EVALUATION OF COMPARATIVE REPAIR METHODS FOR STONE

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A THESIS

in

Historic Preservation

Presented to the Faculties of the University of Pennsylvania in
Partial Fulfillment of the Requirements of the Degree of

MASTER OF SCIENCE IN HISTORIC PRESERVATION

2019

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Acknowledgements

Many thanks to the following people for their guidance and support. I could not have completed this thesis without them.

To the Historic Preservation Department at the University of Pennsylvania – my thesis advisor Roy Ingraffia, Frank Matero, and John Hinchman who helped me shape and refine my thesis. Aaron Wunsch for his valuable writing advice and providing the serpentine I used for testing. A special thanks to Courtney Magill who was always there for me when I needed help.

To Andy DeGruchy, Chris Hertz, and Anthony Hita at Lime*works.*us for their generous donation of materials, for sharing their knowledge, and for helping me prepare my test samples in their lab.

To all of those who took time out of their busy schedules to speak to me about the case studies: Constantine (Dean) Doukakis and Brian Wentz of Keast & Hood, Thomas Ewing of UPenn SAS Facilities Planning & Operations, Marianna Thomas of Marianna Thomas Architects, Vern Knapp and Jennifer Knapp of Knapp Masonry, Lorraine Schnabel of Schnabel Conservation, Rodney Lukens of West Chester University, Van Burriss, Independent Representative for Conproco, Gregory Hess, Cody Wilson, and Ralph Hart of Caretti Restoration & Preservation Services, Rex Cyphers of WDP & Associates.

To Fisher Fine Arts Materials Library for their assistance with 3D scanning.

To Andy Garver, Tim, and John at Pullman who cored my test samples.

To my parents for supporting my many endeavors.

Finally, a heartfelt thank you to Anthony Hita, for his knowledge and support throughout the past two years. He inspired me to become a better conservator. Another 150 pages of words cannot express my gratitude.

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1.0 INTRODUCTION

What are the options when quality replacement stone is unavailable for a masonry preservation project? This is a challenge for many architectural conservation professionals when working on buildings constructed with a stone that is no longer commercially available.

Stone has been a popular building material in America, especially on a commercial scale during the late-19th and early 20th centuries. In Pennsylvania in particular, many quarries during this time period produced prized local stones such as Pennsylvania Blue Marble, Hummelstown Brownstone, and Chester County Serpentine are no longer operating. These materials have been used to construct numerous historically significant architecture in the Mid-Atlantic Region, including the William Strickland's Second Bank of the United States (Pennsylvania Blue Marble), Frank Furness's Academy of Fine Arts (Hummelstown Brownstone base course), and 19th Street Baptist Church (serpentine) in Philadelphia.

While authenticity is one of the guiding philosophies for conservation design, oftentimes compromises must be made in the field for many reasons—cost, availability, compatibility with other materials or structure, schedule, skilled labor, aesthetics and durability. These necessary compromises are the focus of this thesis. Using serpentine as an example, this thesis presents and analyzes several repair or replacement options for projects of various scopes. Two methods are evaluated through testing:

Repair No. 1: Creating a precast face unit with a composite repair material, applied directly onto a substrate such as stone or brick. Lithomex, a natural hydraulic lime-based product produced by St. Astier in France and distributed by Lime*works*.us will be tested for this thesis.

Repair No. 2: Creating a new face or unit replacement with a more commercially available stone, colored with color simulated mineral stain to mimic serpentine. Colorwash Stain, a potassium silicate product produced by PermaTint and distributed by Lime*works*.us will be tested for this thesis.

The first three sections of this thesis present fundamental knowledge of serpentine as a building material, including its history, properties, and deterioration mechanisms.

Instrumental analysis and testing compared the profile and color change of samples before and after accelerated weathering to evaluate their durability. Alteration in profile was analyzed by scanning the samples with a hand-held 3D scanner which created a digital model of the surface. Color change was analyzed with spectrophotometric readings. Water vapor transmission test was performed to evaluate if Repair No. 1 and Repair No. 2 impaired the stones' natural permeability.

Other potential repair methods are addressed through three case studies of past serpentine repair projects. The first of which is College Hall, an iconic Victorian building on the main campus of the University of Pennsylvania. This building showcases three repair/replacement methods: pre-cast stone, stucco repair, and composite repair. The second case study examines Recitation Hall, the oldest building on the campus of West Chester University and home to the School of Education. This project features unit replacement with salvaged serpentine as well as composite mortar repairs. The third studies St. Francis of Assisi Catholic Church in Staunton, Virginia, an English Gothic building in which the serpentine was completely replaced with green granite.

