Consolidation of decayed stones. A delicate problem with few practical solutions

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ABSTRACT: Stone consolidation is almost always a very risky intervention. It is a non-reversible intervention and has serious harmful side effects. Due to these shortcomings, a decision to go for a consolidation action is always difficult to take and it is simple only when it is taken as a "last option" when replacement or full destruction are the unique alternatives at sight. Stone consolidation is needed because stones decay and loose cohesion in the exposed surfaces down to a certain depth. This conservation operation should take into account that type, extent and rate of decay largely depend on the intrinsic properties of the stone and on the extrinsic or environment factors. The combination of the intrinsic and extrinsic decay factors can give raise to multiple degradation forms that largely influence the decision on to consolidate and the options on the type of consolidant and on its application forms. The identification and characterisation of decay profiles is also a relevant step in stone conservation, namely when consolidation is concerned. The paper gives a brief introduction to a few topics on stone consolidation exemplifying with some current stone consolidation products. It quotes some cases of stone consolidation in recent Portuguese experience and presents some illustrations on the use of the microdrilling instrument in the detection of past consolidation actions.

1. INTRODUCTION

Among the different procedures in stone conservation practice, consolidation is certainly one of the most studied problems. However, it is the one with fewer positive results and where many doubts and uncertainties remain. The loss of cohesion and the subsequent erosion of the exposed stone surfaces in architectural objects have challenged masons, architects and curators since important stone structures were first constructed and, more recently, scientists joined the group of active professionals searching for remedies of this long-standing and demanding conservation issue.

Replacement of decayed pieces has been a current and acceptable practice, and it is still used today to an extent and with justifications that vary according to regional and cultural background of the persons involved in the intervention. Within European culture replacement tends to be mostly confined to situations requiring structural functions, leaving a wide range of situations where consolidation is recommended or even needed to prevent total deterioration before replacement is decided. In general consolidation is a risky intervention and is subject to frequent controversy. It is a non-reversible action, its long-term performance can seldom be guaranteed and the harmful side effects are frequent.

Although some positive advances have been made in conservation practice, as published in the scientific literature on this topic, progress is slow. Research is not always straightforward and quite frequently follows self-perpetuating circles or appears to reach dead-end roads with few innovative ideas or new promising research lines. The subject would greatly benefit from a
decisive input from the relevant industry, but the product amounts involved in the conservation activity are not attractive enough to catch the attention of this possible partner. The number of successful consolidating products specifically designed and developed for the conservation activity is minimal and, therefore, researchers have to adapt their objectives to the existing consolidating agents developed by the chemical industry for other more profitable areas of activity.

The LNEC research group on stone conservation has been dealing with this conservation topic since the 80’s and in its experience some of the positive aspects as well as some of the enumerated shortcomings can be found. When selecting this argument for this presentation, the author aimed at bringing his reflections on this important matter to a wider audience and at explicitly stating some key-issues that could bring some benefit to this domain: the continuous need for more and better-structured lab and field research; the collection and diffusion of well documented cases where successful or unsuccessful consolidation interventions were carried out; the involvement of the chemical industry in the development and testing of specific products in cooperation with research teams with experience in the field; the allocation of public research funds to cooperative projects through a dedicated call with the research team(s) assembled by an international jury of experts; the organisation of thematic meetings on this conservation topic - some of them restricted to the best placed researchers on this subject - followed by the publication of the corresponding invited communications.

2. THE NEED FOR CONSOLIDATION

Stone consolidation is needed because stones decay and loose cohesion in the exposed surfaces down to a certain depth. The decision to consolidate can be justified when the loss of the superficial layer of the stone brings about the loss of any eventual historical or artistic value or when the material erosion is jeopardising the overall structural stability of the object or its neighbourhood. The scope and length of the present paper do not leave room to analyse the causes and mechanisms of decay that can bring about the loss of cohesion of the stone surfaces, but the reader should bear in mind that both items are essential to support a correct decision and define the appropriate procedures of any consolidation intervention. With the risk of excessive simplicity and without aiming at being exhaustive, the following topics summarize some relevant aspects of this subject:

i) The type, extent and rate of decay largely depend on the intrinsic properties of the concerned stone. Mineralogical composition, stone texture and structure, porosity (absolute value, type and pore size distribution), mechanical and thermal properties are the key-parameters in this regard. As a first logical conclusion, no consolidation action can reasonably be justified without having access (directly or by deduction) to information on all these aspects.

