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Nano-Lime for Consolidation of Plaster and Stone

Paul D’Armada and Elizabeth Hirst

Abstract

Stone consolidants should, ideally, be physically and chemically compatible with the materials requiring consolidation. The theoretical principle of getting calcium hydroxide into a decayed calcareous substrate, and allowing it to carbonate, has long been understood and was the reason why limewatering (a method refined by Professor Robert Baker in the 1970s and 1980s) was used on several important projects, including the carvings to the west front of Wells Cathedral. Nano-lime has been developed as a method of consolidating limestone and lime plasters because it offers theoretical advantages over traditional materials such as limewater and lime grouts. Preliminary investigations to determine its performance characteristics prior to its specification and subsequent use on medieval wall paintings were undertaken by Hirst Conservation in 2010. Although these tests were limited to only a few materials, results were encouraging and highlighted some of the product’s advantages and disadvantages. The results clearly show that rates of penetration vary significantly according to the type of material, its porosity and other factors. Nano-lime dispersed in alcohol can work well as a consolidant if used in the correct manner, allowing time for maximum penetration, precipitation and carbonation of the nano-lime. This may take days or even weeks for each saturation.

What is nano-lime?

Nano-lime consists of very small particles of calcium hydroxide suspended in alcohol; the average diameter is quoted as 150 nm with a range of 50–300 nm (Table 1). Synthesized under specially formulated and controlled conditions, the production of nano-lime has no similarity with the slaking of lump lime to form lime putty. Nano-lime particles
are much smaller than the conventional particles of calcium hydroxide present in fresh lime putties (8,000 nm) although research has shown that, in an aged lime putty, they can be as small as 200 nm.\textsuperscript{2} The smaller particle size of nano-lime has the advantage of achieving greater penetration into the pores, while the higher surface area/volume ratio allows for greater reactivity.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Ionic radius (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium ion</td>
<td>0.1</td>
</tr>
<tr>
<td>Hydroxyl ion</td>
<td>0.14</td>
</tr>
<tr>
<td>Nano-lime</td>
<td>50–300</td>
</tr>
<tr>
<td>Conventional lime hydrate</td>
<td>Perhaps $10^3$ to $10^4$</td>
</tr>
<tr>
<td>Pore space</td>
<td>Perhaps $10^3$ to $10^4$</td>
</tr>
</tbody>
</table>

Table 1 Sizes of different particles.

1 nm = $10^{-9}$ m

Although lime molecules (dissociated as calcium and hydroxyl ions) in limewater are even smaller (~0.24 nm) than nano-lime particles, water can dissolve only about 1.7 g of calcium hydroxide per litre at 20°C. So while limewater has traditionally been used as a consolidant on friable plaster and stone, it requires many saturations to get sufficient lime into the substrate and its consolidation effect can only be detected after an excess of 150–200 applications. Such copious amounts of water can actually cause deterioration of the stone or plaster through recrystallization of salts and other mechanisms of decay associated with repeated wetting and drying. As such the method may be impractical for a conservation project.\textsuperscript{3}

The main theoretical advantages of nano-limes are:

- they can carry much greater quantities of lime because they are suspensions of lime (rather than solutions);
- no water is involved in the application.

 Nano-limes satisfy the performance criteria usually expressed in any conservation strategy, that the materials used should, as far as is possible, be compatible with the material being conserved and be of predictable behaviour. But like most other consolidation techniques, nano-limes are not reversible. However, initial results on the efficacy and compatibility of nano-lime when used for the treatment of calcareous stone and plaster are thought to outweigh any disadvantage due to its irreversibility.

For the commercial formulations used in tests and in the project at All Saints' Church, Little Kimble described below, the quantity of lime carried is reflected in the name of the product. For example, CaLoSiL®
E-50 carries 50 g of lime per litre, or approximately 30 times more lime than in limewater. Compared with limewater, this particular nano-lime product could theoretically achieve equivalent deposition of calcium hydroxide into a porous material with only a thirtieth of the number of applications.

