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THE USE AND EFFECTIVENESS OF DISPERSED HYDRATED LIME IN CONSERVATION OF MONUMENTS AND HISTORIC STRUCTURES*

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Abstract

The use of dispersed hydrated lime (DHL) injection grout for repair of historic and artistic exterior masonry is a relatively new technique in the field of conservation. As a repair material to stop the ingress of water, DHL is preferable to other fill materials because it is completely compatible with marble, limestone, and sandstone; stable in sunlight; reversible; easy to color-match; and adaptable to the thinnest and deepest of cracks without needing to enlarge them. These characteristics make it very attractive for the most aesthetically sensitive of projects requiring treatment of cracks and small fissures in statuary, monuments, and buildings. Case studies are presented that document methods and materials for DHL-based repairs, provide results of accelerated weather testing, and yield

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observations from several seasons of field monitoring. Findings from recent field modifications to treatments, based on the performance of DHL as a crack repair material, are discussed.

Keywords

dispersed, hydrated, lime, DHL, marble

1 Introduction

In the field of conservation, treatment of small cracks and fissures in exterior marble and limestone statuary, monuments, and buildings has involved numerous repair materials including epoxies, cementitious grouts, and traditional lime-based materials. As conservators, performance, reversibility and long-term effects of these materials on historic masonry are of great concern, and often generate debate among preservation professionals when treatments are proposed. An alternative to epoxy for extensive cracking and micro-fissures is dispersed hydrated lime (DHL) injection grout, a relatively new technique in the field of conservation and a material that is chemically closer to calcareous stones. As a repair material to stop ingress of moisture, DHL is preferable to epoxies because it is completely compatible with marble, limestone and sandstone, stable in sunlight, 100% reversible, relatively easy to match to natural stone's color and texture, and adaptable to the thinnest and deepest of cracks. In addition, DHL has low compressive strength compared to cementitious injection grouts (3.0-10.5 N/mm^2 according to manufacturer's literature). Altogether, these characteristics make it a very attractive repair material for the most aesthetically sensitive of projects. However, these positive characteristics must be judged together with its long-term viability in exposed weathering conditions.

DHL has only appeared in the conservation literature within the last five years.
As DHL is a relatively new material, there is very little available independent testing to guide the conservator or specifier in the use and evaluation of the material. This paper reviews the advantages, challenges and effectiveness of masonry repairs using DHL injection grout by presenting the results of accelerated weathering tests and through treatments performed by the authors on marble and limestone projects. Projects presented include the Barnard Statuary and Mexican War Monument at the Pennsylvania State Capitol Complex in Harrisburg, Pennsylvania; the Tripoli Monument at the US Naval Academy in Annapolis, Maryland; and Indiana limestone facade figures on the Brooklyn Museum of Art in New York City.

2 Dispersed hydrated lime (DHL)

Dispersed hydrated lime is composed of fresh dry hydrated white lime, mixing water, and dispersing aids. The material is commercially produced, packaged and shipped in wet form as a putty. Through the use of an industrial disperser, the lime putty is processed to create a finer calcium crystal than non-dispersed lime putty, or fat lime (Strotmann and Maryniak-Piaszczynski 2000). The result is smaller calcium hydroxide mineral that are more plastic and efficient. When the putty is combined with aggregate powders (such as marble and quartz) to create repair mortars, injection grout, and shelter coat materials, a lower binder ratio can be used.

It is also suggested that dispersion of the hydrated lime also causes carbonizing to occur at a faster rate and more thoroughly than in traditional lime products. This imparts a high degree of early strength with a low degree of shrinkage. Laboratory freeze-thaw testing by the manufacturer according to DIN methods shows good resistance to freeze/thaw (15+ cycles) and chemical contamination (salts).