ii) The type, extent and rate of decay also depend on extrinsic factors that include the climatic conditions (from the regional to the micro scale), the atmospheric composition, the biotic forces, the location of the stone piece in the architectural object, the use and care given to the object. Consequently, consolidation actions should not be acritically extrapolated from place to place and from region to region.

iii) The combination of intrinsic and extrinsic decay factors can give origin to multiple degradation forms. Their precise identification and appropriate mapping are an essential preliminary step for the definition of the practical operations of any conservation action. For instance, powdering zones and areas with contour scaling are not supposed to be consolidated with the same procedure; sand disintegration and multiple exfoliation should be approached in distinct ways. Matching the decay forms and the appropriate consolidation practice is a typical responsibility of the conservator-restorer where scientists should have a qualified and indisputable role.

Except in some exceptional cases, consolidation is not to be applied to sound stones. This means that the part of the object to be consolidated is made of something else than the stone
“originally” applied and that eventually can still be found in the source quarry. A decayed stone layer might be quite distinct from the underlying sound original material. In this context, knowing the composition and properties of the sound stone might not be enough to design and apply a consolidation action and some additional information on this decayed zone may be required for this purpose. The identification and characterisation of decay profiles is a difficult but an extremely relevant step in stone conservation, namely when consolidation is concerned. Figure 1 illustrates two cases where the extensive degradation of a very porous limestone would justify some consolidation actions.

![Figure 1: Plaques, scales and powdering decay forms in soft limestone columns. Very likely, some consolidation was applied in the past (see hard skin in the left side photo)](image)

3. THE CONSOLIDANTS

Limewater (calcium hydroxide) is one of the simplest consolidation products that since long practitioners have at their disposal. Together with a few other chemical compounds (v.g. barium hydroxide, sodium and potassium silicates, fluorosilicates and aluminates) they form a group of inorganic consolidants that promote the improvement of the stone cohesion through the precipitation of inorganic molecules that are supposed to bond the loose particles of the decayed stone (Lazzarini and Tabasso 1986). The chemical similarity between the decayed material and the bonding agent confers in theory a high potential to this group of products but, for several reasons, this potential has not a direct correspondence in practical terms and, when looking at recent produced literature on this subject, one immediately recognises that the inorganic consolidants are very rarely dealt with.

The other category of products includes a vast variety of organic compounds, namely of polymeric structure that include acrylates, vinyl acetates, ethyl silicates, polysiloxanes, polyurethanes and epoxy resins. Their basic active components were mostly (if not entirely) prepared for other purposes than stone conservation and their adaptation to this new use has never been an important objective for the major chemical industries that developed or produced
those products. The available supporting research for most (if not all) stone consolidants was not carried out by the corresponding industrial manufacturers but by independent researchers that are more appropriately placed on the users side. This attitude contrasts with the situation existing in other important target fields of the chemical industry (v.g. medicine and agriculture) and it illustrates how marginal stone conservation is for industry. With a more proactive attitude, these industries could play a decisive role in speeding up the progress of the conservation practice. To make things still worse, most consolidation products are manipulated and supplied by intermediate formulators, sometimes with little knowledge about the products and their properties, and providing very poor scientific and technical information on the products and on the relevant suggestions for application, curing, characterisation and assessment of lab and field performance.

The “history” of consolidants is not particularly well written and explained. The scientific papers deal with this subject only in part and in fragmented terms, most times following individual approaches that cannot be easily (if not at all) integrated in monographic or comprehensive documents that would be of extreme value for the conservation practice. Most of the available literature is produced in an academic environment that seeks scientific recognition but that does not necessarily match the doubts and needs of the professional conservation field. The absence of defined common objectives and the well-known tendency of researchers to follow their own defined approach lead to a situation where most of the produced scientific literature is unused (and eventually unusable) for the benefit of practitioners.