**How does nano-lime work?**

When a substrate is treated with nano-lime, calcium hydroxide is precipitated in the pores of calcareous materials as the alcohol disperses and/or evaporates. As calcium hydroxide carbonates to calcium carbonate, it replaces lost binder or matrix in natural stone and plasters, thereby ‘knitting’ together fine cracks and deteriorated stone, increasing strength and integrity.

The overall carbonation process is represented by the following reaction:

\[
\text{Ca(OH)}_2 + (\text{H}_2\text{O} + \text{CO}_2) \rightarrow \text{CaCO}_3 + 2\text{H}_2\text{O}
\]

Both water and carbon dioxide are necessary for carbonation of the lime, but the carbon dioxide can only react with lime by intimate molecular contact when it is carried in water as carbonic acid ($\text{H}_2\text{CO}_3$). The water required can come from the atmosphere, the treated material itself, by spray application or by adding it to the nano-lime before application. When water is added to nano-lime to increase its reactivity, however, the resultant formation of a calcium hydroxide gel may reduce penetration. Like any slaked lime, nano-lime carbonates more slowly at lower temperatures and will not carbonate at all at 4°C or below.

Consolidants based on the carbonation of calcium hydroxide may not be appropriate for the treatment of pure sandstones because they may eventually introduce calcium salts such as calcium sulfate (gypsum), with well-catalogued detrimental results.

**Application of nano-lime**

Current research suggests that nano-limes have a shelf life of 3–5 months (longer if refrigerated). Suspensions are available in ethanol (the ‘E’ series), isopropanol and n-propanol; those in ethanol have a slightly lower viscosity. Nano-lime can be applied by brushing, injection, spray, pouring, immersion, vacuum impregnation and systematic dripping techniques. Brushing is not as effective as the other methods and
poulticing appears to be generally ineffective, particularly when the nano-lime has a greater affinity with the poultice material (e.g. paper) than with the minerals in the substrates.

For any decayed material, it is important that the degraded zone is saturated with consolidant to a depth beyond the sound material. Treatment can be repeated when all the solvent has evaporated and carbonation of the nano-lime has occurred. The depth to which nano-lime will penetrate into a porous material depends largely on the character and openness of the surface treated, and the prevailing environmental conditions. For example, compact surfaces and those with a gypsum or mineralized crust usually prevent satisfactory penetration, while damp, cold conditions will inhibit evaporation of the alcohol.

Capillary theory suggests that the rate of diffusion of the nano-lime is 2–3 times slower than its alcohol dispersant which, in turn, is approximately 2–3 times slower than water (or limewater). The type of consolidant used and its surface tension, viscosity and volatility are, therefore, important factors, not only for the speed of impregnation but for the quantity of consolidant used (some of it being lost by evaporation). For example, because alcohol not only diffuses more slowly than water but evaporates more quickly, it is more difficult than water to introduce into a porous material. But in cracks and fissures, and where the pores are larger and have less capillarity, alcohol will generally flow better than water. Being non-polar, its molecules are less cohesive than water and, as a result, alcohol wets better than water.

Nano-lime can be used on its own for the consolidation and strengthening of stone, plasters and mortars, or in combination with aggregates and fillers to produce injection grouts or repair mortars.

**Background to research on nano-lime**

The production and utilization of nano-sized suspensions of lime has been studied for more than a decade. The first use of reasonably stable lime dispersions in n-propanol was reported in 2000 by Giorgi, Dei and Baglioni. They studied capillary suction and water vapour permeability of treated and untreated specimens of lime sand mortars, and followed the carbonation of the nano-lime by X-ray diffraction (XRD). The formulations prepared by this team were used for the treatment of wall paintings in Santa Maria Novella in Florence, the nano-lime being applied by brush through Japanese tissue.

Dei subsequently shifted his research to isopropanol dispersions. His work with nano-lime on wall paintings at the Museo del Bargello was published in 2005, with particular attention being given to the question of colour stability. In the following year, he co-authored a scanning
Figure 1  Diffusion of nano-lime (E-25) through Ketton limestone. The maximum penetration is shown by pink phenolphthalein.