2.1 DHL injection procedures

DHL injection grouts are administered using a syringe and fine gauge needle (14-16 gauge). The crack is thoroughly cleaned using distilled water or, in some cases, a combination of distilled water and ethanol (50:50 by volume). The injection grout, which is stored under a thin film of water similar to fat lime, is mixed with a high-speed mixer to increase material flow. DHL is mixed in small volumes of ½ to 1-cup portions using a mono-type kitchen hand mixer. For larger volumes, a mixer attachment for a variable speed power drill is used. Mixing time is typically 2-3 minutes for small volumes. Depending upon the width of the cavity, the grout can be used either undiluted (100%) or with water up to 5% by weight. Water should be added only after initial mixing to achieve the ultimate desired flow. The grout can also be custom-tinted using mineral (alkali-stable) pigments, which should be mixed with a small amount of water prior to adding to the DHL. The manufacturer does not call for post-installation misting. However, the authors have attempted to maintain a damp environment by regular follow-up misting, and shading from direct wind and sun evaporation to assist in carbonization during the initial 48 hour set.

Depending on the exterior environment and exposure, cracks can be filled flush or proud to the stone surface, or topped with a protective shelter coat, to prevent erosion of the DHL from upper surfaces subject to direct weathering. The capping material can be screeded to follow the surface contour, or kept slightly proud in exposed areas. The methods and materials for capping DHL fills are discussed further in the case study provided below.

3 DHL injection grout case study: Barnard Statuary

The Barnard Statuary Group is a 27-figure, Carrara marble sculpture located at the main entrance of the Pennsylvania State Capitol Building in Harrisburg, Pennsylvania. The 93-year-old sculptural group developed numerous cracks and displacement of the figures, as well as movement away from the wall, within 25 years of its creation. It had survived numerous treatment campaigns during repeated attempts to address these issues. In 1996, an extensive conservation program was initiated by The Capitol Preservation Committee (CPC) to conserve and stabilize sculpture groups. (The CPC is an independent Commonwealth committee established by the Pennsylvania General Assembly in 1982 to direct programs to conserve, preserve and restore the Pennsylvania State Capitol and its contents.) This work, which was not performed by the authors, included disassembly and re-assembly of the groups, insertion of threaded stainless steel rods and extensive crack filling with epoxy. A team of conservators designed and implemented a method for cutting out, epoxy injecting, and filling over 3,500 linear feet of cracks in the sculptural groups. Knowing that the epoxy would eventually discolor, the cracks were topped with a cementitious mortar mixture to conceal the epoxy at the surface.

The 1996 work addressed the most significant cracks in the sculpture, reserving treatment of the thinnest cracks and micro-fissures (less than 1mm) for further assessment and testing. These smaller cracks are extensive and considered to be a significant source for water ingress into the sculpture. Since they contribute to ongoing deterioration of the sculpture, a non-invasive method of filling these cracks was important to identify as part of the new testing and treatment. The epoxy fills proved unsatisfactory, as staining and discoloration of the Carrara marble was associated with the injection sites.

In 2001, a contract was awarded to carry out further repairs and consolidation treatment of the Barnard Statuary. Prior to commencing treatments, the project conservation team performed a comprehensive testing program that included accelerated weathering tests to evaluate dispersed hydrated lime for filling cracks and micro-fissures (CSI, 2003).

Figure 1: Barnard Statuary Group, Pennsylvania State Capitol Building, Harrisburg, Pennsylvania.

3.1 Accelerated weathering tests: year 1

In 2001, a comprehensive testing program was designed to assess currently-available consolidants and water-repellent treatments for the Barnard Statuary. The outlined goal of the testing was to evaluate the efficacy and compatibility of a combination of consolidant and water-repellent treatments to improve strength, re-adhere loose grains, and reduce acid damage due to precipitation. As part of that larger testing program, nine cores were treated with DHL injection grout to permit evaluation of the material durability both with and without the added protection of a water-repellent treatment to reduce loss due to precipitation. Accelerated weathering tests were conducted by Q-Lab Florida, a weathering research service, using a QUV chamber. The QUV Accelerated Weathering Tester reproduces damage caused by sunlight, rain and dew. Tested materials are exposed to alternating cycles of light and moisture at controlled, elevated temperatures. The QUV simulates the effect of sunlight with fluorescent ultraviolet (UV) lamps, and simulates dew and rain with condensing humidity and water sprays. Exposure conditions can be varied to simulate various end-use environments.

