Annual project July 2017 – June 2018

Conservation of Swiss Molasses

Stiftung zur Förderung der Denkmalpflege

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Content

Molasses are the most important material in stone built heritage in the whole Swiss plateau. These stones contain swelling clays, which makes them particularly susceptible to weathering. More specifically, dimensional changes of clays resulting from humidity changes can lead to cracking and scaling. In the context of altered monuments, swelling clays also deteriorate the products used for stone restoration very quickly.

Swelling inhibitors are specific chemicals that have been shown to potentially extend the durability of consolidation treatments applied on molasses by inhibiting the swelling of clays. However, such products are viewed with scepticism because of past experiences with other materials successfully tested under laboratory conditions turned out to show poor performance on site. Furthermore, the mechanisms and initiation causes of the typical degradation pattern of swiss molasses have not yet been unanimously cleared.

For this reason, we developed a combination of on-site measurements and laboratory analysis that provide an objective basis for the interpretation of the degradation phenomenon and the recognition of the most detrimental factors, which ought to be minimized or controlled.

During this project, we were able to offer practitioners support and assistance in their decision making, especially when selecting consolidation products and procedures. In particular, we obtained information that lead to practical advice for the ongoing restoration of the cathedral of Lausanne. Further developments of this project also laid the basis for possible extended research campaigns at other historical sites in Switzerland.

An international collaboration between experts in the field of stone conservation has also been established to develop a systematic method for scientific assistance of conservation choices in stone consolidation. Finally, this work has led to the conception of a digital online tool available for free to practitioners to assist in the selection of the best consolidation treatment.

1 Background

1.1 General aspects

The degradation of materials subjected to the environment is a slow and irreversible process that can involve many different mechanisms. In the case of stone in cultural heritage, the crystallization of ice and/or salts in the porous network is considered to be one of the major vectors of degradation. Another important factor is the swelling and shrinkage of clays contained in some stones. This is especially important for many of the Swiss Molasses, extensively used in the construction of buildings of cultural interest. Most degradation processes involve cycles in which the material is submitted to stresses at the microscale. These lead to the accumulation of damage that eventually becomes an issue at the macroscopic scale, either aesthetically or in terms of structural safety. In general, there are critical levels of degradation beyond which the propagation of damage becomes severe. Therefore, restoring sufficient strength before it is too late can avoid the propagation of irreversible damage.

Unfortunately, there are only a very limited number of products that can do this. One of the reasons is that the repair material must be applied in a liquid state and penetrate the damaged material to a sufficient depth. However, in doing so, it must not block water transport, as this has been found to enhance damage due to freezing. Neither should it lead to very different thermal dilation coefficients to those of the original material, as otherwise temperature changes would become a source of damage. Finally, the material must be stiff enough to restore mechanical integrity, but not too rigid, as this could lead to damaging of the original stone in thermal or hygric cycles.

As a result of these numerous limitations, the most widely used product has been ethyl silicates . These are typically used in the form of pre-condensed oligomers, to which a catalyst is added to facilitate their condensation after being applied to the stone.

1.1.1 Ethyl silicates

Ethyl silicates have a long history of use as stone consolidants. As related in a recent review by Scherer and Wheeler [1], this begins with von Hoffmann who was the first to propose the use of these products for the conservation of stone [2]. Since then, various technological modifications have taken place. In particular, the products used today are based on ethyl silicate oligomers. This increases the silicon content, but more importantly reduces the vapor pressure. It allows the product to react in place rather than evaporate after its application. The reaction is enhanced by inclusion of a catalyst, typically dibutyltin dilaurate or a derivative thereof [3].

Other modifications to ethyl silicate consolidants have included alkylalkoxysilanes. This has been done with various objectives. One of these is to increase the hydrophobicity, thereby combining a consolidation and a hydrophobic treatment. The other, advocated by Snethlage and Wendler, was to introduce some flexibility in the silica network, which would prevent the consolidant from transferring too much stress to the stone when exposed to variations of temperature and/or humidity [4].

One of the most important drawbacks of these consolidants is their propensity to crack during their drying. The reasons for this were first explained by Scherer and Wheeler by applying the theory of drying of gels [5]. This basic investigation led to the idea that including particles into ethyl silicate consolidants would be a means to prevent the silica network from shrinking and cracking. The modified consolidants are referred to as particle modified consolidants (PMCs). Another more recently developed approach has concerned the use of surfactants and ormosils for the production of a nano-textured consolidant [6]. Both of these approaches have proven to be efficient in avoiding the cracking of the ethyl silicate consolidant. Their advantages and limitations are discussed below in dedicated sections.

In terms of general limitations of ethyl silicate consolidants, it is also worth pointing out their substantially reduced efficiency on calcitic stones with respect to siliceous ones. This is understood to be a result of the absence (or much lower amount) of surface hydroxyl groups to which the silicate consolidant can anchor itself. To counter this, coupling agents have been proposed. A first approach included coupling agents used in composite materials [7]. One of this is tartaric acid, which can be used as a pre-treatment for limestones [8]. This reacts with calcium carbonate to form a calcium tartrate salt that offers two alcohol functions with which the silicate can react. More recently, it was also found that treatments could act both as coupling agent and consolidant.

1.1.2 Swelling damage and swelling inhibitors

Clay-bearing stones like the Swiss Molasses can expand and shrink in cycles of wetting and drying. In protruding elements, this can lead to severe weathering. Indeed, a thin element can become saturated and expand during wetting cycles. During subsequent drying, the exterior of the stone tries to shrink, but is restrained from doing so by the expanded (wet) core. As a consequence, the outer part of the stone is placed in tension and can crack because of its low tensile strength. This typically occurs on unrestrained and or protruding elements. On Façades, the expected damage is rather one of buckling, leading to the formation of plates, something very typical on the Lausanne cathedral. Buckling is expected to develop during the wetting phase. It involves the propagation of pre-existing flaws below the surface owing to shear forces [9].

A scheme of possible damage mechanisms is reported in Figure 1.

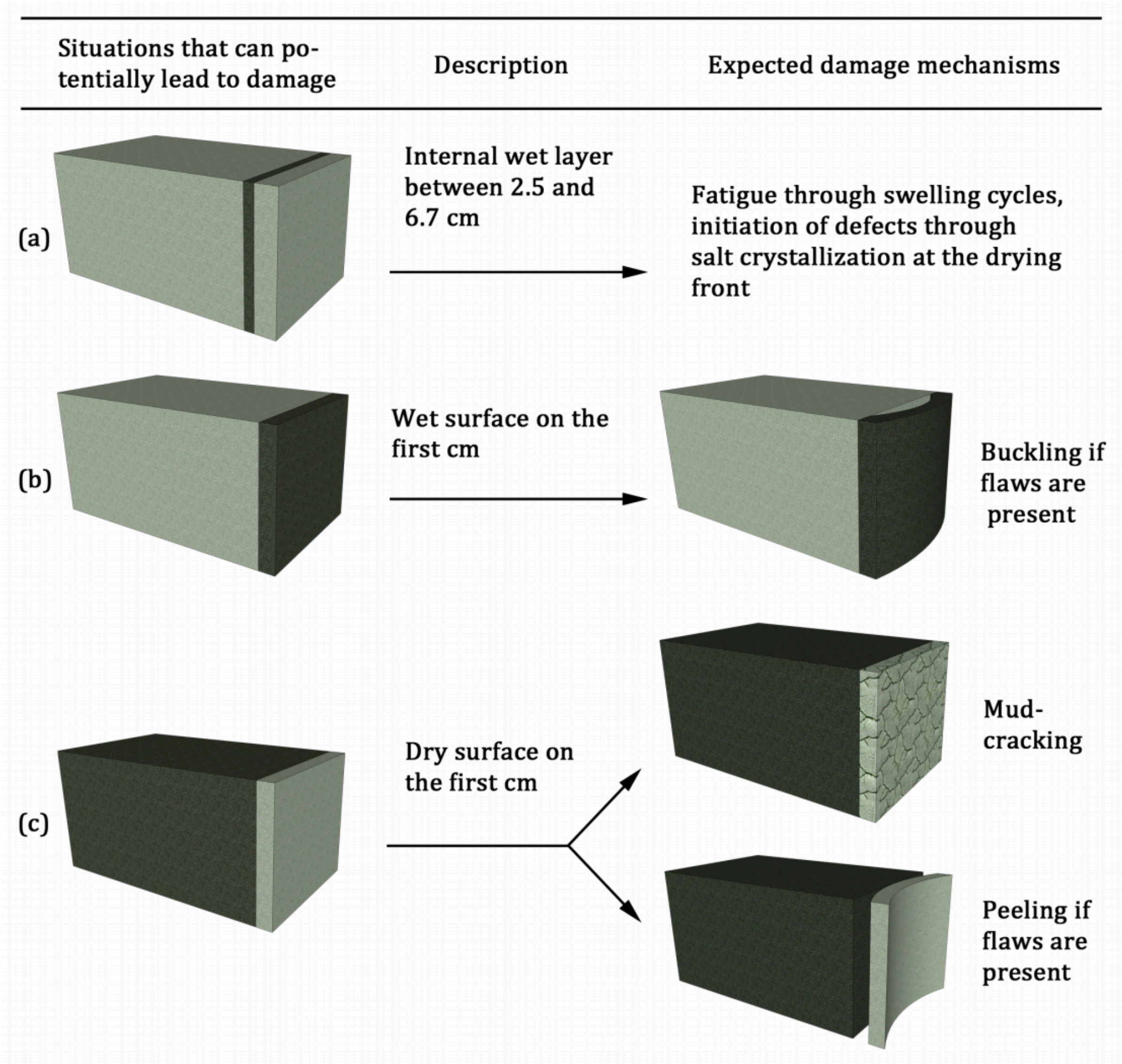


Figure 1 - Possible damage scheme for clay-bearing sandstones as shown in Demoulin, 2016 [10]

The effect of clays in building stones is exacerbated by the near impossibility for ethyl silicates consolidants to be effective [11]. Indeed, their dimensional changes cause the cracking of the consolidant and the loss of most of its benefit already in the first wetting cycle. However, swelling inhibitors have been shown to reduce the swelling strain of clays [12].