Figure 3  Cube consolidated to a depth of 1.5 cm by 20 saturations with nano-lime (E-25).
Consolidation of flaking paint

Injection of fine lime-based grout material

Lime-based repairs

Consolidation of plaster and hairline fractures with nano-lime (E-50)

Consolidation of plaster and hairline fractures with nano-lime (E-25)

Figure 4 Areas of repair and repair types to the wall painting of St George located in the nave of All Saints' Church, Little Kimble, on the north wall between two windows to the east of the door.
electron microscopy (SEM)/energy dispersive X-Ray spectroscopy (EDX) investigation of the mechanism of consolidation, which also discussed the treatment of limestone. A 2007 paper presented some additional details on dilutions and multiple applications carried out in conjunction with the treatment of a wall painting by Agnolo Gaddi in the church of Santa Croce (Florence). The other two members of the 2000 team (Baglioni and Giorgi) extended their work with nano-lime beyond Europe, using it to stabilize wall paintings (and limestone) at the ancient Mayan city of Calakmul in Campeche, Mexico.

The STONECORE project
In September 2008 the STONECORE project (‘Stone Conservation for the Refurbishment of Buildings’) was established with funding from the 7th Framework Programme for Research (FP7) of the European Commission. Coordinated by IBZ-Freiburg (a German research and development company that has now made nano-limes commercially available to conservators), it is a consortium of researchers representing several private companies and public institutions, including the Technical University Delft and the Czech Academy of Science.

Research and tests carried out as part of the STONECORE project included in situ drill resistance, ultrasound transmission and ground penetrating radar measurements, as well as more conventional laboratory tests for gains in compressive and flexural strength. Although they were presented at conferences on stone conservation, two papers reported on the testing of nano-lime on specimens of lime mortars.

Most of the STONECORE findings were disseminated to the conservation community through a series of public meetings. These were held at Litomysl (Czech Republic) and Torun (Poland) in 2010 and at Peterborough (UK) and Freiberg (Germany) in 2011. Speakers at the last of these conferences were from Austria, the Czech Republic, Germany, Greece, the Netherlands, Poland and the UK.

The STONECORE project ended in August 2011. Additional information is available from the project website (www.stonecore-europe.eu), which includes links to the partners.

Some findings from the STONECORE programme
Although many measurements related to laboratory experiments and much of the site work focused on mortars and plasters, the papers prepared as part of the STONECORE programme showed that there is real potential for the use of nano-lime as a consolidant for calcareous substrates, as well as having other possible uses such as a biocide. Some of the results are summarized below.
Despite reductions in porosity of up to 5% after consolidation with nano-lime, it was found that the treatment has little influence on the water transport properties (capillary suction) of the treated materials. Indeed, it can improve these properties where it bridges cracks and allows coherent diffusion of moisture.

Ultrasonic velocity and drill resistance measurements showed that:

- the compressive, flexural and surface cohesion strengths of materials treated with nano-lime increase with the number of applications;
- compressive strength generally increases more rapidly than flexural strength as the number of applications or saturations with nano-lime increases.

Nano-lime in ethanol seems to be a more effective, general purpose consolidant than nano-lime in isopropanol. Test results clearly show that CaLoSiL® E-25 gives higher increases in compressive strength and tensile strength than CaLoSiL® IP-25 (or E-50) for consolidation of limestones and crushed stone dusts (Table 2). The percentage increase in tensile strength, however, was less with E-25 than IP-25 because the isopropanol dispersant did not penetrate as well as ethanol; the nano-lime in the former, therefore, tends to reside in greater concentrations on or near the surface of the treated material. It has been demonstrated that when a consolidant diffuses more uniformly throughout a material, optimum gains in compressive strength are achieved, whereas if more of it resides or precipitates closer to the surface, tensile strength increases at the expense of the compressive strength.

<table>
<thead>
<tr>
<th>Number of saturations</th>
<th>E-25</th>
<th>IP-25</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>50</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>53</td>
<td>43</td>
</tr>
<tr>
<td>6</td>
<td>93</td>
<td>47</td>
</tr>
</tbody>
</table>

Table 2 Relative increase in compressive strength of Maastricht limestone using CaLoSiL® E-25 and IP-25.