DHL injection testing was carried out on cores salvaged from the 1990s pinning campaign. The marble cores were split down the middle of one end then reattached using a dispersed hydrated lime injection grout. This was accomplished by securing the two fractured sections together using a rubber band and then injecting the DHL into the crack in accordance with manufacturer’s specifications. Samples were prepared by pre-wetting the crack with distilled water and injecting the DHL by means of a packer or injection tool. DHL was thoroughly mixed, adding just enough water to permit flow though the syringe. Areas were not subsequently wetted, as manufacturer did not require it. Samples were allowed to cure for a period of one month prior to being subjected to testing.

A group of consolidants and water repellents were selected for evaluation on the DHL-injected cores. The preservative treatment materials were chosen based on their performance, as documented in the conservation literature, and by the experience of the testing team. Consolidation and water repellent materials, included:

- Waterborne hydroxylating conversion treatment (HCT): This product forms a stable, well-adhered, hydroxylated, conversion layer on carbonate mineral grains. The conversion layer dramatically increases the resistance of marble and limestone surfaces to acid attack, and improves the ability of a variety of chemical compositions to react with or bond to such surfaces.
- Ethyl silicate consolidation treatment (ECT): This product is based on silicic ethyl esters. Its extremely small molecular structure enables it to penetrate deeply into deteriorated masonry surfaces and collect at contact points between individual stone grains. An internal catalyst and atmospheric humidity then convert the liquid consolidant into a glass-like silicon dioxide (SiO_2) gel that binds the stone particles together.
- Ethyl silicate consolidation treatment/water repellent (CT/WR): This product is both a consolidation treatment and water repellent treatment. This ethyl silicate treatment, modified with a silane water repellent, replaces the natural binding materials while protecting the treated surface from water-related deterioration.
- Siloxane water-repellent (SXWR): This modified siloxane water repellent was developed for limestone, marble and most other traditional masonry surfaces. It penetrates deeply to provide long-lasting protection without altering the natural appearance of the substrate.
- Silane water-repellent (SWR): This modified, 'neat' silane system offers invisible protection and low volatility. It protects horizontal and vertical concrete and masonry surfaces against water and waterborne contaminants. The small molecular structure of this product ensures maximum penetration and colorless protection of dense, color-sensitive surfaces.

The DHL-injected cores were treated with selected consolidants and water repellents following manufacturer's directions. Due to their small size, the cores were dipped in treatments rather than sprayed or brushed. In the case of the consolidants, immersion is the preferred method of application for smaller objects.

Figure 2: Preparation of DHL injected split marble cores for accelerated weathering testing (2001).

To provide a control that simulated an open, untreated crack, one core was broken but no DHL was injected and no preservative treatments were applied. A small diameter hollow glass rod was encircled around the break on the control sample as an indicator of movement (like a tell-tale for crack monitoring). The core samples were then submitted for accelerated weathering tests and environmental conditioning in accordance with ASTM G 154 Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials.

The QUV chamber has controls for relative humidity, temperature, wind speed, and pollutant concentration. In order to simulate Harrisburg's environment, climatic data was obtained from the National Climatic Data Center and National Atmospheric Deposition Program and used as a guideline. Each 16-hour cycle of the accelerated weathering exposed the samples to UVA 340 lamps in cycles of 8 hours of light at 60 degrees Celsius, 6 hours of condensation at 50 degrees Celsius, 1-1/2 hours in the freezer at -25 degrees Celsius, and thawing for 30 minutes at ambient temperature (22 degrees Celsius) before being returned to the QUV chamber. Changes in surface appearance were visually evaluated at 250-hour intervals.

The testing program called for all samples to be subjected to 1000 hours of exposure. This was regarded as sufficient to simulate general northeast weathering conditions where freeze/thaw cycles can exceed 50 cycles per year. However, circumstances prevented the full exposure for DHL-treated samples in Year 1. Samples were reviewed after 250 hours, or 16 cycles, of exposure, which is nearly 1/3 of the typical freeze thaw cycles for Harrisburg in a season. All samples survived intact. No visual changes were noted in any of these samples—see Table 1.