Recent work carried out at ETH investigated the role of a swelling inhibitor on the durability of the Villarlod molasses, previously consolidated with commercial ethyl silicates, Conservare OH and Wacker OH 100 [13]. It was shown that wetting and drying cycles alter the stone whether untreated, consolidated, or consolidated after treatment with the swelling inhibitor. These changes are similar in relative terms, but, for the consolidated samples, there is a significantly reduced consolidation loss if the swelling inhibitor is present. This confirms the relevance of applying such (or similar) products before the consolidation of swelling clay-bearing stones with ethyl silicates.

Nevertheless, questions concerning the much longer-term behaviour subsist as the pores in the silicate gel might create enough capillary pressure to cause damage, even if the stone does not expand. Also for this reason, it is particularly important to characterize the water penetration profile, which allows to make considerations about the nature and depth of the accumulation of stresses due to clay swelling.

It is also important to remark that previous research has shown how the swelling of clays cannot be reported as a primary cause of formation of scales. This is because the mechanical stresses exerted by clay swelling is sufficient to open and propagate pre-existing cracks, but not to open new ones[9].

Therefore, the existence of pre-existing flaw is a condition necessary for contour scaling to occur. Freezing damage or salt crystallization are considered the most likely mechanisms at the origin of the formation of flaws in stone facades. The identification of the processes that lead to these first weaknesses can potentially offer an opportunity to hinder the initiator of the damage.

1.1.3 On-site monitoring

Aware of the importance of understanding the real conditions to which stone monuments are exposed, we developed various sensors for on-site monitoring together with Rino S.A.R.L, a Swiss SME active in consulting for the preservation of cultural heritage. Various types of customized sensors were used to measure the temperature (T) and relative humidity (RH) in the atmosphere and at the surface of stones. A more advance method, however, has been developed for the cathedral of Lausanne within a research campaign supported by the technical committee of the cathedral, but carried out on internal funding in the years preceding this funding. This method is based on the use of wireless sensors developed by Smartmote®, which allow the measurement of RH and T, but also liquid water content (through impedance measurements).

The data is continuously uploaded on a cloud server through a Smartbase that collects the signal sent by the Smartmote®, thus allowing for a continuous observation of the parameters at all times. These measurements are intended to observe the material response to certain environmental conditions. Once the specific behavior under characteristic exposure conditions is characterized, we can infer that the behavior will be similar for similarly exposed zones. For this reason, we associate our measurements for T, RH and impedance to a specific set of weather conditions (namely precipitation, wind speed, and wind direction), which we study on the basis of weather data collected from local sources (IDAWEB) and equipment installed on-site. Wind driven rain can then be estimated at each location on the cathedral with different methods, including the ISO Standard (2009) [14].

2 Project Approach

2.1 Expansion of on-site measurements at Lausanne Cathedral

Figure 2 - Bird view of the cathedral of Lausanne and markup of the south transept (retrieved from https://goo.gl/maps/H4FBYf5WpEBC8p1c9 May 2019)

2.1.1 Installation of additional sensors

In relation to the ongoing restoration campaign at the cathedral of Lausanne, new locations on the façade became accessible for the installation of additional sets of sensors to measure temperature, relative humidity, and liquid water content.

A zone of great interest was selected on the west arm of the south transept. This zone was completely restored in 1882, in the framework of the restoration of the painted portal and demolition of the flying buttress. Much of the stone blocks were found to be extremely degraded, and were replaced by a local molasse similar to the original Grey of Lausanne (probably a molasse from Crissier). This indicates that this specific exposure is a detrimental one and will most probably lead to significant degradation once again. As the stone is still in good conditions, its analysis, in particular water penetration and distribution, should provide important clues as to how scales start to form.

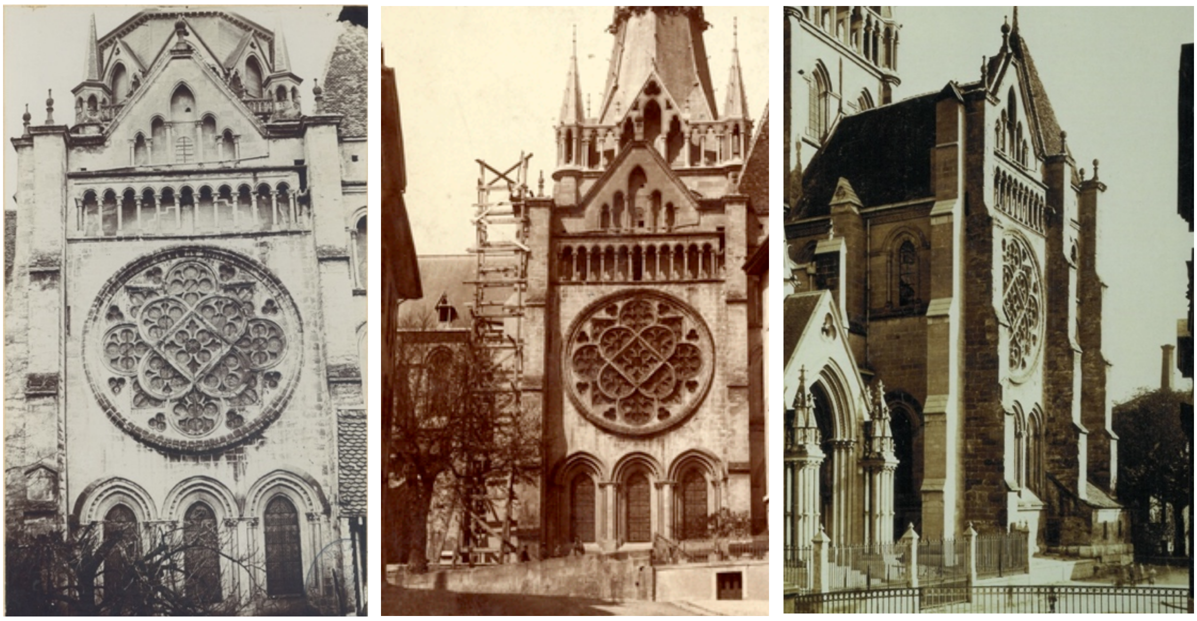


Figure 3 - West facing cross of the south transept before, during, and after restoration. From left to right: Simon Jules, 1860-1873 ref:SB 52 Aa 32/1 [®Archives cantonales vaudoises]; Célestin Louvrier, 1883 ref:MHL127633 [®Musée historique de Lausanne]; anonymous, -1908 ref: ACal_21 [®Archives cantonales vaudoises]

The same type of sensor was already installed with success on the flying buttresses of the south Façade (see section 1.1.3). Therefore, a similar approach was used for the placement of the new sensors. In particular, a guide was used to drill holes of 5 mm in diameter for the placement of the sensors at 6 different depths. Depths of 1, 2, 4, 6, 8 and 27 cm were chosen, as previous data indicated that the area of the stone most subjected to stress accumulation lies between 3 and 6 cm. The depth of 27 cm was chosen as a control of the conditions at the core of the stone block. Two holes for each depth were necessary for the installation of pairs of electrodes for the measurement of impedance. An additional hole was made at each depth for the installation of the RH and T measurements.

The drilling was performed on the north facing wall of the buttress, perpendicularly to the direction of the intended depth of measurement, as schematized in Figure 4.

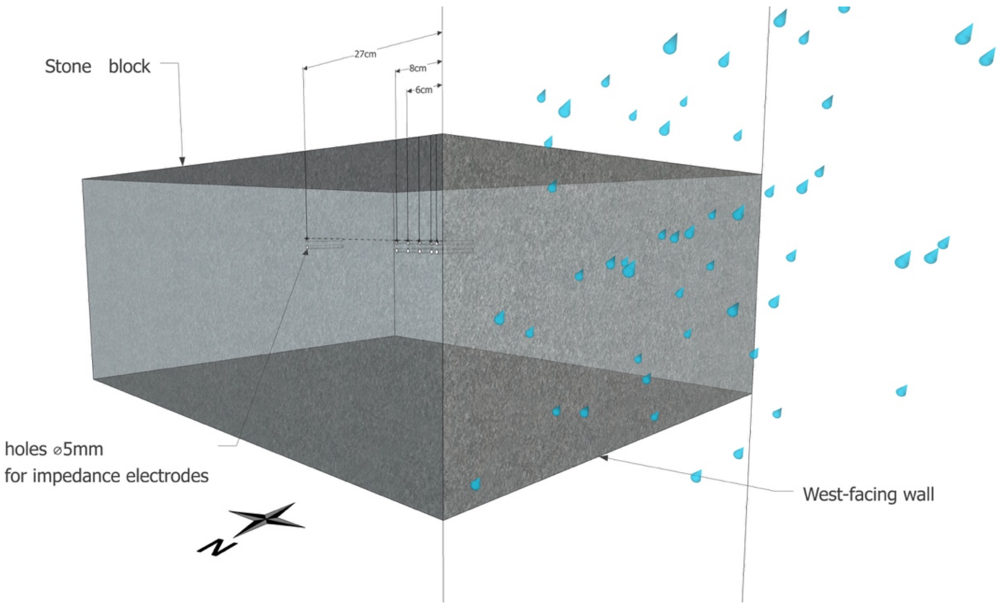


Figure 4 –Scheme of installation of wireless sensors

Figure 5 - Drilling operation and completed installation of Smartmote at the Cathedral of Lausanne. South transept.

T and RH sensors were protected against liquid water by a porous teflon layer, then simply inserted at the chosen depths. Impedance sensors require more attention when embedded, as a continuous, conductive contact must be ensured between the electrodes and the stone. For this, we used a conductive silicon (EMI/RFI Conductive adhesive ref: SS-25-1) provided by Silicone Solutions (Cuyahoga Falls, OH, USA). An insulating polyurethane foam board was then installed over the perforations, to ensure no interference from the open side to the measuring sensors (Figure 5).