There have been a number of reports of white haze formation from the carbonation of lime on the surface. This can be mitigated by either starting with a low concentration of nano-lime and increasing it with each application, or preventing evaporation of the alcohol (which might otherwise cause feedback of the nano-lime to the surface) and removing any excess nano-lime immediately after treatment with a sponge. White haze formation on the surface is more likely when using nano-lime
dispersed in isopropanol, because having a higher molecular weight than ethanol, it does not penetrate as quickly. If necessary, the white lime haze can be removed later using steam.

Results also suggested that, the denser the stone or the more compact the aggregate in a plaster or mortar, the higher the consolidation strength achieved.

**Nano-lime used in combination with ethyl silicates**

Tests carried out as part of the STONECORE project suggest that nano-lime may also be used in conjunction with ethyl silicates, especially when consolidating larger voids and areas of delamination, even in very damp outdoor conditions. This is because nano-lime acts as a catalyst for the hydrolysis of the silicic acid ester (ethyl silicate) and as a coupling agent, enhancing the bond to stone surfaces. The amorphous calcium silicate hydrate gel formed can fill larger voids than silicic acid ester or nano-lime alone, and becomes hydrophilic faster than ethyl silicate; however, the water absorption and capillarity of the treated material may be lowered as a result. Tests and assessments using SEM demonstrate that the strengths of degraded materials can be doubled with only one pre-treatment with nano-lime followed by one treatment with an ethyl silicate.

Further research into the combined use of nano-lime and ethyl silicates on possible adverse effects with salts such as gypsum is necessary before this treatment can be fully approved. This is particularly important for the conservation of historic fabric, which is often persistently damp and therefore likely to contain salts (e.g. sulfates, chlorides and nitrates), which have probably contributed to the failure in the first place.

**Project-oriented studies**

The treatment carried out to the wall paintings at All Saints’ Church in Little Kimble, Buckinghamshire, in 2010 was the first large-scale use of nano-lime in the UK. The decision to use it was partially guided by the in-house programme of laboratory studies summarized below. Some related studies were performed by Emily Howe in 2006–07 in conjunction with the treatment (with E25) of small areas of the Lichfield Angel, an early medieval limestone sculpture excavated in 2003. Equally encouraging were the many Italian nano-lime publications on mural treatment and the STONECORE presentations by Musiela describing the work on the cellars of the Middle Castle, Malbork, on the façade of the Cathedral of the Visitation Order, Warsaw, and in the Cathedral Basilica in Torun, Poland.
Diffusion of nano-lime in ethanol (E25) into limestones

As part of the in-house experiments, the transport characteristics (by capillarity) and penetration rates of E25 into laboratory samples of three unweathered UK limestones (Weldon, Ketton and Clipsham) were measured using a continuous feed of E-25 into the stone surface and negligible loss of ethanol by evaporation (Figure 1). Because evaporation of the ethanol on the surfaces of the material to be treated would considerably reduce diffusion rates, the rates reported here may be the maximum possible without vacuum impregnation. The data are shown in Table 3 and presented graphically in Figure 2.

Rates of diffusion of E-25 are from 0.02 to 0.5 cm per minute. The variation is considerable from stone to stone, despite only modest differences in measured water absorption and porosity. This is presumably because of differences in pore size distribution. The water movement data parallel the results for E-25; water penetrates considerably faster than E-25, primarily because water has a surface tension more than three times that of ethanol.

The maximum depth of deposition of the nano-lime particles, as measured with phenolphthalein, was 4–5.5 cm (consistent with results from other researchers). For most consolidation of plaster and calcareous stone, this depth of treatment is satisfactory. While the test samples
had not deteriorated, weathered stone would be expected to show even deeper and faster transport of the nano-lime. In a second round of phenolphthalein testing, carbonation of the material deposited in the pores was observed after three days. Figure 3 shows limestone dust (in a metal cube) consolidated to a depth of 1.5 cm and a strength of 0.2 Pascals after 20 applications of E25.

Consolidation of powdering paint

Limited laboratory tests were undertaken to determine whether unbound (pigments applied in water) paint surfaces could be sufficiently consolidated with nano-lime when applied in increasing saturations and different concentrations.