In order to maintain the lowest level of intervention necessary to achieve the desired results, the CPC decided to proceed with DHL alone for filling of the remaining cracks in the Barnard Statuary during the summer of 2001. The results of the field tests are discussed in section 3.3.

Table 1 Testing Results for Fissured Cores Subjected to QUV Exposure – Year 1

Stone Testing Treatment Report for the Barnard Statuary Group
Pennsylvania State Capitol, Harrisburg, PA

Core Sample Number	**Year Prepared**	**Treatment Performed**	**Hours in QUV Chamber**	**Results of Testing**
F-1	1	DHL	250	No changes to crack
F-2	1	DHL	250	part of sample broke off
F-3	1	DHL	250	No changes to crack
F-4	1	DHL+HCT	250	No changes to crack
F-5	1	DHL+HCT	250	No changes to crack
F-6	1	DHL+HCT	250	No changes to crack
F-7	1	DHL+HCT+ECT	250	No changes to crack
F-8	1	DHL+HCT+ECT	250	No changes to crack
F-9	1	DHL+HCT+ECT	250	No changes to crack
F-10	1	Untreated/Glass tube	250	No breakage or cracking observed

3.2 Accelerated weathering tests: year 2

In an effort to better understand how the DHL would perform though a complete winter season, continuation of the accelerated weathering testing was approved and carried out in 2002. Eleven newly-treated cores, along with the previous year's 10 cores, were subjected to 750 hours of accelerated weathering testing and reviewed after 250 hour cycles.

Results were judged on the ability of the DHL fill to withstand exposure until complete failure. Results are shown in Table 2. The least amount of surface loss to the DHL fill was obtained when the cores were treated with a consolidant and/or water repellent. 2001 core samples treated with DHL fills followed by HCT and ECT exhibited the least amount of failure after 1000 hours of exposure, or 64 cycles. These results suggest that the consolidation treatment increased durability of the DHL. However, further studies were not performed to determine if other physical changes occurred in the DHL after consolidation treatment.

Table 2: Testing Results for Fissured Cores Subjected to QUV Exposure – Year 2

Stone Testing Treatment Report for the Barnard Statuary Group
Pennsylvania State Capitol, Harrisburg, PA

Core Sample Number	Year Prepared	Treatment Performed	Hours in QUV Chamber	Results of Testing
E-1	2	DHL+SWR	750	Failure before 750 hrs
E-2	2	DHL+SWR	750	Slight erosion of DHL fill material/fill still intact
E-3	2	DHL+SWR	750	No Change to fill material
E-4	2	DHL+SXWR	750	Slight erosion of DHL fill material/fill still intact
E-5	2	DHL+SXWR	750	No Change to fill material
E-6	2	DHL+SXWR	750	No Change to fill material
E-7	2	DHL+CT/WR	750	Slight erosion of DHL fill material/fill still intact
E-8	2	DHL+CT/WR	750	No Change to fill material
E-9	2	DHL+CT/WR	750	No Change to fill material
E-10	2	DHL	750	Slight erosion of DHL fill material/fill still intact
E-11	2	DHL	750	Slight erosion of DHL fill material/fill still intact
F-1	1	DHL	1000	Failure before 1000 hrs
F-2	1	DHL	1000	Partial failure of one mended area before 250 hrs
F-3	1	DHL	250	Repair failed before samples could be placed in chamber
F-4	1	DHL+HCT	1000	Failure before 1000 hrs
F-5	1	DHL+HCT	1000	Slight erosion of DHL fill material/fill still intact
F-6	1	DHL+HCT	<1000	Failure before 1000 hrs
F-7	1	DHL+HCT+ECT	1000	No Change to fill material
F-8	1	DHL+HCT+ECT	1000	No Change to fill material
F-9	1	DHL+HCT+ECT	1000	No Change to fill material
F-10	1	Untreated Control	1000	No breakage of glass tube tell tale.