The “ideal” consolidant would be a product that is able to restore the strength as well as the other physical properties of the decayed stone layers to the level of the sound stone that existed before degradation and to achieve it without any harmful side effects. In the actual conditions, consolidation processes are not entirely mastered and, in practice, we know very little on how to restore a decayed stone into what it was before degradation. And to make things more complex, harmful side effects are very frequent in consolidation actions, suggesting that there is still a long road ahead until full mastering of the process is reached. Mastering the process implies to deal with numerous variables which turns this objective a complex engineering problem (see Sasse et al. 1993, Sasse and Snethlage 1996, Sasse, 2001 for examples of such an approach).

Leaving the inorganic consolidants without further analysis (let us hope that researchers keep going trying to improve them and to find new and more effective solutions) let us pay a brief visit to some groups of stone consolidation products on which we have carried out some lab and field studies: the ethyl silicates, the acrylic and the epoxy resins. Polyurethanes, a promising group of consolidants (Guidetti et al. 1992, Auras 1993, Chiavarini et al. 1993, Littmann et al. 1993) will not be addressed here for lack of space and little personal experience of the author on this type of products.

The ethyl silicates are probably the widest used stone consolidant. After hydrolysis and condensation, ethyl silicates originate colloidal silica that is deposited inside the porous structure. The silica molecules are chemically alike to the silicate minerals and therefore they exhibit a very good compatibility with stones having a silicate-based composition. In turn, they show no affinity to carbonate minerals and some authors have shown that calcite may even act as inhibitor of polymerisation (Danehey et al. 1992, Goins et al. 1996a,b). In spite of this drawback, ethyl silicates have been frequently used as consolidants for carbonate materials, namely in Portugal, for instance, in Torre de Belém, in Lisbon (Delgado Rodrigues et al.1998) and Igreja de Santa Cruz, in Coimbra (Castro et al. 1990, Delgado Rodrigues et al. 1997). This apparent contradiction illustrates one of the current problems of stone consolidation: it is known that this is not the optimum consolidation product, but it is used in the absence of anything better. Recently, some research groups have tempted to improve the behaviour of ethyl silicates as consolidant for carbonate stones and two promising lines are now giving their first steps: the elastomerisation of the ethyl silicate by means of the addition of some silane molecules (Boos et al. 1996) and the pre-treatment with an organic reactive in order to prepare the carbonate minerals to adhere to the silica molecules (Weiss et al. 2000).

Experiments carried out in LNEC with carbonate rocks have shown that current ethyl silicates induce a very slight strength increase, but the main positive characteristics are their very high
capacity of migration inside the stones, the slight reduction in water vapour permeability and the absence of strong interfaces between treated and non-treated zones. Very likely, these are important arguments for justifying the wide use that has been made of them and they shall be taken as an incentive to keep going with the research to improve their properties.

The acrylic resins have a wide acceptance in many fields of conservation of cultural heritage and they have also been used in stone conservation. Some reported cases have turned them widely known and their application in the consolidation of the S. Petronio Cathedral, in Bologna, (Rossi-Manaresi 1981, Nonfarmale 1975, 1981) have even coined a neologism for the consolidant used there: the “Bologna cocktail”. It includes the well-known Paraloid B72, a methyl acrylate ethyl metacrylate, together with Dri-Film, a silicone based water repellent. Results obtained with this formulation in porous carbonate stones (up to 26% porosity) have shown that the consolidation effect is confined to not more than 2mm depth, even in the most porous varieties.