Panels of plaster board were painted with red ochre pigment dispersed in water so that the resultant paint film would be completely unbound upon drying. The boards were then treated with the nano-lime solutions and left uncovered to allow carbonation of the consolidant.

When lightly abraded with a finger, none of the paint was significantly stabilized or consolidated. Scotch tape further demonstrated the lack of pigment cohesion. The results of these preliminary trials showed that the nano-lime tended to carbonate on the surface rather than within the pigmented layer, which remained decohered. The higher concentrations showed more of a white lime haze on the surface of the paint.

The reported successes in the treatment of plaster and wall paintings, including frescoes, strongly suggest that further testing is required — perhaps using pigments bound in different media, followed by further appraisal and more specific tape testing.15

<table>
<thead>
<tr>
<th>Limestone type</th>
<th>Rate of diffusion of CaLoSL® E-25 (cm per minute)</th>
<th>Rate of diffusion of water (cm per minute)</th>
<th>Water absorption % by weight (Stone Directory)</th>
<th>Water absorption % by weight (test sample)</th>
<th>Porosity % by Volume (test sample)</th>
<th>Density g/cm3 (test samples)</th>
<th>Distance of penetration of nano-lime (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weldon</td>
<td>~ 0.45</td>
<td>~ 1.4</td>
<td>~</td>
<td>8.5</td>
<td>18.4</td>
<td>2.0</td>
<td>5.5</td>
</tr>
<tr>
<td>Ketton</td>
<td>~ 0.1</td>
<td>~ 0.4</td>
<td>9.8</td>
<td>6.7</td>
<td>15.4</td>
<td>2.14</td>
<td>4.5</td>
</tr>
<tr>
<td>Clipsham</td>
<td>~ 0.02</td>
<td>~ 0.08</td>
<td>4.7</td>
<td>7.7</td>
<td>17.5</td>
<td>2.1</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Table 3 Rates and distance of capillary diffusion in three different limestones (Hirst Conservation).
Recent use of nano-lime at All Saints’ Church, Little Kimble

Introduction
Following the successful use of CaLoSiL® products in several European projects, its use was considered by Hirst Conservation for the consolidation of a scheme of historically important medieval wall paintings at All Saints’ Church, Little Kimble, Buckinghamshire.

Little Kimble is a village at the foot of the Chiltern Hills, about 5 km south of Aylesbury. The Grade I listed church, part of the Diocese of Oxford, is a small, flint-clad building constructed in the twelfth century. The walls are decorated with a highly significant scheme of wall paintings, dated to the early fourteenth century. Today, the most important surviving paintings, found principally on the nave walls, are the scenes of saints and of the Virgin and Child. Perhaps the best known of these is a depiction on the north wall of St George as a Knight Templar, bearing a shield with the red-on-white cross.

Condition
The wall paintings were treated by Professor E. W. Tristram, c.1930. The surfaces were covered with wax, which was a favoured treatment at that time as it visually strengthened the image and consolidated the paint coating. Unfortunately, this type of impervious coating resulted in problems with many British wall paintings, as the movement of moisture and salts inevitably caused failure of these early paintings especially in damp English churches. Eve Baker and her team removed this wax from many medieval paintings and work was also done at Little Kimble, c.1972. Professor Robert Baker and Mrs Baker also secured the surfaces with sensitive repairs and grouting, using non-hydraulic lime plaster. Their restoration has proved to be effective as the condition of the wall paintings at Little Kimble has remained generally stable, despite poor environmental and building conditions.

In recent years the parish has endeavoured to improve the overall condition of the building. This included a programme of roof repairs completed in 2004 and further building works undertaken in 2007. Improved drainage was installed in 2009 to reduce rising damp.

A condition survey was undertaken in 2005 when the entire surface of each of the wall paintings was gently tapped to detect areas of instability (possible delamination of the plaster from the stone). In many instances, the hollows detected were stable and corresponded with areas of old losses and cracks that had since been repaired. However, some of these areas displayed movement when gently pressed, indicating the long-term
potential for loss and the need for repair, although comparison with an earlier condition report in 2001 suggested that the wall paintings were relatively stable.\textsuperscript{18}

The investigations included monitoring of the environmental conditions within the church, and an assessment of the impact of the building envelope on the condition of the medieval wall paintings. The church had a hard plaster dado, which was applied as an earlier intervention prior to the Baker restoration. The impermeable nature of the plaster would have caused rising damp to be forced higher up the wall and into the region of the paintings. It was considered beneficial to remove this plaster and replace it with a breathable lime plaster.