Finally, all methods studied in this thesis through testing and case studies are evaluated to form a general guide for the selection of stone repair method when in-kind replacement is not a viable option.

1.1 Limitations

Almost every building undergoing a repair campaign has its unique challenges and conditions. This paper recognizes it is not possible to present a full compendium of solutions for repair approaches. This thesis does not propound one method over another. It presents data through testing, conjures a list of criteria, and analyzes which method(s) could be the most appropriate based on specific project goals. It is my hope that the readers of this thesis will find the data valuable in their pursuit of the best conservation solution in their given situation.

Given the limitations of the thesis, only a selected number of tests were performed to evaluate the durability of repairs 1 and 2. Future evaluation of the other variables would likely be helpful in providing a fuller view of the two focused repair/replacement methods. A full discussion is available under Section 11. Recommendations for Further Testing.

2.0 A BRIEF HISTORY OF SERPENTINE

2.1 Introduction

Serpentine, a green stone generally believed to be named due to its color resemblance to that of a serpent, was a widespread building stone in the Mid-Atlantic during the late 19th to early 20th century. It is often suggested that serpentine rose to popularity among the Victorian Era's love of a polychromatic palette.[1]

2.2 Formation and Quarries in Chester County

Serpentine is considered a local stone, once actively quarried in Northeastern Maryland and Southeastern Pennsylvania in places such as Lancaster County and Chester County. The formation of serpentine in Chester County began approximately 600 million years ago.[2] The rock is formed when magnesium silicates go through a chemical change induced by hot fluids, the same process as the formation of talc (which often present as veins in serpentine). A pure serpentine rock is called serpentinite and is composed of a group of minerals including chrysotile (a fibrous, asbestos mineral), antigorite (a corrugated variety), and lizardite (fine-graned and platy).[3] Serpentine quarried in Southeastern Pennsylvania often contains other minerals such as iron, talc, chromite, magnetite, chlorite, mica, feldspar, tourmaline, and quartz.[4]

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[1] Dorchester, "The Evolution of Serpentine Stone as a Building Material in Southeastern Pennsylvania." 18
[2] Ibid., 18.
[3] Farndon, *Illustrated Guide to Rocks & Minerals*. 223
[4] Dorchester, 19.

Serpentine was actively quarried between the 1720s to the 1880s. The earliest records of quarrying serpentine date back to the mid-1720s when the rock was quarried near building sites (usually farmhouses) in limited quantities and the quarries closed once the structures were completed. Chester County saw the commercialization of serpentine quarries from 1868 to 1895: Dunlap and Martin's Quarry from 1870s to 1920s, McCluer's Serpentine Quarry from 1870s to 1900s, and Carter and Reynold's Serpentine Quarry from 1875 to an unknown date. The stone quarried in Chester County has travelled as far as Racine, Wisconsin and New Orleans, Louisiana.[5]

The Serpentine Ridge Quarry, known as Brinton's Quarry, was the most successful in Southeastern Pennsylvania. It may have been operating as early as 1730s, with the heyday lasting from 1870s to 1895, and closing in 1931 when the owner, Joseph H. Brinton, died. The quarry offered dimensional stone, ashlar stone, rough stone and custom-cut stone to architects and builders. Brinton's Quarry was the supplier of serpentine used to construct College Hall, which was featured in the quarry's advertisement.[6]

2.3 Deterioration Mechanism of Serpentine

Being a porous, alkali stone, serpentine is susceptible to sulfur-based acidic atmospheric pollution. Many serpentine buildings in the urban environment fared poorly where coal industry thrived in the late 20th century: coal burning raised sulfur dioxide content in the air. The 1930s saw the rise of automobile industry and nitrogen

[5] Dorchester, 25 – 44.
[6] Ibid., 25 – 44.

oxide produced by cars compounded the deterioration of serpentine. Exposure to these chemicals reduced serpentine's natural luster, color, and hardness. Sulfuric acid in the atmosphere turns iron-rich olivine and chromite in serpentine into limonite, which becomes a pale-yellow crust on the surface. Although it reduces the stone's aesthetic quality, it serves as a protective layer. It is common to observe different degree of deterioration patterns on individual stones because of their mineralogical inconsistencies. [7]