When confronting our results with the reported good performance of this “cocktail” in the Bologna Cathedral, we have to conclude that apparently both things do not match. In our opinion, Paraloid B72 has been used indiscriminately whatever the substrate is, and this is certainly a mistake that explains some of the discrepancies found when analysing the performance of this consolidant. In fact, the stone used in the Bologna Cathedral is a very dense limestone (the rosso di Verona) and marble, both having the relevant void space mainly made of fissures and not of pores. Their typical degradation forms consist of the enlargement of fissures and the occurrence of scales of several sizes. Paraloid B72 is able to penetrate through these fissures where it builds up some adhering bridges between the fracture walls and therefore it plays the role that is expected to be effective for such a degradation form. In spite of the larger size, the connectivity is poorer in the porous stones, and this characteristic forces the consolidant to stay in the outer stone layer where it promotes a high increase in strength but with serious harmful consequences in terms of the stone subsequent behaviour.

In practical terms, these results seem to demonstrate that Paraloid B72 (and may be all the other acrylic consolidants) acts like an adhesive or gluing agent and not as a traditional impregnating consolidant as we usually see it. When properly used in the situations typified above with the dense, fissured or fractured limestones, Paraloid B72 (and alike) can be of valuable use, but it may turn very risky or even disastrous when used inadequately in stones with spherical pores particularly in the very porous ones (Figure 2).

Another category of consolidating products includes the epoxy resins. This group of chemicals includes a wide range of products, where some of them have been used in stone conservation (Domaslowski 1969, Gauri 1974, Marinelli 1975). Of particular interest are the cyclo-aliphatic epoxy resins that have better characteristics than other epoxy types, namely in terms of their resistance to UV radiation. One of the consolidation products of this type is the EP 2101, from EUROSTAC, that has been used successfully in the deep consolidation of some granite columns (Cavaletti et al.1985) and that we have also tested in LNEC both with granites and with carbonate rocks. This product has shown an excellent impregnating capacity, both in fissured materials like granites and in porous varieties such as the carbonate stones.
In fact, we were able to consolidate granite specimens in about 7cm depth and limestones on more than 2cm, under normal environment conditions. It is not place here to analyse in detail the performance of this consolidant, but just to highlight some of its peculiarities. The reported success of the consolidation granite columns (Cavaletti et al.1985) gets a total confirmation in our previous results (Delgado Rodrigues and Costa 1996) (Figure 3) but our recent research studies on carbonate stones leave us with some doubts on the adequacy of this consolidation product for porous materials (Ferreira Pinto, PhD thesis, in preparation).

While in fissured materials the epoxy resin seems to produce a more or less gradual strength increase, in porous stones the consolidation is mostly confined to the outer stone skins, in a such a way that a sharp boundary is created between the outer very hard layer and the inner less consolidated and consequently less resistant zone. Its impregnating capacity is higher than that of Paraloid B72 and the transition between outer and inner zones is less sharp, but in large terms these two consolidants seem to act in much a similar way. The conclusion can, thus, be very similar. The epoxy resins are well suited for fissured or fractured stones, where they act mostly as adhesives, but they are much less appropriate, if not completely inappropriate, for porous stones, even for those having very large porosity.

4. MANY THEORETICAL RESULTS AND FEW PRACTICAL SOLUTIONS

Among the conservation activities, consolidation is certainly the one that presents more difficulties to practitioners. They face a complex material with diversified evolution mechanisms that turn them virtually unique at each practical intervention. They are prepared to take into account the nature and decay state of the stone and its water content, they know that the result depends on the type and concentration of the consolidant, on the type of solvent, on the application technique and on the contact time. In such a complex domain, they need the help of the scientific community, but, when seen from their side, most scientific results are not easily transferred into practical ideas or solutions or even try to “solve” problems that they don’t have
or that they feel in rather different terms. A better and more frequent dialogue between scientists and practitioners would bring great benefits for the conservation practice.