On close inspection, original surfaces were powdering and veiled with cobwebs, bat guano, dirt and salts. Salt pustules had erupted on the paintings in many places and the edges of paint films had delaminated in areas adjacent to some of the repairs. Numerous hairline cracks in the surface could also be observed. Some previously repaired and filled cracks, most notably in the window reveals and around the doorways, had begun to open up again.

It was apparent that, while the paintings themselves were quite stable, the walls had many later plaster repairs that had begun to fail, which was particularly obvious at lower levels, with patches of white efflorescence and blistering. The previous sensitive, tinted lime repairs and localized limewashing around the paintings done by Eve Baker remained sound.

As lime was a successfully ‘tried and tested’ material in this church, it supported the rationale that, given the ongoing problems of moisture movement, intervention should be based on porous materials and lime-based treatments. Accordingly, the use of nano-lime on the wall paintings was fully justified for this project. As a stable environment within the church is not obtainable in the foreseeable future, it seemed inappropriate to make extensive use of synthetic resins. The nano-lime suspension, CaLoSiL\textregistered, was chosen as a consolidant because it is believed to allow better evaporation of moisture from the damp fabric within the church.\textsuperscript{19}

A subsequent re-examination was performed in June 2009 to update the condition report in anticipation of the conservation treatment.\textsuperscript{20} The treatment of the paintings was discussed with the client\textsuperscript{21} and English Heritage\textsuperscript{22} before final specifications were agreed and works instructed.

\textbf{Conservation}

The conservation work was undertaken in 2010. Emergency consolidation with Plextol B500 acrylic dispersion was required in a few localized areas but, in general, avoided in favour of nano-lime. Bat and
bird droppings, cobwebs, dust, loose and imbibed dirt, together with some salt efflorescence, were removed from the surface.

Failing, cementitious and gypsum plasters of no historic importance, mostly at dado level below the historic paintings, were taken off. These were replaced with lime plasters to improve the aesthetics of the church interior and to allow moisture in the walls to evaporate at heights lower than the paintings.

Larger delaminations, cracks and voids could be stabilized using non-hydraulic lime putty and fine aggregate (sand and stone dust). Nano-lime materials were used for the fine cracks and fissures to avoid the introduction of undesirable amounts of water into the plaster and the drilling of holes to facilitate the use of catheter tubes and pipettes. Most of the cracks in the wall plaster at Little Kimble were hairline or very fine, and not particularly unsightly or disfiguring. Such cracks are ordinarily left unfilled as potential stress relief opportunities should the wall structures move due to thermal or hygric fluctuations or building subsidence. The challenge in this instance was that they were often adjacent to delaminating plaster and paint layers that required stabilization. Figure 4 shows the areas of repair and repair types to the wall painting of St George.

As the walls might have contained some residual moisture in places, it was deemed beneficial to pre-inject the relevant areas or cracks with industrial methylated spirits (IMS) to help dry them out (Figure 5). This would allow better penetration of the nano-lime as moisture-filled pores would impede its diffusion. CaLoSiL® E-25 and/or E-50 were injected slowly into the cracks until apparent saturation of the adjacent deteriorated plaster had occurred. The product was not allowed to bleed onto the surface of the painting, thereby avoiding formation of the unsightly haze of lime that can occur as alcohol (in this case ethanol) evaporates. (If it does occur, it can be removed quickly with cotton wool dampened in IMS.)

It can take up to 24 hours for the alcohol in nano-lime formulations to evaporate. The result is deposition of the nano-lime particles in the pores of the plaster and between fine layers of delamination. In this project, 8–10 applications to saturation were applied by syringe over several days to all deteriorated areas. On average, ten 10–50 ml applications of E-25 and/or E-50 per application were applied in each area requiring consolidation.