Like many porous building materials, water in the form of liquid or vapor can infiltrate the stone through any number of ways. Moisture collects in cracks or pores and expand when the it freezes, causing damage to the stone. Freeze thaw cycles are common in the northeastern region where many serpentine buildings are located. Moisture may also active subflorescence of salts, either innate or drawn from the atmosphere, ground water, or other building materials such as mortar. Many buildings constructed with serpentine had their surfaces reconstituted or were demolished because of the stone's deterioration.[8]

2.4 Serpentine and Architecture

American architecture trends were often inspired by European designs, especially English. The English's experiment with polychromatic design began in the 1840s and rose to popularity a decade later as "Victorian Gothic". The design concept in

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[7] Brown, "Assessment and Evaluation of Consolidation Methods on Serpentine Stone at the 19th Street Baptist Church, Philadelphia, PA." 18 – 20.
[8] Brown, 21 – 22.

the early days can be further characterized into structural vs. permanent and painted vs. applied, with a third, "polytexture", introduced in 1856. The American interpretation of Victorian Gothic often focused on structural polytexture—using different colored stone to create a visually stimulating design, a trend possibly attributed to the availability of a wide selection and quantity of stones. Also worth mentioning is a subcategory referred to as the Collegiate Gothic. While not always polychromatic, this technique adopted Victorian Gothic architectural elements such as polytexture and bold forms with delicate trims and carvings.[9] Examples on the campus of University of Pennsylvania include College Hall, Logan Hall, Fisher Fine Arts Library, and Houston Hall.

Jane Elizabeth Dorchester, who studied the evolution of serpentine as a building stone in southeastern Pennsylvania in her thesis, suggested that the rise of serpentine was bound to the development of vernacular architecture, and from there, advanced to a material used in monumental architecture designed by architects. She further divided the use of serpentine into four periods: The Folk Building Period (1727 – 1843), the Conservative Period (1843 – 1867), the Monumental Building Period (1867 – 1895), and the Final Building Period (1895 – 1931).[10]

The structures built in the Folk Period are considered vernacular or folk architecture and defined as "non-high style building; it is those structures not designed by professionals; it is not monumental; it is un-sophisticated; it is mere building."[11] As

[9] Ibid., 58 – 71.
[10] Ibid., 77.
[11] Upton and Vlach, *Common Places*. p. xv.

mentioned, early serpentine buildings were farmhouses, barns and other utilitarian structures with stone mined in private quarries.[12]

Gradually, serpentine was incorporated into more design-conscious, mid-Victorian houses of wealth residents in Chester County, moving into what Dorchester called the Conservative Building Period. These houses were conservative interpretations of Greek and Italianate styles, hence the name.[13]

The Monumental Building Period coincided with the commercialization of serpentine. Architect-designed buildings of this period included Philadelphia's Academy of Natural Sciences by James Hamilton Windrim, a number of university buildings in West Chester University and University of Pennsylvania, including College Hall by T.W. Richards. Dorchester posited that local architects such as Elijah J. Dallett, Jr. and T. Roney Williamson, along with Frank Furness, may have based their polychromatic design on serpentine, which contributed to the material's popularity in this region.[14]

Serpentine also owed its prominence to the efforts of Joseph H. Brinton, owner of Serpentine Ridge Quarry (aka Brinton's Quarry), who was a shrewd businessman. He placed strategic advertisements of monumental buildings constructed of his serpentine in newspapers and magazines.[15]

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[12] Dorchester, 78.
[13] Dorchester, 89 – 90.
[14] Ibid., 3 – 6.
[15] Ibid., 90 – 104.

A change in architectural fashion, launched by the World's Columbian Exposition in 1893, marked the beginning of decline for serpentine as a building stone. Polychromatic buildings were going out of style, replaced by monochromatic white buildings, symbols of moral and civic virtue during the City Beautiful Movement. There are no documented newly quarried serpentine buildings after 1931 after Brinton's Quarry closed.[16]

[16] Ibid, 115.

3.0 BRIEF BACKGROUND ON COMPOSITE REPAIR MORTAR AND MINERAL STAIN

3.1 Composite Repair

Composite repair, also referred to as "plastic repair" or "mortar repair", is a masonry patching technique using an amorphous material to recreate an area that can be made to closely resemble the host masonry through tooling, aggregate additives and color simulation. This ancient technique was used to repair building stones damaged in transit or correct carving mistakes. Composite repair is suitable for patching small areas of loss, typically less than two inches in depth since excessive buildup may become unstable. Although many contemporary commercial products can be built up by applying the material in smaller lifts[17], sometimes supported by pins or anchors. It is also applicable for rebuilding corners, carvings, or reliefs.