![Ultrasonic profile graph](image)

Figure 3: Ultrasonic profile in a granite specimen treated with EP 2101, a cyclo-aliphatic epoxy resin. The penetration depth reaches about 7 cm (in Delgado Rodrigues and Costa 1996)

There is a vast literature on themes directly related to stone consolidation and papers on virtually any relevant subject that we may point out have certainly been published somewhere. However, this proliferation of studies is not accompanied by a serious effort to integrate all the dispersed research results into comprehensive solutions for the real practical problems that more directly affect the conservation practice. The actual situation requires that a team of experts takes this subject on hands and start a programme of international discussion on the theme of stone consolidation. This could be accomplished through the organization of restricted and open meetings aimed at the production of monographs and manuals that would be extremely useful for practitioners and could fill the role of textbooks for students and research trainees. It is not the question of preparing and providing receipts to the conservation practice, but rather to gather and assess the dispersed information in a critical way and to make it available outside the restrict group of conservation scientists.

A vast number of historical buildings and stone objects are made of carbonate rocks. The sedimentary varieties of this group of stone materials are highly diversified in composition, porosity, texture, as well as on their mechanical properties. They may vary from very dense and resistant to very porous and soft varieties. They are sensitive to acid rain and quite frequently decay through powdering and multiple scaling. In this vast group of stone materials, one can find severely damaged situations where consolidation is frequently inevitable. However, consolidation of materials of this important group meets a challenging and unsolved problem: the stronger consolidants such as acrylic and the new epoxy resins promote the development of strongly contrasting interfaces and risk to induce severe long-term harmful effects, while the less harmful products, such as the ethyl silicates, are mostly chemically incompatible with the carbonate minerals and therefore they promote very slight strength increases.

Recent research has attempted to overcome the poor performance of the ethyl silicates and some promising trends are showing up in the market of consolidating products, consisting on new additivated ethyl silicates having an increased capacity to bond to carbonate surfaces and
having more plastic and less brittle behaviour (Boos et al. 1996) and the HCT method that consists in a pre-treatment of the carbonate materials by creating a hydroxilated layer to which the ethyl silicates will easily bond, thus increasing the consolidation capacity and stability in time (Weiss et al. 2000).

Lab research protocols followed by conservation scientists do not help practitioners to grasp through the results in their search for practical solutions. From the strictly scientific point of view, an innovating research protocol can be perfectly justified, but very likely this will turn things still more difficult to the practical seeker. Standardisation doesn’t favour innovation, and innovation is highly necessary in conservation science. However, it is highly advisable that research conservation scientists discuss their results bearing in mind how close or distant they are from the more current research protocols.

5. A FEW PRACTICAL EXAMPLES FROM PORTUGUESE EXPERIENCE

The experience with stone consolidation in Portugal is not very rich. The scientific interest for these matters started in the earlier 70’s but with scarce human and material resources. The practical know-how remained at a very low level for more than two decades after this start and only recently we can find skilled restorers and operators capable of carrying out high quality consolidation operations.

As far as the author can trace, the first comprehensive study that envisaged a specific consolidation intervention was carried out in 1990 in LNEC and it was intended to give practical solutions for the safeguard of the Renaissance façade of Santa Cruz church, in Coimbra (Castro et al.1990). For contingency reasons, this intervention was not carried out immediately and later in 1997 LNEC was requested to update those studies and to provide solutions for the intervention that was commissioned at that time. In a new report (Delgado Rodrigues et al. 1997) the relevant research material was presented. The most valuable part of the façade is made of a micritic limestone (the Ançã stone) having 26-28% porosity and presented an extremely advanced degradation condition, with powdering and scaling producing heavy surface losses. From the extensive lab testing programme addressing the aspects of effectiveness, harmfulness and durability, it was concluded that acrylic based consolidants would create a superficial layer with excessive strength contrast with the underlying non-treated zones and therefore such kind of consolidants was rejected. The ethyl silicate has shown a slow strength increase, but it has shown that it was the only solution that could allow the existing soluble salts to cross the treated layer without excessive damage (Figure 4). This treatment was considered to have capacity of slowing down the degradation rate and therefore it was accepted and applied.