Because carbonation occurs more quickly near the surface, better consolidation might have been achieved by allowing each application of nano-lime to carbonate fully before the next was applied. However, this could have taken days or weeks; the limitations of a site-based project did not allow more than 24 hours between applications. Some areas were consolidated using this method before injecting lime-based grouts.
addition, some larger fragments and areas of delamination were treated with CaLoXiL® injection grout, which is a more concentrated form of nano-lime in ethanol also containing marble powder.

As described above, tests made before the project began both informed and guided the decision to use the nano-lime method. Although no quantitative evaluation was undertaken in situ after treatment, a gentle tapping (‘sounding’) after several days of the formerly unstable areas of plaster indicated that these were now well-adhered and stable. Moreover, in areas where the nano-lime had been injected or carefully brushed behind loose flakes of thin paint and/or plaster layers, the consolidation was also successful without any visible change to the surface. Figure 6 shows work in progress on the wall paintings of St George and St Clare.²³

**For the future**

There is little doubt that nano-lime is an important addition to the range of materials suitable for consolidation of porous substrates. But despite the rapid increase in the literature on nano-lime as a conservation material, it is clear that more technical and practical studies need to be undertaken. For practitioners, it is important to have a broader range of
published case studies that describe the materials and conditions most suited to nano-lime treatment.

One key issue is effectiveness. This is often judged in the laboratory on specimens that do not fully simulate the circumstances encountered in the field. Where field testing has been done, in situ evaluation is frequently undertaken too soon after treatment, that is, without taking account of the aging effects of fluctuating temperature and moisture, and the cyclical crystallization of salts.

To provide an enhanced picture of the potential value of nano-limes in the consolidation of plaster, there should be more comparative field testing and sharing of findings through conferences and publications. Those significant full-scale treatments that have been carried out in the past ten years should be revisited and the results re-evaluated to improve the way in which nano-limes are used in the next decade.

This would be of enormous value to the conservation profession, aiding in decision-making when the details of the treatment (product, diluent, concentration, application technique) are supplemented by environmental monitoring data. As part of this process, the Building Conservation Research team of English Heritage has begun a two-year research project to provide greater understanding of the parameters for site-based treatment of weathered limestones. This project is being carried out in conjunction with the Department of Architecture and Civil Engineering at the University of Bath.
Acknowledgements

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Biographies

Paul D'Armada, BSc (Hons), PGCE
Paul D'Armada joined Hirst Conservation in 1986, having studied and taught earth sciences and physics. As Principal Conservation Scientist, he has significant in-depth understanding of materials science as well as conservation. A specialist in historic plaster and paint analysis, Paul is also a specialist paint technician, advising on the specification of appropriate paint systems (both traditional and modern), together with their production. His most recent research paper focuses on the innovative technique and use of nano-lime technology.

Elizabeth Hirst, ACR, IHBC, FRSA
Elizabeth Hirst is the principal conservator of Hirst Conservation (established 1986). She trained as a stone and medieval wall painting conservator under the auspices of Professor Robert Baker and Mrs Eve Baker. As an architectural conservator, she advises on material consultancy, fine art and historic buildings conservation. She joined the editorial board of the Journal of Architectural Conservation in 1995, becoming a consultant editor in 2005. She was also co-editor of Windows: History, Repair and Conservation.

Notes

5 Dei, L., Radicati, B. and Salvadori, B., ‘Sperimentazione di unconsolidante a base di idrossido di calcio nanofasico sugli affreschi della Cappella del Podestà


14 See www.restauro.pl for information on these nano-lime projects.

15 Tape testing of surfaces treated with nano-lime was discussed by Giorgio, Dei and Baglioni in their 2000 article (see note 4). It is a technique often used for the study of paint chalking. See Methods C and D of ASTM D4214–07 Standard test methods for evaluating the degree of chalking of exterior paint films.


19 The manufacturer’s website is www.ibz-freiberg.de.


21 Andrew Argyrakis of the Church Buildings Council (CBC), formerly the Council for the Care of Churches (CCC)

22 Represented by Robert Gowing.

23 See Tristram, E. W., *op. cit.* for a description of these two wall paintings.