Proper preparation is essential for the success of a composite repair. The deteriorated material should be removed, and the repair area should be cut into a square or rectangle.[18] Application of composite repair mortar to regular shaped cavity is easier and it also forms a stronger bond. The surface should be consolidated if necessary. Many products specify pre-wetting the host masonry. This is done to avoid the host masonry from drawing too much water from the repair mix, causing it to cure too rapidly which often result in discoloration or cracks. This condition is referred to as flash cure.

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[17] A lift is defined as the amount of amorphous material, such as grout or mortar, placed in a single continuous operation.
[18] Pons, "Performance Analysis of Composite Repair of Sandstone." 37

The composition of a repair mix is like that of mortar, it contains a binder, aggregate, and water. Pigments can be added to simulate the color of host masonry if desired. The aggregate and binder can also be adjusted to represent the density, appearance, and texture of surrounding original material. *Stone Conservation, Principles and Practice* describes the ideal characteristics of a repair mix as:

> …integral color and grain-matching, usually derived from a calculated mix of selected, graded sands. Its binder should be inert and resilient to external weather conditions. The final product should have a similar vapor permeability to the stone itself, but be slightly softer (and therefore sacrificial). Ideally, it would also be reversible."[19]

Scott M. Pons, who analyzed the performance of composite repair on sandstone in his thesis, listed other important performance considerations for a composite repair from multiple conservation publications:[20]

1. Consistency – the composite repair mix must be workable, with the proper fluidity to fill the repair area and at the same time, able to retain its shape while setting.

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[19] Henry and Pearce, *Stone Conservation*. 83

[20] Pons compiled his data from: John Ashurst and Nicola Ashurst, "Mortars, Plasters and Renders," in *Practical Building Conservation,* vol. 3 (Hants, England: Gower Technical Press, 1988); Michael P. Edison, "Custom Latex-Modified Cement Repair Mortars for Masonry," *Concrete Repair Bulletin* (July-August 1991): 7-9,22; A.S. Iveson, *Masonry Conservation and Restoration* (London: Attic Books, 1987); P.R Hill and J.C.E. David, *Practical Stone Masonry* (London: Donhead, 1995); Dean Korpan, "Composite Stone Repairs at Drayton Hall," *APT Bulletin* 14 (no. 3, 1982); Michael F. Lynch and William J. Higgins, *The Maintenance and Repair of Architectural Sandstone* (New York: New York Landmarks Conservancy, 1982); S Peroni et al., "Lime-Based Mortars for the Repair of Ancient Masonry and Possible Substitutes," in *Mortars, Cements and Grouts Used in the Conservation of Historic Buildings: Symposium Held in Rome 3-6 November 1981* (Rome: ICCROM, 1982); C. Selwitz, *Research in Conservation: 7, Epoxy Resins in Stone Conservation* (Marina Del Rey: Getty Conservation Institute, 1992); Giorgio Torraca, *Porous Building Materials: Materials Science for Architectural Conservation,* 3d ed. (Rome: ICCROM, 1988); Weiss et al.

2. Setting Time – the mix must be able to set properly under the working environmental conditions. Many products specify working and initial curing temperatures around 45 to 90 degrees Fahrenheit. Expensive environmental control provision must be set up if natural conditions fall out of this range, driving up the project cost. Otherwise, work must be suspended, causing disruption to construction schedule and potentially driving up the project cost.
3. Dimensional Stability – shrinkage of repair mortar lead to cracking and detachment from host masonry, leading to potential safety concerns. Cracks also opens an opportunity for water infiltration, detrimental to both patching material, its host masonry, and the structure itself. The mortar should have similar modulus of elasticity and coefficient of thermal expansion with its host masonry, so it expands and contrast on a similar rate to avoid damage to either material.

Common mixes for composite repairs include lime-based or Portland cement-based mortars, occasionally acrylic resin-bound and oxychloride mortars.[21] However, many Portland cement-based mortars have caused severe damage to their host masonry due to incompatibility of physical and chemical properties. A detailed discussion can be found in the discussion of natural hydraulic lime under Section 4.1.