3.3 Field testing of DHL crack repair

Subsequent to the 2001 testing, the authors began a 5-year cyclical maintenance program to monitor the condition of the sculpture group, including all repairs. DHL crack repair was initiated during the summer of 2001. In this first year, vertical and horizontal cracks were filled similarly; the DHL was filled flush with the marble surface and no misting of the fills was performed. (Misting of the fills was not performed as part of the testing program and, therefore, was not performed in the first year of field application.) Field application results proved less successful than anticipated following the 2001 accelerated weathering test results. While DHL fills on vertical and partly protected faces were remarkably stable, those installed on upper exposed areas were subject to erosion and loss from driving rain and runoff.

Figure 3: DHL injections beginning in 2001 were intended for filling fine cracks less than 1mm in width. Epoxy injected cracks from the 1996 repair campaign, now yellow in color, are also visible.

Figure 4: On-site mixing of DHL for injection.

Additional accelerated weathering testing performed in 2002 completed the 1000 hours of exposure for the 2001 samples, and provided 750 hours of testing for newly-prepared samples. Failures in the DHL-injected cores were similar to those observed in the field applications. The cores treated with preservative treatments performed better, on average, than those with DHL alone. Deteriorated fills on the sculpture were maintained or replaced as needed in the summer of 2002. No consolidation or water repellent treatment of the sculpture was approved by the CPC at that time. Therefore, application procedures remained similar to those in 2001, although fills in exposed areas were left slightly proud on the surface of the marble.

In 2003, the previous year's fills on exposed horizontal surfaces showed deterioration again, suggesting that the durability of DHL is not sufficient in these locations and in this environment. A decision was made to protect DHL-filled cracks by a more durable shelter coat or capping material. To address the durability issue, field tests initiated in 2003 used a number of modified DHL and lime-based mixtures in both injections and as capping material to protect the fills in these skyward-facing locations.

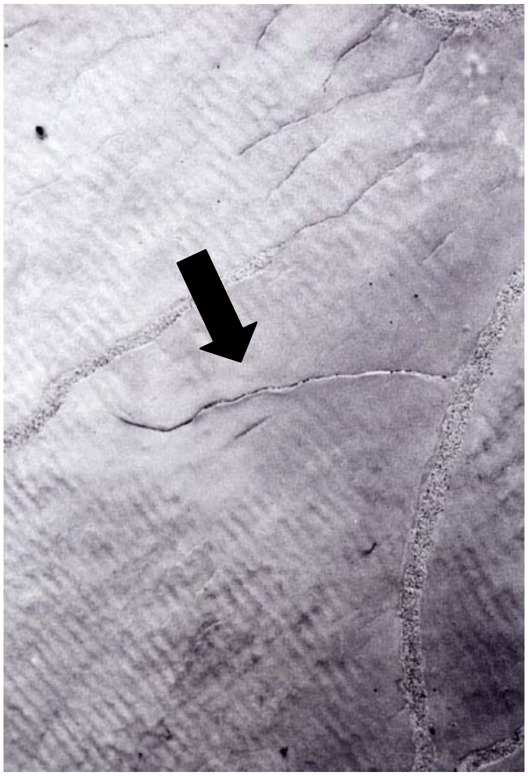

Figure 5: Inspection of DHL filled cracks in 2003 identified failures in exposed locations. DHL had eroded from cracks after a period of one year.

3.4 Field tests for DHL-NHL injection and capping

Although DHL had performed well in protected locations on the sculpture, it had not proven durable in exposed locations. Therefore, injection and capping mixtures using natural hydraulic lime (NHL) and DHL were prepared. A range of NHL was tested from the most feebly-hydraulic to the most hydraulic; designated as NHL 2, NHL 3.5, and NHL 5. Mix ratios were 1:1 and 1:2, DHL to NHL. The mixtures were injected onto the surface of the cracks and also used to cap filled cracks. The caps were allowed to remain proud in less visible areas of the sculpture that receive direct rain and runoff. All fills were misted intermittently for 2 to 3 days after application. Although the manufacturer's literature for DHL does not call for subsequent wetting after installation, NHL must remain damp during the curing period.

Prior to beginning the 2004 maintenance, these fill and cap test locations were inspected. Although it was difficult to improve on the crack-filling characteristics of the original DHL formula, some success was noted in the survival of capped fills. After a period of one year of exposure, only the filling/ capping materials consisting of NHL 5 mixtures with DHL remained in good condition. Results are shown in Table 3.