2.1.2 Condition survey of degraded areas

The west-façade west of the transept, left of the west-arm described in the previous section, was the main object of the 2017-2018 restoration campaign of the south transept. Several areas show significant degradation and were therefore selected to receive a consolidation treatment. Drilling resistance measurements (DRMS) were performed to characterize the extent and depth of degradation of stone blocks showing contour scaling or disaggregation. These measurements were necessary to evaluate the state of the substrates selected from treatment, as well as serving as a basis for comparison of the cohesion of the materials before and after the application of a consolidation treatment.

Such measurements were not performed within this grant, but are planned for June 2019, when the ethyl-silicates will be fully cured.

DRMS measurements were performed using a Drilling Resistance Measurement System (DRMS) from Sint technology (Florence, IT), with a 50mm drill bit. The DRMS was mounted on a customized shelf attached to the scaffolding to improve repeatability of the measurements. The drill settings were adjusted to a rotational speed of 300 RPM and penetration speed of 20 mm/min.

The measurements (Figure 6) showed that the general cohesion of the substrate, as well as the degradation depth, in zones selected for treatment was much more severe than initially thought. The results showed that the degradation was well over the 5 cm that the DRMS technique can probe. A subsequent sampling of core drills in

Consolidation campaign 2017-2018

In spite of this project aiming at assisting the restorers in their decision making during the consolidation campaign of 2017-2018, the timing imposed by the technical committee obliged the practitioners of Sinopie Sàrl to make a treatment proposal in early 2017. As a result, consolidation treatments were selected before the results of this project could be obtained. The decision was to apply known ethyl silicate products (Wacker OH 100).

zones of interest confirmed that the degradation went as far as 7 cm beneath the surface. This information is very important when consolidation treatments are being considered. If the chosen product does not penetrate enough to restore cohesion in the whole degraded zone and anchor this to the healthy stone beneath it, there is a high risk of induced damage. The formation of a hard, consolidated crust over a not coherent substrate would accelerate, rather than slow down, the formation of contour scaling [15].
Such a significant degradation depth, therefore, compels to perform preliminary tests to verify the effective treatment penetration and, accordingly, ponder whether consolidating is an appropriate choice. Except in the cases where specimens for such preliminary tests can be directly extracted on site [16], the test of penetration of the consolidation treatment will have to be performed on mock samples.

Another consequence of the data obtained was thus the realization that the freshly quarried samples normally employed for laboratory testing of durability of consolidation treatments were not sufficiently representative of the onsite material. For this reason, a choice was made to postpone the laboratory testing at simulated weather conditions, to focus instead on protocols to produce pre-degraded samples to use as a basis for durability studies. A controlled artificial weathering is necessary to ensure a homogeneity of the samples when comparing different treatments.

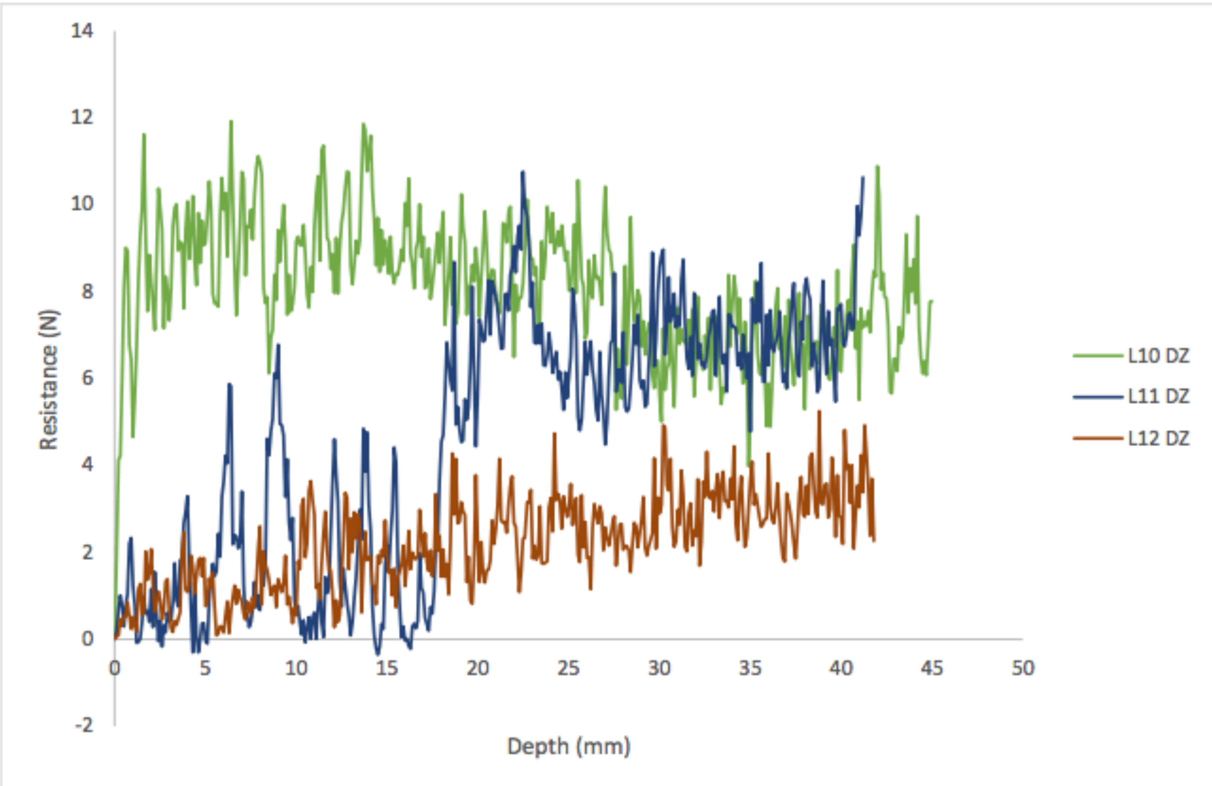


Figure 6 - DRMS curves from three types of observed substrates. L10: substrate in good conditions; L11: zone where a scale has already detached, and the degraded failure zone is exposed; L11: zone of disaggregation, probably due to salt crystallization damage.

2.2 Laboratory testing

2.2.1 Reproduction of weathered samples for laboratory tests

Villarlod Molasse is a material of choice for testing the behavior of swelling clays-bearing molasses quarried in the Swiss plateau. This is because this particular rock type shows a pronounced swelling behavior, and is therefore a good model of difficult cases where swelling behaviors hinder the consolidating action of treatments.

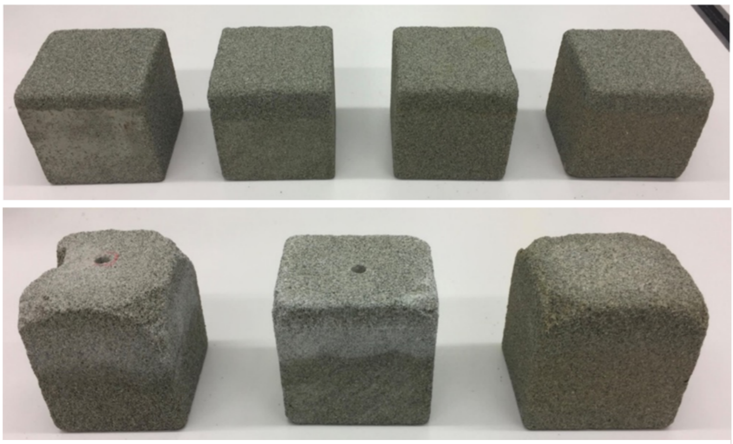


Figure 7 - Villarlod molasse cubes, subjected to variousl artificial weathering protocols by acid attack with hydrochloric acid (top) and sulfuric acid (bottom)

Freshly quarried stone is routinely used in laboratory tests. The onsite survey of the substrates that will receive a consolidation treatment raised the doubt that both the consolidating action and the effect of the swelling behavior might significantly differ from the ones of non-degraded samples. However, a protocol for the production of artificially degraded clay-bearing molasses, was not available at the time. Therefore, we performed a study to establish a reliable protocol for producing artificially degraded mock-ups of Villarlod Molasse.

Based on the limited literature on pre-aging of sandstones with a carbonate matrix, a controlled acid attack was selected as the most suitable method. The intended mechanism is to degrade the samples with diluted acid solutions to partially dissolve the carbonate cement of the stone, inducing granular disintegration and increasing porosity. Two categories of samples were be produced; non-contaminated samples for studies on consolidation and swelling inhibition, and salt-contaminated samples that can be used to study the susceptibility of a consolidation treatment to contaminations found on historic monuments (Figure 7). Hydrochloric acid (1.4-5.6M) was used to obtain non-contaminated samples, as most chlorides are highly soluble and may be extracted by desalination. Sulfuric acid (0.6-1.4M) was used to obtain sulfate-contaminated samples, as sulfates are abundant on the façade of the cathedral of Lausanne [17].

The degradation was characterized by mass loss, Ultrasonic Pulse Velocity Measurements (UPVM), Scanning Electron Microscopy-Energy Dispersive X-Ray (SEM-EDX), lateral dilatation swelling tests, and mechanical testing with a mini three-point bending test setup (TPBT). The artificial degradation was compared to naturally degraded stone in situ at the Cathedral of Lausanne by a Drilling Resistance Measurement System (DRMS) (Figure 8) . It was found that a repeated impregnation by sorptivity with a 0.7M solution of sulfuric acid was ideal to reproduce conditions observed on-site, and possibly tune the desired depth of degradation. A salt contamination with Calcium and Magnesium sulfates localized within the firs 4 mm of depth of the degradation was also obtained. Such results are perfectly compatible with known measurements of sulfate contamination on facades of Swiss building of historical interest [17].