[21] Henry and Pearce, 83

3.2 Mineral Stain

The invention of mineral stains or paints[22] as a system for masonry coating is credited to Adolf Wilhelm Keim, who patented his mix of liquid potassium silicate and inorganic pigments in 1878. Potassium silicate (also known as waterglass) itself dates back to the middle ages. People referred to it as Liquor Silicum, it was produced by melting pure quartz sand with alkali.[23] Keim's invention was built upon multiple experiments and treatises established in the early 19th century. He posited that potassium silicate is an appropriate vehicle which would allow pigments to bond permanently to a plastered substrate. He developed a system which can be used to coat any porous, rigid, and silica rich substrate such as stone and unglazed brick.[24]

Potassium silicate stain is non-film forming, unless multiple coats are applied. It bonds to substrate by absorption and creates a crystalline key in the pores of the host masonry. Therefore, its durability is linked to penetration depth. With a shallow penetration, the stain will be lost as the substrate erode. It will not bond to impermeable substrates. According to Lime*works*.us representatives, a simple test can be done to determine if a substrate is appropriate for application. Spray a few drops on the test surface, if the water is absorbed after a few minutes, the substrate is appropriate. If test surface does not absorb the water, the application of stain will likely be unsuccessful.

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[22] Stains are often semi-transparent while paints are opaque.
[23] KEIM History
[24] Prah, "A Performance Evaluation and Assessment of Mineral Silicate Coatings for the Restoration of the Exterior Concrete at Jackson Lake Lodge." 31 – 33

Manufacturers often advertise mineral stains as low in volatile organic compound. Since it establishes a chemical bond with the substrate, the treatment is non-reversible. It is retreatable in most cases if the substrate is still permeable enough to absorb the stain.

4.0 INTRODUCING LITHOMEX AND COLORWASH STAIN

Lime*works*.us provided the testing materials for this thesis. The composite repair samples were made with their product, Lithomex, manufactured by St. Astier with lime quarried in the quarry of the same name and colored with alkali resistant pigments and mica flakes as an inclusion. The potassium silicate stain samples, using Rainbow Sandstone as substrate, were treated with Colorwash Stain manufactured by PermaTint.

4.1 Lithomex

Quarry and Manufacturer

Lithomex is a composite repair mortar produced by St. Astier, a manufacturer of natural hydraulic lime (NHL) mortar and derivative products in France. The product is extracted from St. Astier's quarries in the Périgord area of Dordgne. The six-mile limestone deposit is over 62 miles thick, formed by marine sediment of crustacean and corals approximately 75 million years ago. A relatively homogeneous layer of calcareous rock, with silica and trace amounts of other elements, was formed thanks to the area's gentle current. This relatively pure limestone produces lime of consistent quality. The site was surveyed by Louis Vicat in 1833 and determined to be appropriate for the production of natural hydraulic lime. St. Astier begun their industrial production in 1851.[25]

[25] Chaux et Enduits de St Astier, "Raw Materials & Production of St Astier Pure and Natural Hydraulic Lime."

Natural Hydraulic Lime

NHL is produced by burning limestone. NHL's hydraulic properties derive entirely from its natural chemical composition, meaning it does not contain any additives. In many cases, NHL products may be more appropriate as a patching material for historic structures than those made of Portland cement. NHL, like stone, consists exclusively of natural minerals and chemicals. It is more similar to stone in terms of vapor permeability and mechanical properties than Portland cement. Because Portland cement is harder and denser than most stones, it experiences lesser dimensional change from load or movement caused by temperature fluctuations. The differential in movement leads to the damage of the weaker material – the stone. Being less vapor permeable, moisture is likely to be trapped behind the patching material, leading to the deterioration of the substrate. Using Portland cement-based patching material on weaker substrate or structures originally built with lime-based mortar or render will likely lead to early failure.[26] In the past 150 years, many composite repair mixtures based on Portland cement have resulted in loss of color, producing damaging salts, causing deferential erosion to surrounding original masonry, and cracking or separation from its substrate.[27]

Application

Lithomex is specially formulated for the purpose of repair or simulation of brick, stone, and terra cotta using NHL and appropriate aggregates. The product comes in

[26] Holmes and Wingate, *Building with Lime*. 121
[27] Henry and Pearce, 83

powdered form and is ready to use by mixing with a specified amount of water at the job site. The naturally off-white product can be color simulated to match desired hue using alkali resistant pigments. Additional inclusions such as colored sand or mica can be added to simulate the appearance of host masonry.

Lithomex bonds directly to pre-cleaned and pre-wetted substrate. A mold can be used as necessary. Wet tooling may be applied at thumbprint hardness[28] to recreate the original texture, further carving and shaping can take place at any time after the mortar is set. More information can be found in Appendix A – Product Data.