The intervention carried out on the Tower of Belém allowed LNEC to participate in another challenging study, namely on the testing and selection of consolidants (Delgado Rodrigues et al. 1997, 1998, Delgado Rodrigues and Ferreira Pinto 2000). The stone is a very dense limestone, but the blocks exhibit a remarkable variability in quality, including pure varieties with porosity in the order of 1-2% and varieties containing a certain (not very very high) amount of clays, usually concentrated in thin veinlets and with slightly higher porosity and poorer performance. The external surface was in a fairly good conservation state and only a couple of situations really raised some conservation problems that would eventually need consolidation. One of these situations consisted in surface powdering occurring in zones where black crusts existed or had just fallen. The other situation consisted of a few blocks badly decayed by multiple scaling, spalling and fragmentation, in connection with swelling decay mechanisms triggered by higher contents in clay minerals. Based on laboratory and field studies, it was advised that the heavily decayed blocks could be consolidated with a cyclo-aliphatic epoxy resin, provided that a long contact between the product and the stone could be guaranteed. This objective was accomplished by the conservator-restorer by means of moulds adapted to the blocks serving as containers where the consolidants could stay for several hours in contact with the stone (Proença 2000). Due to the difficulty in consolidating the powdery areas, the consulting experts
team, based on the LNEC results, decided to apply an ethyl silicate in the surfaces where consolidation was assessed to be less risky. For the main portal, where powdering is largely occurring, the intrinsic value of the surfaces raised some doubts on proceeding even with ethyl silicate and only lime-water was applied hoping that science and technology could provide in the near future safer and more effective solutions.

Dealing with consolidation may also mean identification and characterisation of past consolidating interventions. Cases where consolidation has promoted decay are not rare and in some situations it is not simple to confirm that actual decay is linked or promoted by eventual past consolidation actions or are simply due to normal decay mechanisms. When chemical identification of products is achieved it constitutes a definite answer but it gives little help on the extension and depth of consolidation and, in many cases, this identification is just not possible. For the particular situation of soft rocks, a new tool recently developed under a EU research project (Tiano et al. 2000) can be of great help and bridge some of the existing gaps. The equipment consists of a portable microdrilling device that measures the drilling resistance in depth offered by the stone, during a drilling operation under strictly controlled drilling rotation speed and advancing rate. Results from a recent study carried out under the framework of the preparatory studies for the intervention in Porta Especiosa (Coimbra), illustrate the use that can be given to this new instrument (see Figure 5 for an example of this kind of results).
Figure 5: Drilling force graphs in consolidated (a) and non-consolidated areas (b) of the same stone block.

The graph indicated as b) in Figure 5 corresponds to an area of the stone block where a stone chip had recently fallen off leaving a fresh surface exposed. In this precise spot, past consolidation was absent with total guaranty. By comparison with this graph, the drilling force profile indicated as a) shows a marked superficial strength increase due to an old consolidation treatment. Just for clarification, it should be noted that the drilling bit has a triangular shape, fact that explains totally or in part that the initial part of the graphs starts from very low forces, a fact that do not corresponds to reality. This situation can be corrected manually or avoided by using drill bits with a flat tip.

This same equipment was used for laboratory characterization of the strengthening action of some current consolidation products. Figure 6 displays a few graphs obtained with two acrylic resins (Paraloid B72 and ACS 2001), and another one corresponding to an ethyl silicate (TG – Tegovakon V). The two acrylic resins show a pronounced strength peak in the first 3mm of the stone specimen, decreasing rapidly to values close to the non-treated graph. Worth noting is the correspondence of these two graphs with the formation of a fracture with about 2mm thick during the salt crystallization test illustrated in Figure 2. The graph of TG, on the other hand, shows a small strength peak and an extended band with a slight strength increase in more than 15mm in depth. This corroborates the easy impregnation capacity of the ethyl silicate and, at the same time, the low consolidation capacity that is currently attributed to it when applied in carbonate stones.
Fig 6: Typical drilling force versus depth for some current consolidation products. The graphs compare two acrylic resins (B72 and ACS) and one ethyl silicate (TG) with the non-treated stone (NT). Adapted from Delgado Rodrigues et al. (in preparation)

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