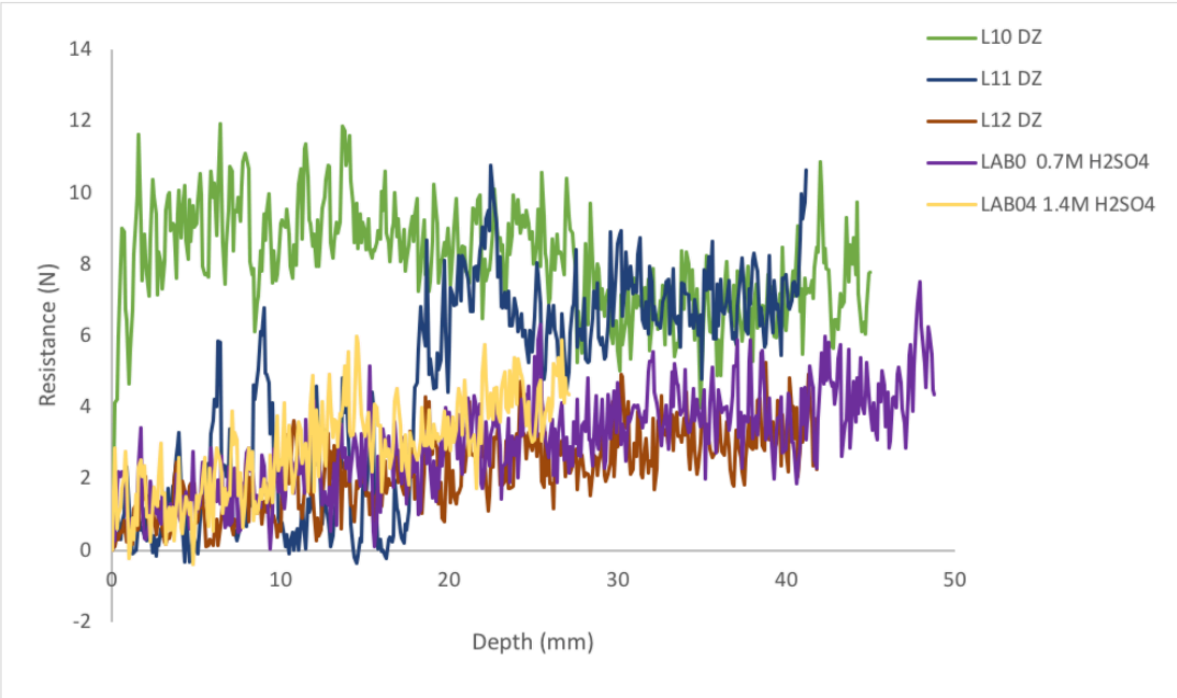


Figure 8 - Comparison of DRMS curves obtained on-site (L10,L11,L12) and on artificially weathered samples (LABO)

2.3 Data analysis

The on-site measurements on the south transept over a period of one year showed the most interesting results. The impedance measurements highlighted a water distribution behaviour that was not measurable with Relative Humidity measurements, over a period of over four months from December to middle April.

To better understand the meaning of such measurements, a pre-calibration of the impedance electrodes had to be carried out in the laboratory on similar materials. This allows to estimate ranges of saturation of the stone with liquid water. Impedance, similarly to measurements of electrical resistance, shows decreasing values with increasing water contents, as evidenced by the calibration curve in Figure 9. It should be noted that such results are strongly dependent on the porosity of the specific materials [18], [19], so that when using other stones such calibrations can only be used to provide qualitative or semi-quantitative estimates of water contents. However, they do nevertheless provide reliable assessments of relative differences. For this reason and from now on, we will keep referring to the capillary saturation ranges shown in Figure 9, but show the on-site measurements in terms of their impedance values.

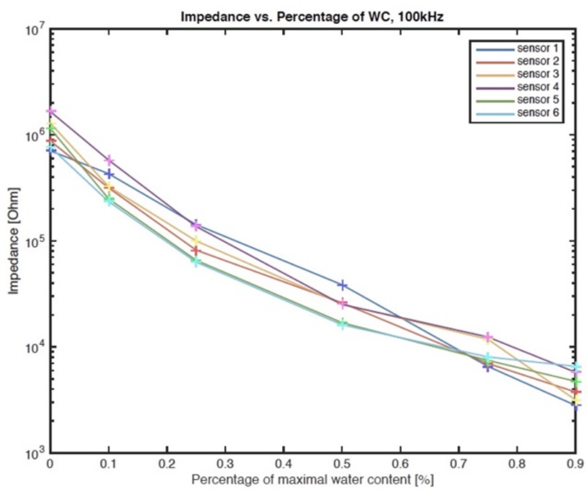


Figure 9 - Impedance measurements on Molasse of Villarlod, for different grades of capillary saturation (expressed in % of pore volume filled by liquid water) [9].

A first important piece of information offered by the on-site measurement campaign is the presence of liquid water in the core of the stone blocks over the whole year (Figure 10). The same result had been suggested by the measurements performed on the south flying buttress, but could be related to this architectural element being a particularly exposed one. The new data on the transept demonstrate that the same behaviour is observed on architectural facades that are exposed to the weather from one face only. This result is particularly relevant for questions concerning both the transport of soluble salts that could potentially cause crystallization damage and the risk of freezing damage in winter.

Another peculiar observation was made during the summer months. As could be expected, the water content generally decreased throughout the depth of the stone blocks. However, their cores remained wet, although the stone got drier closer to the surface, due to the higher air temperature and lower relative humidity between June to October (see Figure 10).

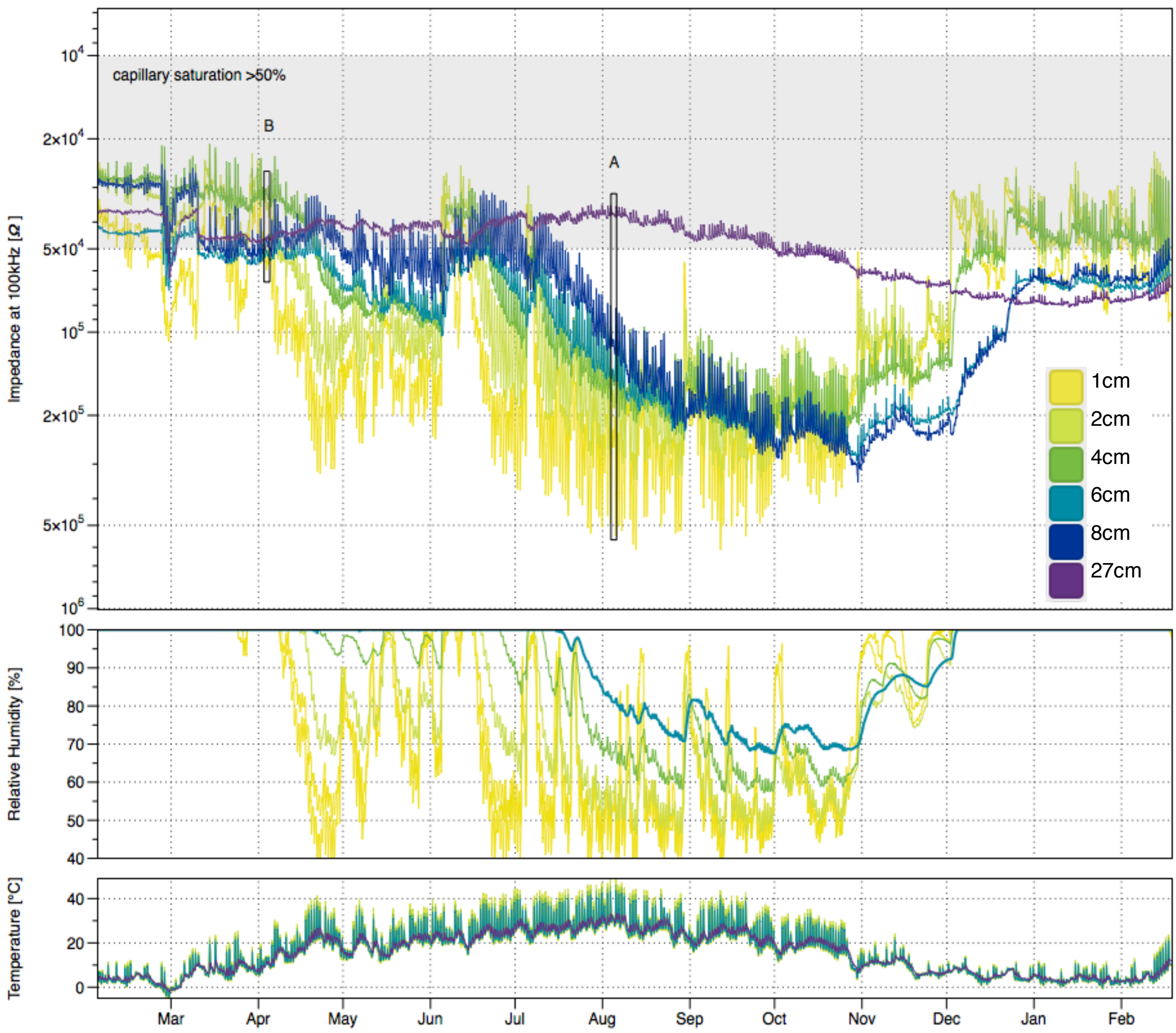


Figure 10 - On site measurements over a one year period at the cathedral of Lausanne. South transept, west face of west arm. Sections marked A and B are highlighted in Figure 11.

From November on, a less intuitive behaviour is often observed. The core of the stone maintains a high, though somewhat lower water content. Closer to the surface, we observe initially a slight lowering of the capillary saturation (at 8cm and 6cm depth), followed by a clear saturation zone around 4 cm. Then around 2cm, we once again find a decreasing water quantity. Finally, the measurement closest to the surface shows the highest variability, depending on the occurrence of rain events, as could be expected.