Table 3: Barnard Statuary Testing: DHL Crack Injection Capping Materials

Performed summer 2003; monitored summer 2004

Materials	**Ratio**	**Comments**
DHL & NHL 2	(1:1)	failed
DHL & NHL 2	(1:2)	failed, although better than 1:1 ratio
DHL & NHL 3.5	(1:1)	failed
DHL & NHL 3.5	(1:2)	failed, although better than 1:1 ratio
DHL & NHL 5	(1:1)	good condition
DHL & NHL 5	(1:2)	good condition

In the summer of 2004, a new procedure, using DHL in the cracks and capping with a modified NHL-lime putty-marble powder mortar, was used on those surfaces that had proved most susceptible to failure. NHL 5 was mixed dry with fine marble powder, lime putty, and casein. Casein was added to help increase flow behavior of the material, as well as add some adhesion properties. Water was added until the mix reached a consistency capable of flowing easily through a syringe. Mixing ratios are provided in Table 4. The NHL mixtures were injected onto the surfaces of the cracks. These caps were not screeded, but were allowed to remain proud. Ideally, the consistency of the mix was such that the caps spread out slightly, thereby creating a gentle slope as opposed to a stiff peak and avoiding the creation of “undercuts” at the edges of the caps that could catch water and cause the caps to be undermined and fail (a problem observed in capping from the previous year’s field tests). All caps were misted intermittently for 2 to 3 days after application.

Preliminary observations after four months of service showed no failures on these fills. We intend to inspect these sites in early spring of 2005 to confirm the effectiveness of this revised method. 2005 will be the final season of treatment under the current contract. The previously-installed fills that have been identified as having suffered losses will continue to be filled using DHL alone. However, capping methods and materials will continue to be assessed and modified as necessary, and yearly maintenance recommendations will be provided.

Table 4: Barnard Statuary Testing: DHL Crack Injection Capping Materials

Performed Summer 2004; to be monitored summer 2005

Materials	**Binder Aggregate Ratio**	**Comments**
Mix 1: 2 parts NHL 5 .5 part Fine Marble Powder .5 part Ultra Fine Marble Powder	(2:1)	Friable, powdery, does not hold together well, difficult to inject, applied with stainless spatulas; could be injected if mixed very wet
Mix 2: 1 part NHL 5.0 1 part mix 1 gallon lime putty to 1 quart casein .5 part Fine Marble Powder .5 part Ultra Fine Marble Powder	(2:1)	Water added to consistency of sour cream, making mixture creamier and easier to inject. However, liquid tends to separate upon injection. Covered with gauze and misted.
Mix 3: 1 part NHL 5.0 .5 part mix 1 gallon lime putty to 1 quart casein .5 part Fine Marble Powder 1 part Ultra Fine Marble Powder	(1:1)	Covered with dampened gauze and plastic to keep moist; early indication of good performance and durability.
Mix 4: 1.5 part NHL 5.0 .5 part mix 1 gallon lime putty to 1 quart casein .5 part Fine Marble Powder .5 part Ultra Fine Marble Powder	(2:1)	Did not show early indication of good performance and durability

Figure 6: Injection of an NHL cap over a DHL filled crack in 2004. DHL is still wet and appears darker in the crack than the NHL.

Figure 7: This area of the sculpture base is subjected to water runoff. Here all DHL fills were capped with NHL. This area is not visible from the normal viewpoint of the sculpture and therefore the caps were left proud.

4 Project-related use of DHL for crack repair

In addition to the extensive work carried out at Barnard Statuary, the authors have used DHL as a crack injection material for several marble and limestone projects since the year 2000. Field application has been the primary source of performance information. DHL has been used to repair cracks at the Mexican War Monument, a 64-foot high Carrara and Lee marble monument constructed in 1868 on the Pennsylvania State Capitol complex grounds in Harrisburg, Pennsylvania; The Tripoli Monument, a more than 200-year old Carrara marble sculpture first located in the Washington, D.C. naval yard, moved to the U.S. Capitol grounds, and finally moved to the Naval Academy in Annapolis, Maryland in 1860; and a series of thirty18-foot tall Indiana limestone figures and pediment group that adorn the facade of the Brooklyn Museum of Art.