Properties of Lithomex

Properties	Details
Suitable substrate	Brick, stone, concrete, metal lath
Bulk density	82.5 to 85 lbs/ft^3
Cure time	Initial: 7 days, full: 28 days
Flammability	Not flammable or combustible
Solubility	Slight soluble in water
Water permeability	.25 ml.m.day
Vapor permeability	.75 gr.m^2.hour.mmHg
Tensile strength (at 28 days)	345 PSI
Compressive Strength (at 28 days)	1051 PSI
Elasticity Moduli	7690 Mpa at 28 days
Shrinkage	.085%
pH	12 – 13
Melting point	840 F
Incompatible materials	Acids, non-rigid substrate

Table 1. Published properties of Lithomex[29]

[28] when a material, such as mortar, has dried to a stage where a person can easily leave a thumbprint on it when pressing down.

[29] Lime*works*.us, "St-Astier-Lithomex-Technical-Data-Sheet.Pdf."

4.2 Colorwash Stain

Colorwash Stain is manufactured by PermaTint and distributed by Lime*works*.us. The water-based material is slightly translucent; therefore, when the stain is applied, the texture and color of the substrate can be visible. The level of visibility depends on the number of coats applied. Transparency can be increase by diluting the pigmented paint with Colorwash Stain Clear. Stock colors can be blended for color simulation.

Application

Colorwash Stain is suitable for pervious, chemically neutral or alkaline, rigid substrate such as concrete, stone, bricks, mortar, plaster, and drywall. However, it is not appropriate for floor application due to mechanical abrasion. Additionally, the stain is chemically incompatible with gypsum plaster. The substrate should be cleaned, consolidated if necessary, and pre-wetted before application with brush, roller or spray.[30] Detailed technical information can be found in Appendix A – Product Data.

Properties

Properties	**Details**
Suitable substrate	Concrete, stone, unglazed bricks, mortar, plaster, drywall
Incompatible material	Acid, non-rigid substrate, some metals
pH	8.5 – 9.0
Cure time	Initial: 12 hours, full: 10 days
Flammability	Not flammable or combustible
Solubility	Slight soluble in water

Table 2. Published properties of Colorwash Stain[31]

[30] Lime*works*.us, "Colorwash Stain for Masonry Technical Data Sheet."
[31] Lime*works*.us, "St-Astier-Lithomex-Technical Data Sheet"

5.0 EXPLANATION OF FOCUSED METHODS

One of the main concerns when deciding intervention methods for building owners and architectural conservation professionals is the durability of the repair. Owners want to have maximum value for cost, primarily associated with service life. A durable repair retains its function and appearance over time without needing constant maintenance. The durability of two non-in-kind repairs are evaluated through profile alteration and color change before and after accelerated weathering and vapor permeability test.

5.1 Repair No. 1: Composite Repair Method

Repair No. 1 proposes creating a precast face unit with a natural hydraulic lime based composite repair mortar, applied directly onto a substrate such as stone or brick. This thesis analyzes composite repair mortar's function as a surface treatment, such as patching an area of loss or cast in a mold to create a unit replacement.[32] Patching is a kind of repair where composite repair mortar is applied directly onto an area of loss. The mortar is color simulated to match surrounding masonry and tooled using methods defined by the project's specifications. Unit replacement is defined as casting the wet mix of composite repair mortar in molds according to the specifications of individual projects, such as dimensions, color, and texture. The cast replaces the entire unit of non-load-bearing stone. The replacement unit is secured to the back-up masonry using pins,

[32] Depending on the manufacturer, most composite repair mortar has a compressive strength between 700 to 1100 psi. They may have limited load carrying capacity as approved by a structural engineer. However, it is not within the scope of evaluation.

anchors, or other appropriate methods. The surrounding masonry joints should be filled with chemically compatible lime-based mortar of lower or comparable compressive strength and higher vapor permeability. The composite repair mortar should have similar vapor permeability as its substrate in order to allow proper drying of the wall assembly. Moisture trapped behind the repair material may lead to deterioration of the substrate, and the repair will detach from its host masonry. In addition, the prolonged presence of moisture may cause increased erosion and deterioration of surround wall assembly.

In most cases, composite repair can be reversed by mechanical methods using proper tools. There will be minimal to no damage to the host masonry if it is performed with caution. The bond strength between the repair mortar and stone varies primarily according to the porosity of the stone. Stronger bonds will be more difficult to remove.