Two sections from Figure 10 are selected to illustrate daily fluctuations in summer (A) and in winter (B) (Figure 11). They highlight the main points outlined above, in particular the core of the stone remaining wet and the large fluctuations of the surface layers. The higher capillary saturation between 2 and 4 cm in winter and highlighted in Figure 11B is compatible with the typical zone of development

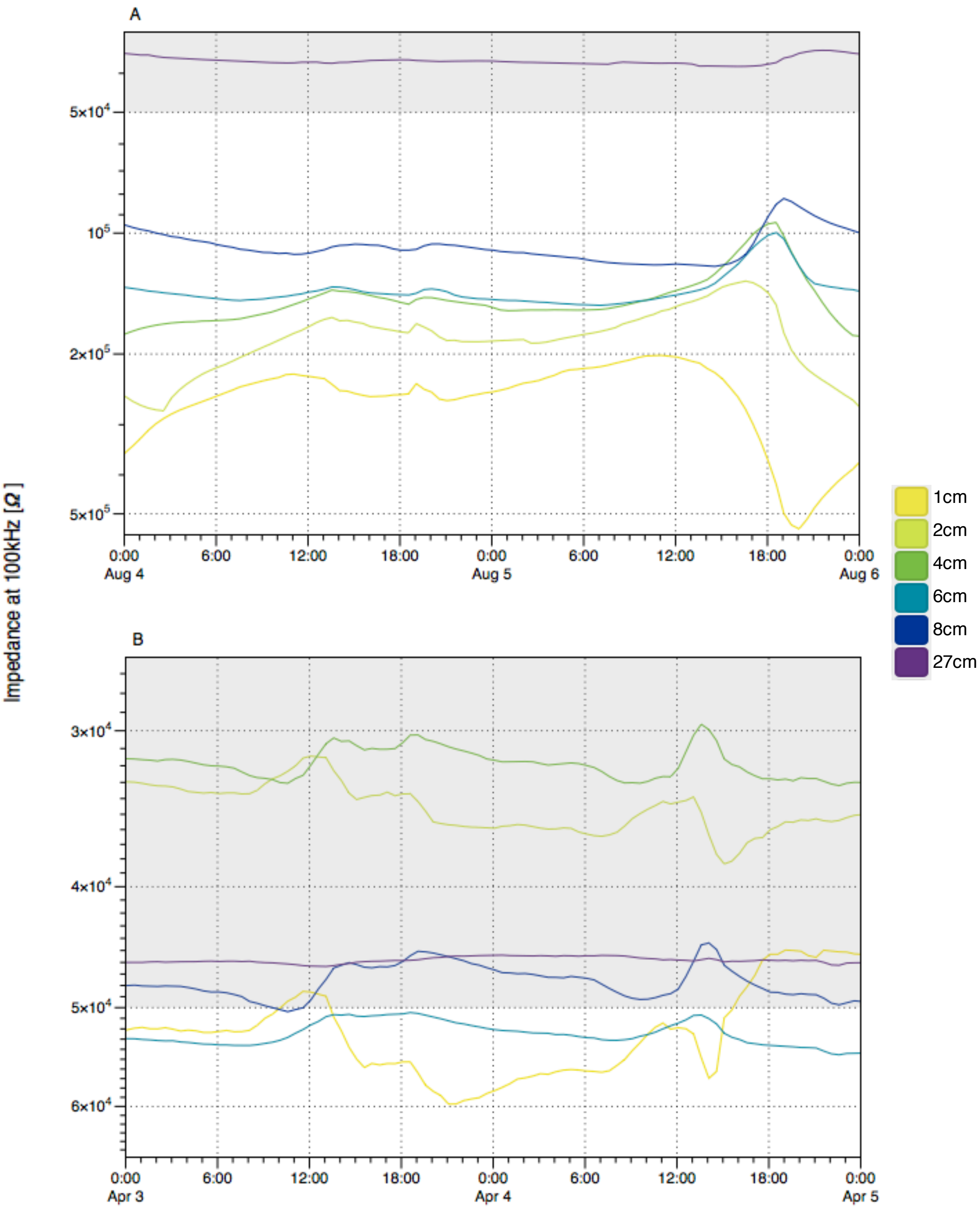


Figure 11 - Detail on water distribution patterns in summer months (A) and winter months (B)

of damage for this orientation. Such differences in water content at the different depths cannot justify the formation of damage solely due to clay swelling. However, these results suggest that freezing might play a particularly important role in the development of cracks at these depths.

The risk associated to freezing damage is confirmed by impedance measurements during freezing events. To clarify this point, it should first be mentioned that the capability of ice to transmit electrons is much lower than that of water. Therefore, when freezing occurs, impedance increases in relation to the amount of water freezing. Our measurements clearly show this in Figure 12. In that figure, we have selected the period from February 21 to March 4 days (plots on the right) during which freezing takes place, starting February 25th (Vertical line). From that point on there are a couple main observations to make. First the impedance values start to fluctuate much more the previously. Also, there fluctuations are generally correlated with changes in temperature. Specifically, when these go below zero degrees, impedance tends to increase and vice-versa. An exact alignment of these changes can however not be expected as the impedance measurement probes are related to a volume (with a thickness on the scale of the distance between the sensors =1,5cm) and is less local than that of temperature.

Importantly, it can be expected that the highest damage will occur between 2cm and 4cm, and at 8cm. This is because freezing damage increases with the degree of saturation and undercooling and it is at these depths that the combination of both is most critical.

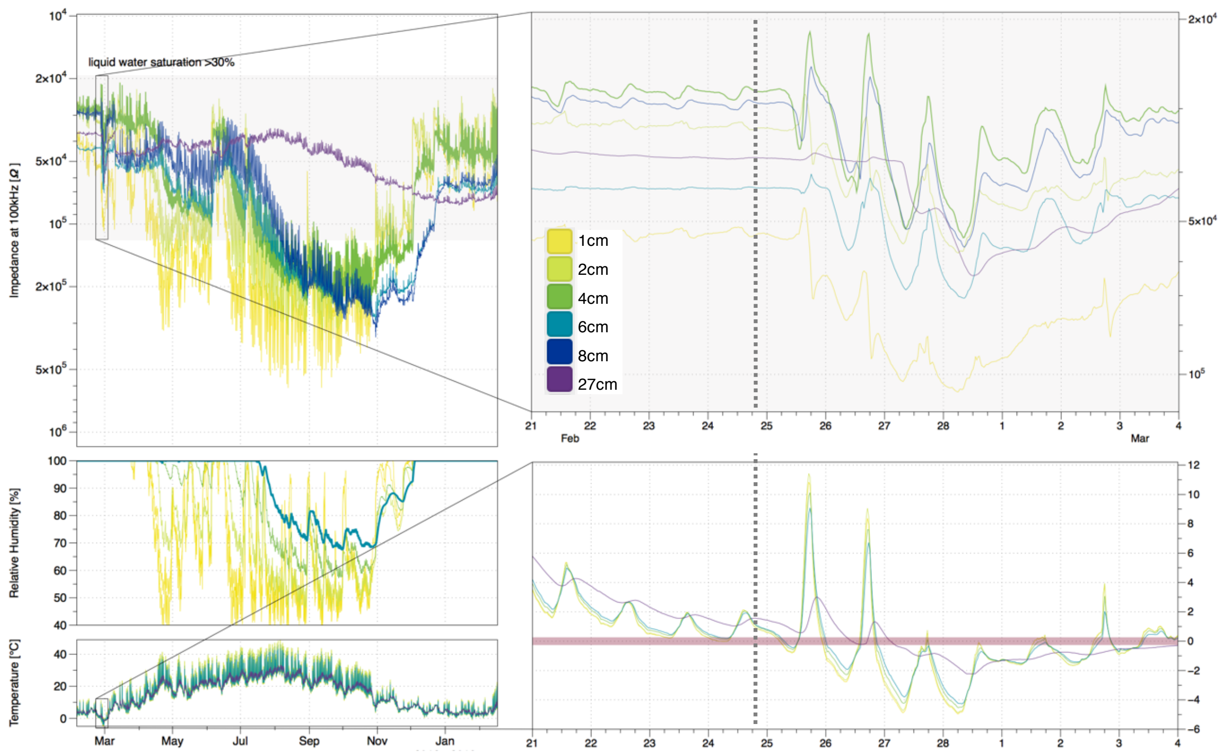


Figure 12 - Freezing phenomenon as shown by impedance measurements at the cathedral of Lausanne, South transept, west facing wall of west arm

2.4 Development of conservation strategies

The information gathered during our on-site measurement campaign and laboratory testing was useful to give suggestions for the development of conservation strategies for the Cathedral of Lausanne and – potentially – for other monuments in the Swiss plateau:

1. Consolidation treatments must be applied only after assessment of the characteristic depth of degradation at each specific façade orientation;
2. Pre-tests must be performed to ensure that the penetration depth of the treatment is higher than the gradient of degradation in the stone blocks. In the case of the zones observed at the cathedral of Lausanne, a quantity of 6L/m^2 of Wacker OH 100 was estimated;
3. The use of hydraulic mortars for repair is recommended, as conditions optimal for carbonation of lime-based binders (porosity not saturated with liquid water and relative humidity between 70% and 40%) only occur over a 3 months period from August through October;
4. Measures for the protection of the façade over the coldest weeks in winter might be useful to prevent the initiation of contour scaling.

3 Milestones

3.1 Rilem Technical Letter on Consolidation of Stone

The work carried out under the financing of the *Stiftung zur Förderung der Denkmalpflege* initiated a larger collaboration between experts in the field of stone conservation. A joint effort was made to build better synergies between the work of researchers and the one of on-site practitioners.

As a result, we submitted a proposal to RILEM Technical letters for a review paper on the use of consolidants, bringing together knowledge from research and experience from practice. RILEM Technical letters is an invitation only journal from RILEM which is published in diamond open access with a resulting very high visibility and accessibility.