4.1 Mexican War Monument

Conservation of the Mexican War Monument began in 2002 and has continued through 2004, with work occurring in the late summer each year after a thorough inspection of the monument. Similar to the Barnard Statuary, DHL-injections of fine cracks and fissures in the marble were performed in the first year of treatment, assessed and maintained as necessary for the next two summers. Over the first two years of treatment, DHL fills on upper exposed areas were subject to erosion. Without a capping material, loss was slightly less than the loss observed on the Barnard Statuary, which may be related, in part, to the site location. In 2004, cracks were refilled with DHL and then capped with the NHL-lime putty-marble powder mortar also used to cap Barnard Statuary fills. The monument will be inspected next spring to confirm the effectiveness of these capping materials.

4.2 Tripoli Monument

Conservation treatment of the Tripoli Monument was undertaken in 2000 to clean the monument and properly repair the numerous cracks and fissures. "Selective" filling of approximately 90 linear inches of cracks was performed using dispersed hydrated lime injection grout on the upper level of the monument, where the figures are located. The DHL grout was injected into cracks and then topped with 100% DHL. The cracks were covered with a pigmented layer of high-purity lime shelter coat. DHL in upper surfaces became eroded within one year.

4.3 Brooklyn Museum of Art

The figures and pediment group of the Brooklyn Museum of Art were treated during cleaning and re-pointing of the entire McKim, Mead and White facade in 2001. Treatment included replacement of losses, cleaning, stabilization, composite patches, dutchman repairs, and injection with DHL. Projecting features, including hands and sculptural attributes that were carved separately and attached to the main stone blocks, had developed cracks at the joints and internal pins. An exterior stainless steel armature was mounted to provide support for the appendages in case the weathering limestone eventually failed. The cracks were filled with DHL to within 3/8" of the exterior surfaces. These cracks were then topped with custom color-matched restoration mortar to encapsulate the DHL and bring the surfaces flush with the stone. The same method was used to treat a collection of 18th Century grotesques in a Pennsylvania private collection in 1999. Both series of treatments have survived the intervening time period.

5 Conclusion

Limited accelerated weathering tests have shown that DHL is not durable in exposed environments where materials are subjected to more than 16 cycles of freeze/thaw. However, durability is increased by the application of a consolidant and/or water repellent. Furthermore, DHL has proven to be susceptible to weathering (as verified by field use), especially in the northeast United States where pollution is high, the pH of rainwater is lowered, and freeze/thaw cycles are typically between 50 and 90 per year. In field tests at the Barnard Statuary (Harrisburg, Pennsylvania), all applications of DHL without additional capping material in skyward-facing locations, which were susceptible to driving rain, sitting snow and ice, and runoff, eroded within the crack after one year. Recent field tests have shown that natural hydraulic lime (NHL 5) mixed with DHL, and NHL 5 mixed with fat lime and casein can be applied over the DHL-filled cracks that are susceptible to direct weathering to provide a durable protective capping material.

Maintenance should always be taken into account when using DHL as an injection grout material. Projects in which DHL is being considered as an injection grout should be accessible and likely to be maintained. If DHL is selected for use on locations that are not regularly accessible for inspection, conservators may choose to install a more durable capping material, such as lime-based mortars or natural hydraulic lime mortars.

As opportunities arise for further analysis of the durability of DHL in the repair of monuments and historic structures, accelerated weather testing should again be undertaken. Absent the limitations of time and material resources, accelerated weathering tests remain a valuable technique for understanding the performance and durability of the material for outdoor use. Accelerated weathering tests should also be used to assess the performance and durability of capping materials, which have thus far only been subjected to one year of field tests. Additional weathering cycles, to determine at what point or by what simulated "year" the capping materials may fail, would be a good indicator of maintenance scheduling. To date, tests have only taken into consideration the performance and durability of the DHL. Future analysis of masonry materials repaired with DHL would be beneficial to determine the impact, if any, of long-term exposure of the masonry to DHL, which includes additional chemical components such as dispersing agents.

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