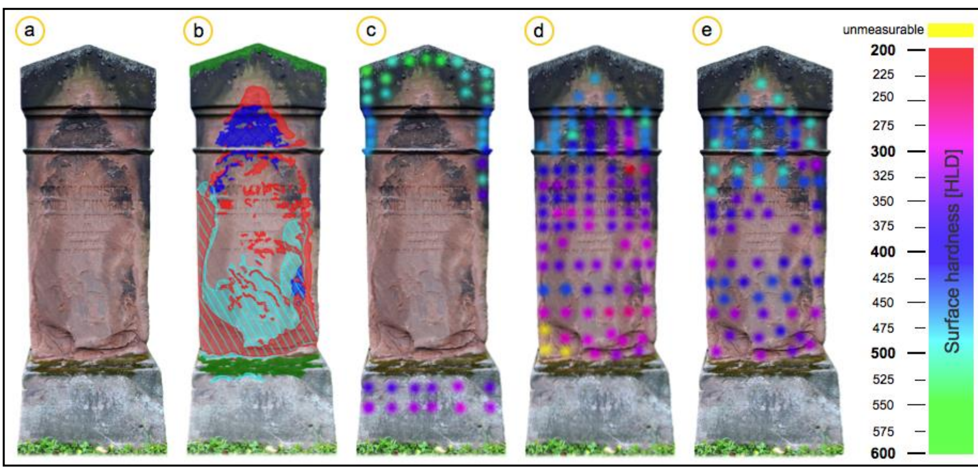


*Fig. 6: a) The Schneider tomb before consolidation and restoration. b) Damage mapping of the monument with indications of microbiology (green), sanding areas (red), gypsum crusts (blue) and delamination (light blue). c) Surface hardness of the parts exposed to rain water, viseble due to the dark discoloration. d) Surface hardness of the weathered areas of the monument. e) Surface hardness after the consolidation treatment.*

## 5. Discussion and conclusions

By comparing the compressive strength with the surface hardness it becomes clear, that the highly porous, poorly cemented chalkstone shows no linear relation between the values of the two different methods but a continuous decrease (Fig. 7a). In contrast the two other stones exhibit a nearly linear relation (Fig. 7a). There is probably a direct correlation between the surface hardness and the compressive strength, if the consolidation affect reaches less than 100% in comparison to the non-treated stone. The relation between the porosity and the surface hardness for the Remedios tuff and the chalkstone show a linear relation. The same is also the case for the Chiluca tuff (Fig. 7b). There is a clear relationship between porosity and surface hardness. Ultrasonic velocity and surface hardness show a nearly linear relation for the two low bound stones (chalkstone and Remedios tuff) and a linear regression for the Chiluca tuff (Fig. 7c). That indicates, that for the two low bound (chalkstone and Remedios tuff) stones a linear relation between surface hardness and ultrasonic velocity can be detected.

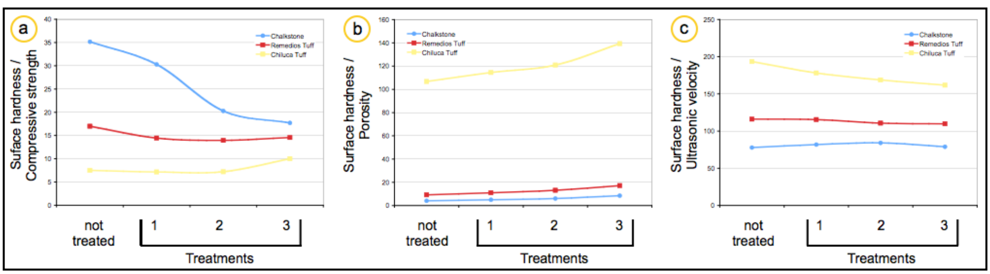


*Fig. 7: a) Relation between surface hardness and compressive strength. b) Relation between surface hardness and porosity. c) Relation between surface hardness and ultrasonic velocity.*

Our data shows that even a low consolidation affect can be detected by surface hardness measurements, whereas the affect measured by compressive strength is not always clearly comparable. In the case of stone types with a low increase of compressive strength, a clear correlation between the measured surface hardness and compressive strength could be shown. A clear effect could be detected by surface hardness in situ at the two tomb monuments. Thus, surface hardness measurements can be used for understanding the conservation state as well as a means for evaluating the consolidation. Moreover, it can be used as a suitable tool for non-destructive testing in stone conservation.

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