Following up on our proposal, we have written our paper with a group on international experts in order to strengthen the contact and impact of our work. The colleagues involved as co-authors are Dr. Enrico Sassoni (Università di Bologna, IT), Prof. Dr. Francesco Caruso (University of Olso, NO), Véronique Vèrges-Belmin (LRMH Paris, FR), Prof. Dr. George W. Scherer (Princeton University, NJ, USA), Fred Girardet (RINO Sàrl, Blonay, CH), Prof. Dr. José Delgado Rodriguez (National Laboratory for Civil Engineering | LNEC, Lisbon, PT), Prof. Norman R. Weiss (Columbia University, NY, USA), Prof. Dr. George Wheeler (Columbia University, NY, USA).

An important aspect of this paper is that it exploits the experience of the authors to identify the needs most often encountered on site when dealing with conservation of stone, and collects a list of solutions that research offers to such problems.

While the text is currently under revision, a draft version is reported in the appendix of this report.

3.2 Digital advisor for consolidation treatment choice

Another highlight was the initiation of a separate project to assist practitioners in their decision making. A digital assistant was conceived, which offers a list of recommended treatment solutions targeted for a given case scenario. Each user can give indications about his case study by answering a series of question on an online quiz. Relevant answers are collected and used to exclude treatments that would prove ineffective or, even worse, detrimental. Automated conditional logics are then used to generate a list of best candidate products.

This tool has been created as a demo version, and is currently under further development.
The demo version can be accessed on the dedicated website page https://consolidantfinder.ucraft.net.

4 Budget

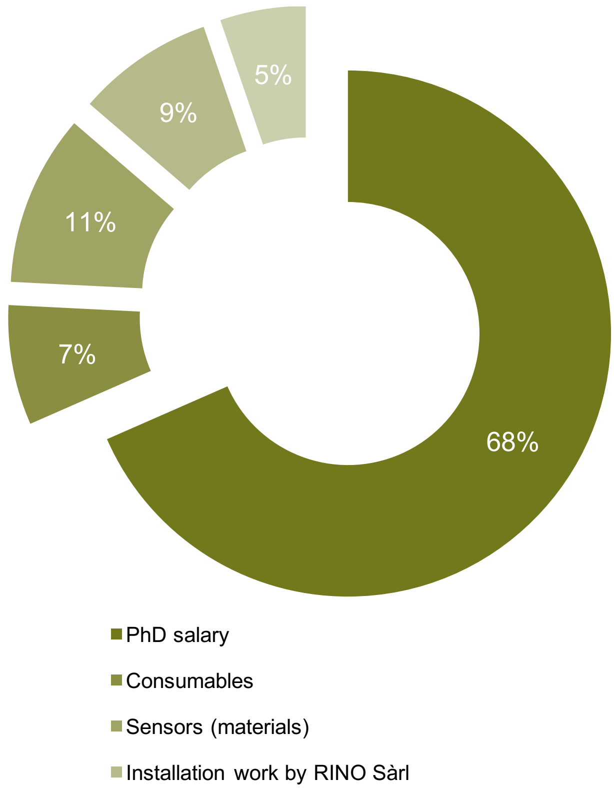
The repartition of the budget expenses is shown in Table 1. Coherently with our initial proposal, most of the resources were dedicated to PhD salary, followed by materials for on-site sensing and on-site sensor installation.

Unplanned higher expenses were due to the decision of performing supplementary on-site measurements at the request of the practitioners involved in the ongoing consolidation campaign at the south transept. Nominally, some site visits for the measurement of the drilling resistance on different locations along the west façade of the west arm.

A workshop dedicated to the results obtained could unfortunately not be organized, due to health issues encountered by the person in charge of this work.

A decision was made to redirect this funding into the communication of the results at different conferences and seminars.

Table 1 - Repartition of project expenses



5 Schedule

An updated schedule of the tasks performed is reported in Table 2.

Coherently with what discussed in Section 2, the effective schedule of tasks performed differs from the one shown in our proposal, due to a change in the research line chosen, according to the needs of the case studied.
Also, owing to severe health issues of the PhD candidate working on this project towards the end of the funded period, some of the activities were unfortunately subjected to substantial a delay. An extended research period with a lower degree of work intensity was funded by the Chair of Physical Chemistry of Building Materials at ETH Zürich, to allow for completion of the selected tasks.
This extended research period is also displayed in Table 2.

Table 2 - Schedule of tasks

	TRIMESTER												EXTENDED RESEARCH PERIOD							[costs uptaken by PCBM]				
	I			II			III			IV			V			VI			VII			VIII		
task																								
EXPANDED ON-SITE MEASUREMENTS in Lausanne																								
Survey and choice of new locations																								
Placing of sensors																								
Characterization of critical cycles																								
DRMS measurements																								
LABORATORY TESTING																								
Selection and purchase of stones for testing																								
Selection of possible treatments																								
Preparation of samples for laboratory testing																								
Exploratory tests for mock degraded samples																								
Systematic testing of samples																								
DATA INTERPRETATION AND DEVELOPEMENT OF CONSERVATION STRATEGY																								
Analysis of results																								
Comparison with previous data																								
Optimization of conservation strategy																								
MILESTONES																								
Rilem technical letter																							♦	
Website																							♦	
Finalization of work and reporting																							♦	♦

6 Benefits realized and outlooks

In our proposal, we stated as main target of our research the delivery of *clear and complimentary information to assist conservators in their decision-making*.
Indeed, the consolidation of the exchange between research and practice has been the main success of this work.
Our measurements provided a set of directly-usable results for the on-going research, guiding the conservator in the tuning of their procedures to the specific site of interest. In addition to this, a more general set of recommendation for the conservation of Swiss molasses was also developed.
The peculiar water distribution pattern distribution pattern allowed us to give some useful insights for the understanding of the formation of contour scaling on swiss molasses. More especially, freezing damage was found to have a distinctive role in the formation of flaws at a characteristic depth.

More generally, this work has put the basis for a closer collaboration between restorers and researchers at the cathedral of Lausanne. Further collaboration projects are to be expected at the Cathedral of Lausanne and other sites of interest in Switzerland, thanks to the establishment of a fruitful communication between ETH Zürich, and companies active in conservation companies across Switzerland such as RINO Sàrl and Sinopie Sàrl.
Furthermore, a much larger collaboration has been established between experts in stone conservation across Europe and the USA. This work has had as a main outcome the sensitization about the importance of a synergetic work between practitioners and researchers.
We are confident that this work will initiate a much larger conservation between the two fields, also thanks to the publication of a fully accessible paper on Rilem Technical Letters.
Finally, this work has put the basis for an ambitious project, the development of an automated tool to help practitioners navigate the information provided by research. This will not only allow for better conservation practices, but also foster innovation in both the on-site practice and the academic world.

Annex

A - List of References

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B - Rilem Technical Letter on stone consolidation

Table of Contents

3

Introduction

Research on durability has been gaining importance in the building industry over the past decades. This has led to a boost in the development of products and methodologies, many of which have also found applications in the conservation of historical structures. While research in the conservation of built heritage was also making substantial progress in the same period, this further fostered the understanding of mechanisms of decay, their origin and possible ways of mitigating them.

Yet, as is often the case in interdisciplinary fields, the knowledge transfer between academia and practice has been relatively disappointing for both sides. The lack of a common "language" causes difficulties in converging on common targets. On the other hand, the simple misunderstanding of the purposes of each other's work probably also holds up progress. This is most definitely the case in the field of stone preservatives.

The research community is generally pressured to provide "universal" results. For this reason, it puts a lot of effort in developing internationally accepted standard methods for testing, which aim at providing results that are comparable for different products and across different laboratories [1], [2]. Such standard tests are performed at controlled temperature/humidity conditions, on uncontaminated samples of freshly quarried or artificially aged material. Their outcomes are intended as a guide for the applicability and potential success of treatments, with the assumption that these reflect similar (or, possibly, improved) performances on-site, more or less regardless of how different the exposure conditions may be. It is however rare to see practitioners having the time or resources to follow up the information provided by research, so they run systematic tests themselves to verify the effectiveness and durability of planned treatments in their specific on-site conditions [3]. Because real conditions are expected to be different from laboratory ones, this gap causes practitioners to feel that researchers lack awareness of practical issues and hence to overlook information that would be useful to them.

One of the targets of this letter is to help researchers and practitioners to better understand each other's perspective on practice-relevant problems relating to stone consolidation. As a consequence, we have structured the review around the following topics and related questions:

1. Background: What is a consolidant, what should it do and when should it be used?

2. Some needs from practice: What are practitioners most concerned about? Is research addressing these issues sufficiently?
3. Some answers from research: What research outcomes can already be used to solve current practical issues? What upcoming results should we look forward to?
4. Common questions for practitioners and researchers: How can better synergies be implemented between research and practice?

In doing this, we hope to give scientists an informed evaluation of the most needed research, and, at the same time, provide practitioners with a synthetic overview of the insight that research can offer in terms of consolidant selection, application and monitoring. Hopefully, this will also motivate practitioners and researchers to engage on a higher level of discussion, to define essential research questions going beyond site- and case-specific issues. We believe such a paper is timely and can help the field evolve towards new horizons.

1 Background

A consolidant (from the Latin *com-* "together" + *solidare* "to make solid"; *consolidare*, “to make into one body”) is a product used to restore strength to a degraded material . However, it must also easily, deeply and homogeneously enters the stone. The treated material must recover properties as similar as possible to the underlying substrate, both aesthetically (color, gloss) and physically (thermal expansion, strength, water and vapor transport, etc.). Furthermore, consolidants should be durable, never cause any degradation of the substrate, and not preclude the possibility of a different treatment choice in the future.

Some of these requirements can be satisfied more easily than others. For instance, a good penetration depth can be ensured by reducing the contact angle (θ) and the viscosity (η), while good vapor and water transport can be obtained by selecting hydrophilic products. However, because other requirements cannot be easily defined in terms of measurable material properties, practitioners prefer to define consolidant expectations in a much broader sense.