Scope of Evaluation

The scope of evaluation includes the material's ability to maintain its tooled or cast surface texture and color exposed to weather. When it is applied directly onto a stone, the substrate's health will directly impact its durability. Therefore, the composite repair mortar must be chemically and physically compatible. While chemical compatibility is not studied due to time limitation, physical compatibility is examined though vapor permeability.

5.2 Repair No.2: Mineral Stain Method

Repair No. 2 proposes creating a new face or unit replacement with a more commercially available stone, coated with color matched potassium silicate stain to mimic serpentine. First, a suitable stone is selected based on its compatibility with the environment and surround masonry in terms of chemical and physical properties. For example, limestone may not be suitable in an environment where heavy acid rain is expected. The sulfuric acid in acid rain breaks down the calcium carbonate in limestone in a neutralization reaction and the stone dissolves in water. The replacement stone should have similar surface texture to the stone it is replacing so it can better blend in with its surrounding. If tooling is desired, the stone should have a workable hardness. Finally, it should be suitable as part of the wall assembly. If a locally sourced stone is determined to be appropriate, it has the added benefit of saving transportation cost and energy.

After the appropriate stone is selected, color simulation is performed, usually by the manufacturer if the service is available. Since potassium silicate stain is semi-translucent, the base color of the stone will have an impact on appearance when a stain is applied. This must be considered during color simulation. The texture and color of the base stone can enhance the appearance by providing natural visual variations. If tooling of the surface is desired, it must be done before the stain is applied.

Potassium silicate stain can be applied with a brush or a sponge, sprayed on, or using a combination of methods to achieve the desired result. Each application method will create a slightly different appearance. Brush application tends to produce a heavier and more even coating. The surface texture and color of the stone is more prominent with sponge application, but it tends to produce a thinner coat. A mixture of methods and colors can be used to produce a more natural appearance than one coat of a single color. However, complicated techniques require skilled labor and more material, therefore increasing cost.

The staining of stone can be done in a workshop before installation or in the field after installation. Each has advantages and disadvantages. A workshop provides a climate-controlled environment where the process is protected from weather and temperature fluctuations. It allows the work to be done anytime of the year. In addition, the stone can be stained lying horizontally, which will allow the coating to dry evenly and may increase the penetration depth. However, the stone cannot be dressed once the stain is in place, therefore the project team must ensure the dimensions are correct. The logistics may be more time consuming and an error may be costly. In addition, the prepared stones must be transported with care. Damaged stones may need to be repaired on site. While staining in field may avoid some headaches, the project team should set up environmental protection to keep the coating free of rain, debris, and within the manufacturer's specified working temperatures. Application on vertical surfaces is generally more difficult. The applicator may be working from a less comfortable position depending on the terrain of the building. Precaution should be taken to avoid stain accumulation or drips because mistakes are difficult to correct. Potassium silicate stain is non-reversible. It can only be removed using mechanical methods that reduce the host masonry past the depth of penetration of the stain. However, it can be retreated if the substrate passes the spray test.

Scope of Evaluation

The scope of evaluation focuses on the mineral stain's ability to maintain its color when exposed to weather and the impact on the natural vapor permeability of the substrate. The physical and chemical properties of the substrate will have major bearing on the durability of the stain. The coating may deteriorate at the same rate as its host masonry since it is a surface treatment. The substrate's pore size and distribution may influence the depth of penetration, which is directly linked to the longevity of the treatment. Tests on different types of stone would provide a more comprehensive evaluation of its performance, however, given the time frame of the thesis, the stain was only tested on Rainbow Sandstone.

6.0 TEST SAMPLES PREPARATION

Four types of samples were created for testing: salvaged serpentine, composite repair mortar cast, untreated Rainbow Sandstone, and stained Rainbow Sandstone. Three samples of each type were tested to generate sufficient data for comparison. The dimensions for the samples were configured to fit the brackets of the weatherometer. Based on the dimensions of the brackets, the samples were cut or created as 3 inch (width) by 4 inch (length) and 1/2 inch (thickness) panels.

6.1 Salvaged Serpentine Samples

The serpentine stones were salvaged from Woodland Presbyterian Church, located in the Spruce Hill neighborhood of West Philadelphia, Pennsylvania. The stones retain remnants of gray or orange foreign materials adhered to the surface. The surface that is the flattest and free of residue is likely the face, which is most appropriate surface to be tested since it was exposed the elements when it was on the building. The serpentine samples were cut with a wet-cutting masonry saw. Due to safety concerns, the samples were cut to about 3/4 of an inch in thickness then trimmed with masonry grinder to 1/2 inch.