Consolidation treatment refers to the combination of a consolidant and the technique and conditions used to apply it. A single product may be involved in countless consolidation treatment types.

Reversibility refers to the expectation of being able to remove a consolidant if this turns out to be necessary any time after its application. It must not be confused with *retreatability* (i.e., possibility to apply another product, at later stages), which any consolidant should allow. *Durability* is the ability to maintain its function over time. *Compatibility* is a more blurred – but crucial – concept. In short, it means that an applied treatment must not accelerate the degradation of the surrounding substrate.

Each of the above terms embodies a large number of required material properties. In section 3, we will show how scientific research has tried to answer such needs.

-- *table* --

2 Some needs from practice

Selecting the best consolidation treatment involves an optimization process among many different and sometimes contradictory requirements ranging from material properties to ethical decisions and financial aspects [4]. In this section, we address questions that are of direct concern to conservation scientists and try to outline how conservation science and scientific research can contribute, with rational insight, into the overall and more complex decision-making process for in situ application.

2.1 When is consolidation necessary?

The first critical choice in a conservation campaign is whether to apply a consolidation treatment or not. Conservators must weigh cost-benefit ratios, where the cost is not only financial but also involves the risk of reducing the durability of the material, corrupting its authenticity, or erasing information it contains (see section 2.2). For this reason, it is important to act only when absolutely necessary and not to postpone the intervention until the material has degraded too much for the consolidation to be beneficial.

A key question is: where does one draw the line between avoidable and urgent?

Answering this question is essential but not trivial. On the positive side, remarkable progress has been made in measuring the extent of degradation of the substrate in quantitative terms [5]. However, attempts to relate this to an urgency and/or usefulness of consolidation remains rare [6]. In our opinion, this situation could be greatly improved by developing numerical indicators for the necessity of a treatment. Such an "urgency" rating-term would of course have to accommodate the variations of exposure, material make-up and condition across any given monument, in addition to including the notion of "acceptable damage".

2.2 Success versus Induced risks: where is the acceptable trade off?

As mentioned in section 2.1, the selection of a consolidation treatment entails a delicate balance between its potential benefits and the possible harm to the substrate or disadvantages from the ethical or financial point of view. To deal with this challenge, there have been attempts to define a scoring system to quantify both the performance of a given treatment with an "efficiency index" [7] and the risk of possible drawbacks by "incompatibility risks"[3], [8]. This approach is promising in that it offers an unbiased tool to help practitioners select the best possible treatment or mindfully decide to do nothing. Both methods use some highly context-dependent input that can only be determined via preliminary laboratory and field evaluations. This means that such scores will rely on estimations based on intrinsic properties that are - in most cases - scarce or not direct to the point, due to the lack of consensus over the methodologies employed [9]. The following two paragraphs review the two subjects of greatest concern: the validity of laboratory results for the actual consolidation practice (section 2.3) and the demand for more convenient methods for on-site assessment (section 2.4).

2.3 Usability of laboratory test results

Results obtained by laboratory testing are taken with a grain of salt by on-site practitioners. This is due to differences between laboratory and on-site conditions that cast doubt on the direct transferability of the research findings to practical situations. The practices in laboratory testing of consolidation products more often criticized are [10]:

- the frequent use of fresh stone samples, substantially dissimilar from the degraded substrate for which the treatment is needed;
- the evaluation of performance under environmental conditions never occurring on-site, whether too extreme or constant throughout the test;
- the frequent adoption of application procedures that cannot be implemented on-site, due to either practical, safety or financial reasons.

At the origin of this apparent discrepancy between research and practice lies an effort to design lab tests in such a way that they can be reproduced easily and anywhere, in order to offer results that are comparable regardless of the time and place at which they are obtained. This drive to the "universalization" of testing procedures contrasts with the site-dependent factors affecting the product performance, such as orientation, exposure and substrate condition. Implicitly, it is assumed that absolute performance is affected by specific conditions, but that relative performance will nevertheless follow the outcome of laboratory testings. Despite many efforts [1], [10]–[12] the conservation community has not yet fully come to grips with this issue and resolving it often appears as wishful thinking, so that standard tests equally approved by scientists and practitioners are still lacking.

To address this issue, some researchers propose to develop rational criteria to define laboratory testing conditions that best represent the field conditions of interest [13], [14]. The appealing aspect of this approach is that it delivers durability results that could be directly useful to practitioners.

However, in view of being able to compare material performance over time and between projects, it ought to be complemented by more standard tests with fixed conditions to create some sort of material performance baseline.

2.4 The relevance of on-site assessment

Despite the many advanced non-destructive techniques (NDTs) available today, and the strong desire from practitioners to obtain more information on the performance of consolidants *in situ*, systematic on-site assessments still remain rare [9]. Advanced techniques are rarely applied, and, if they are, require significant time and financial investments, as well as the presence of highly specialized operators [15]. A more effective option has been to build up networks of academics and specialists who offer conservation science services for practitioners [16]. This improves the situation, but does not resolve the problem that most often practitioners only have a narrow choice of field tests (see 2.4.1). Therefore, to promote on-site assessments as a regular step during and after the application of consolidants, more research should be dedicated toward developing affordable and simple, yet meaningful, methods that can be used routinely.

2.4.1 Evaluation of effectiveness

The term *effectiveness* is often used to define the "extent of success" of a treatment. This depends on many aspects, first and foremost on how the goals were defined (see section 4.1). For now, we assume effectiveness to be solely an indication of the ability of the consolidant to improve the stability of the substrate[1]. Thus, some specific material properties can be used to measure it.

Changes in permeability, porosity and/or hydrophobicity can serve as indirect indicators of the presence and distribution of the consolidant regardless of its effect, while strength and hardness directly reflect the consolidation. Most often these properties cannot be measured on-site by means of NDTs, so that practitioners resort to "proxies" obtained from available simple field test methods, such as scratch tests, brush tests, tape pull-off, water drop and the resonance pointer [18]. More rigorous approaches include imaging, ultrasonic or impact techniques. Yet, none of the above mentioned NDTs offer enough information about the properties of the material beneath the surface. In this respect, the Drilling Resistance Measuring System (DRMS) seems to be the only method commonly adopted to obtain information through the depth of the substrate, despite the difficulties caused by its weight, geometry and partially destructive nature. It is also important to bear in mind that DRMS, like any other measurement of hardness or strength, is best performed after leaving the consolidant to cure for enough time[2]. Conversely, DRMS can be useful while planning an intervention

[1] Another important requirement for the success of a consolidation treatment is the aesthetical compatibility, commonly evaluated in terms of "color change". The measurement of this parameter is quite straightforward, thanks to the accessibility of well-established portable colorimetric techniques. For this reason, the authors decided not to discuss this aspect and focus instead on more problematic assessments. Readers interested in the topic can find useful insights in [17].

[2] Especially in the case of ethyl-silicate based consolidants, it has been shown that environmental conditions can have a large influence on the curing time (i.e., the time needed to reach full hardening), lengthening it in some cases to up to three months. In such cases, a measurement of the elastic modulus after four weeks would underestimate the consolidation by

to determine the needed consolidation time and depth (see section 4). This can also serve to determine the minimum time during which scaffolding should remain in place to test the outcome of an intervention.

However, additional methods are needed to provide feedback during an ongoing consolidation campaign, for instance to assess the penetration depth of the product. Portable NMR devices have been developed over recent years and may find applications in such problems [21]. An invasive, but practical solution to this problem was proposed within the Stonecore project, where an ultrasonic device for depth profile measurements was developed [22].

2.4.2 Medium- and long-term assessments

A successful short-term consolidation offers no long-term guarantees. For this, the consolidant must not cause an accelerated degradation of its surroundings, in addition to maintaining the mechanical integrity of the treated stone as long as possible.

Assessing this requires the planning of regular visits after the treatment and demands long-term dedication. This is rarely the case, and, in addition to the lack of convenient NDTs, leads to a lack of data about long-term consolidation performance.

For those cases where monitoring is done, a simple but useful comparative strategy has been suggested by Laurenzi Tabasso. It consists in leaving an untreated patch as a reference point to be compared even only visually to the rest of the treated zones [2]. Despite the usefulness of this simple approach, issues remain about which methods should be employed to obtain more objective measurements of the consolidated areas over time.

In practice, it is accepted that most consolidants degrade over time and that additional treatments will be needed at a later stage. From a philosophical point of view, this has a certain appeal since it means that the consolidant, while not reversible, is also not eternal. From a practical point of view, it raises the question of when this additional treatment should be applied. The measurement of the remaining consolidation efficacy is challenged not only by the lack of adequate NDTs, but also by the reduction in accessibility once scaffolding is removed. For this, strategies for the long-term monitoring of historical structures should be developed possibly borrowing from approaches used in studies of durability of concrete structures, where targeted embedded sensors or instrumented robots or drones for regular checkups are being developed [23], [24].

3 Some answers from research

about 50% [14]. Preliminary laboratory studies could serve to determine the minimum time during which scaffolding should remain in place to test the outcome of the intervention. Recent studies have shown that curing of ethyl silicate is greatly accelerated by post-treatment with a water/alcohol solution [19], [20] Many of the questions raised by conservation practice can currently find an answer in the academic literature. However, the usability of these results is hindered by the inherent scattered nature of scientific publications. In this section, we will try to summarize the most significant findings and the most promising ongoing research for a list of problematic issues normally encountered in conservation practice.

3.1 Change in transport properties

A consolidant inevitably affects to some degree the water and vapor transport properties of stone. Characterizing such changes is of great concern since large changes of these properties are generally considered to be undesirable. From a pragmatic point of view, and overlooking a more detailed discussion on the consequences of changing transport properties after consolidation, we can thus assume that a "safe objective" would be for consolidation to only have a limited impact. It must however be kept in mind that the effect of any treatment is strongly substrate- and application method- dependant. Therefore, case-specific evaluations should also be recommended.

Fortunately, the physics behind water and vapor transport are well known, and depend only on a few parameters, which reduce but do not eliminate the need for time-consuming and costly testing. For example, it is known that vapor transport is dominated by the pore geometry, so that we expect a consolidant to affect it if it coats or partially fills this porosity. In practice, this means that resins would clearly reduce vapor transport and that their impact should be assessed. In contrast, and, in first order, ethyl silicates would be expected to have a much lower impact on vapor transport[3].

Liquid water transport also depends on pore geometry. Large pores take up water faster, but to lower heights (in vertical rise cases), while small pores lead to slower ingress, but greater heights of capillary rise. However, in terms of liquid transport, the chemical nature of the consolidant plays a bigger role than in vapor transport, because it affects the wetting angle and, as a consequence, the sorptivity. Consolidants that increase the contact angle of water with the treated stone decrease its capability to transport liquid water. This may force water to evaporate behind the treated zone. This can eventually lead to local water accumulation that might enhance freezing or salt crystallization damage.

3.2 Adhesion and cracking

The effectiveness of a consolidation treatment is strongly influenced by how well the consolidant adheres to the substrate. This is determined by the fundamental chemical affinity of the consolidation product with the surfaces of the minerals constituting the substrate, by the morphology of the hardened consolidant at the interface ("hooking" onto the substrate), and by the mechanical

[3] As in many cases, the reality is complex. For example, the creation of bottlenecks after consolidation, may enhance capillary condensation and in turn accelerate vapour transport in certain relative humidity ranges [25]. It is important for the readers to be aware of such issues, but discussing them is clearly beyond the scope of this paper.

capability of the consolidant-mineral interface to allow a distribution of shrinkage stresses, thus preventing the detachment of the consolidant from the substrate.

From the chemical point of view, one can roughly group consolidants according to their selective affinity to either silicate or carbonate stones. Alkoxysilanes only adhere well on the OH- rich surfaces of silicate minerals, while lime-, barium hydroxide-, calcium phosphate- and oxalate- and tartrate-based treatments are most effective on carbonate substrates. Coupling agents can also be used to functionalize the surface to receive otherwise chemically incompatible treatments. In particular, specific modified TEOS (often amino-functional silanes) have been historically used to add hydroxyl groups on the surface of carbonate minerals, thus making them compatible with alkoxysilane treatments [26]. Polymeric resins, on the other hand, have in general a larger compatibility with different types of substrates, thanks to the complexity of their chemistry.

As mentioned above, however, these considerations regarding surface chemistry are not sufficient to predict the quality of adhesion. The mechanical interlocking with the substrate, and the ability of the treatment to bridge loose grains in the substrate or fill cracks are also essential for obtaining an effective treatment. The physico-mechanical qualities of the treatment can be optimized by ensuring that the thickness of the deposited layer is lower than a critical value (characteristic of each product), below which cracking during drying does not occur. This is especially important in the case of brittle consolidants such as the alkoxysilanes, and can be achieved, for instance, by varying the concentration of the active ingredient [27]. Another approach to prevent cracking consists in reducing the capillary pressure gradient during drying. This is done by decreasing the evaporation rate with additives to the starting products [28]. In any case, the complexity of the characteristics of the substrate will play a key role on the final bond between the consolidant layer and the substrate. Among the most important characteristics are: roughness, pore geometry, orientation of the mineral phases exposed, and presence of water and soluble salts [29]. For this reason, it is of vital importance to perform preliminary testing to correctly tune the properties of the chosen product for each specific stone substrate (see section 4) and decay profile.

3.3 Conditions of application and curing

As previously mentioned, the success of a given consolidation treatment depends on several factors: the penetration depth of the consolidant, its distribution in the pore system, as well as the thickness of the consolidant layer or deposit. All of these are strongly affected by the method of application, but also by the conditions of the substrate immediately before the application and during the curing period [30]. For this reason, several studies have focused on testing the performance of different products by varying such parameters. Despite the reasonable skepticism about the applicability of the results of such tests outside of the specific conditions of the experiments performed, this type of research can offer general indications on what issues one should mostly worry about, for different types of products.

For instance, alkoxysilanes are known to vary in performance due to the water content of the substrate (see also footnote 1), as an excess of water would accelerate the condensation reaction and hence influence the distribution of the product in the porous network [31]. Phosphate-based treatments, on the other hand, are most vulnerable to the presence of salts, as they can lead to the formation of more soluble phases of calcium phosphate with respect to hydroxyapatite (the most stable calcium phosphate).

Evidently, more detailed predictions about the on-site performance cannot be offered without taking into consideration the specificity of the substrate (even for different zones on the same façade!) and the multitude of factors varying simultaneously during a real application campaign (skill of the operator, climate, actual amounts applied). A few studies have shown that Design of Experiment (DOE) can be a powerful tool in such cases, as it offers the possibility to predict the outcomes for systems with complex multi-factor interactions in a given range, using only a limited number of experiments [34].

3.4 Effect of salt contamination on consolidation success

Salts are considered to be one of the most important causes of damage in building stones. This develops through crystal growth in the porosity of these materials, leading to stresses that damage the stone. In first approximation, we can consider that the depth at which salts are found corresponds roughly to the depth at which a consolidant would be required to act. Thus, in this part of the stone, the consolidant action may be affected by the presence of salts, even if their amounts have previously been reduced by desalination [35]. While much attention has been paid to the possible negative effect of salts on the durability of consolidants, very few studies have looked systematically at their influence on the effectiveness of consolidation itself [36], [37].

The impact that salts may have on the chemistry of the condensation reactions will depend on the nature of the consolidant and the solvent with which it is applied, as this will determine whether salts may dissolve or not. Independently, the presence of salt crystals may also limit the contact surface between the consolidant and the pore walls, which would reduce their performance. That issue would be exacerbated if the salts later dissolve in the presence of water, leaving behind gaps in the consolidated zones.

3.5 The influence of biofilms

Biofilms are generally identified as a concern in relation to the performance in practice of consolidation interventions. However, as with salts there are little to no systematic data about whether or to what extent this really is an issue that we should be concerned with. What is generally stated is that a prior cleaning treatment, typically by means of commercial biocides or cultures of viable bacteria, is recommended [38]. This appears a reasonable approach. However, it should be underlined that the consolidation should mainly be within the stone and that unlike salts, biofilms are mainly (but not exclusively) found on the outer surface of the stone. Clearly this issue deserves more investigation with a development of adequate sample preparation and testing methodology being a high priority.

3.6 Dealing with clay bearing stones

Clay-bearing stones – especially those with a high content of swelling clays – can be weak materials that need frequent conservation. They are in particular susceptible to cycles of wetting and drying because of these clays [39]–[41], and the related studies of this phenomenon provide a good basis for investigating more specifically their interference with consolidation.

The presence of clays does not dramatically influence the characteristic penetration or adhesion of ethyl silicates in different stone types. Rather, it can even have a beneficial effect on limestones, as the clays provide hydroxyl groups for the TEOS-based consolidants to bind to [42].

However, when subjected to wetting/drying, most of the consolidation benefit offered by ethyl silicate can be lost within just a few cycles [43]. This is because alkoxysilanes are typically brittle once cured, and hence unable to withstand stresses exerted by the swelling clays. As a possible solution to this issue, swelling inhibitors have been proposed as a pre-treatment and preliminary results suggest that they can indeed extend the service life of TEOS-based consolidants [44].

A negative effect of the presence of clays on the consolidation with other types of products has not been highlighted in the literature as of now.

4 Common questions for practitioners and researchers

Several parts of this manuscript emphasize the importance of the connection between the work of the scientist and the conservator. As explained, researchers are able to a large extent to provide the information necessary to ensure a successful execution of a treatment. On the other hand, the direction of scientific research itself should better incorporate the experience of conservators, who have a good sense of the potential issues relating to application and real site conditions. In this respect, preliminary collaborative studies and dialogue become a vital moment in conservation science, as they represent the occasion for practitioners and scientists to define together questions of common interest.

4.1 The importance of preliminary assessments

As was made apparent in sections 2 and 3, there is no product that can give the certainty of success on any given substrate. For each case, conservation specialists face a list of often contradictory requirements that are case dependent and that force them to make compromises. Understanding to the utmost the different constraints substantially helps select beneficial actions and avoid ineffective or – even worse – harmful ones.

It is important not to set expectations too high and to recognize that hoping to acquire a complete knowledge of the substrate, of all products and of the whole literature is unrealistic. In other words, the perfect solution does not exist. The choice of a treatment always involves a certain degree of uncertainty, but this does not mean that the most established products, or those that one has most used up to then, are the most appropriate. Preliminary assessments are important means to identify specific problems and to encourage consideration of less known, possibly more suited treatment strategies. To achieve this, the following factors are worth characterizing:

- Nature of the substrate and preferably also its composition
- Morphology of the porosity and cracks
- Type and depth of deterioration
- Type of consolidation needed (fill cracks or restore cohesion)
- Actual moisture content
- Amount and type of salt contamination
- Presence of biocontamination and if so its nature
- Specific conditions for treatment application (climate, accessibility)
- Conditions to which the consolidant will be subjected (potential degradation of the consolidant)

The knowledge of these aspects can be used to narrow down the list of suitable treatments. In section 6, we propose a possible method for the selection of the most fitting products for different case scenarios.

For some problems, however, an answer may not yet exist. It is in this moment that preliminary assessments turn into an important opportunity for practitioners to define questions, and for scientists to take up the challenge to work on this unexplored but relevant territory.

4.2 Pre-testing

Whether a traditional or a novel product is considered for a treatment, it is of utmost importance to test consolidants before they are applied on an object of cultural interest. The strategy must be adapted case by case to ensure that the targeted effects are reached. In particular, reaching the necessary depth of penetration is essential.

bright future for interdisciplinary conversations. This may be the right moment to rethink the way research is presented and find ways to reorganize laboratory results into more navigable resources.

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