Figure 1. Salvaged serpentine samples, S1, S2, and S3. (Photography by author, 2019)

Properties

Color – the sample displayed a variation of colors from light yellow-green, olive, to dark brownish-green. Three bulk colors were identified using the Munsell system:

1. 10 Y 6/2 Pale Olive. This was determined to be the base color of the stone because it was the most abundant and a good overall average of the variations.
2. 10 Y 4/2 Grayish Olive. This was on the darker end of the range of colors, a gray, brownish olive shade.
3. 5 Y 5/2 Light Olive Gray. This was on the lighter end of the range, a pale grayish-yellow green shade.

Texture and topography – The surface of the stone was uneven and rough to the touch. There were many ridges and pits, with the greatest variation in height measuring approximately 3/8 of an inch out of the three samples. Thin veins of roughly 1/64 of an inch orienting in a uniform direction were present in portions of Samples 1 and 2. Deep crevices were present throughout in all three samples.

Fabric – Moderate grains were just visible to the naked eye. Flecks of shiny minerals up to 1/8 of an inch, likely mica, were present throughout all three samples. The samples were also examined under a microscope. At approximately 60x magnification, flecks of black minerals, some of which were visible sporadically to the naked eye, were abundant throughout the sample. Most grains appeared semi-translucent green or pale-yellow under the light of the microscope. A white, sugar like substance covered a large portion of the surface, some of which was visible to the naked eye.

Luster – Waxy and dull.

Hardness – 2 (Mohs' Scale)

6.2 Composite Repair Mortar Samples

The composite repair mortar samples were created with the goal to closely mimic the color and texture of the serpentine panels. Lithomex can be color simulated using alkali resistant, UV stable pigments. A Lithomex color formula was developed to simulate the each of the three bulk colors identified on the serpentine panel using the

Munsell System. The pigmented, powdered Lithomex was mixed with water, pressed into molds, then tooled to create a stone-like surface.

Methodology

The first step was to develop three Lithomex formulas to simulate the Munsell colors of the serpentine. The three colors were 10 Y 6/2 Pale Olive, 5 Y 5/2 Light Olive Gray, 10 Y 4/2 Grayish Olive. All three formulas were developed using the same method, starting with the base color, Pale Olive. Lime*works*.us has a library of past samples and formulas to aid the process. A sample closest Pale Olive was selected from the library. Using its reference code, the formula was retrieved from the database. The original *Limeworks.*us formula consisted of set amounts (in grams) of unpigmented Lithomex and lime-fast pigments. The exact amounts were measured using a digital scale to the nearest .005 gram, then blended for five minutes in Robo Coupe, a combination processor which is appropriate for the purpose of dispersing powdered contents. The powdered form of the Lime*works*.us formula was compared to Pale Olive on the Munsell chart. Based on the comparison, different pigments were added gradually, weighed and recorded, until ideal approximation of the target color was reached.

The color of pigmented Lithomex stabilizes after seven days when it reaches initial cure. Under ordinary circumstances, the simulated Lithomex sample should reach its target color at this stage. It is inspected for quality and to determine if subsequent adjustments to the formula is needed. A full color simulation process usually takes about two to three weeks at Lime*works.*us. However, in the case of Lithomex, the powdered form is a near representation of its cured color.[33] Due to time constrains, the powdered form was used to evaluate the likeness to target color. While an attempt is made to recreate a close representation of serpentine samples using Lithomex in order to demonstrate its aesthetic potential, time constrains did not allow unlimited trial and error. The main goal is the evaluate durability by measuring color change, not to create a facsimile. Therefore, dry powdered proximity to target color was deemed adequate for the purpose.

After the three target colors have been successfully simulated, the powders were ready to be mixed with water and pressed into molds. A special mold was custom made by Lime*works.*us for the purpose. The wooden mold contained 16 slots measuring 3 in x 4 in x ½ in each. The slots were lined with duct tape for ease of demolding. Although only three samples were needed for testing, sixteen samples were made as an effort ensure there will be at least three quality samples.

3.60 kilograms of Pale Olive, 1.20 kilogram of Light Olive Gray and 1.20 kilogram of Grayish Olive powdered Lithomex were made by weighing out the ingredients listed on their respective formula on a digital scale, then blended in the Robo Coupe for five minutes. Lithomex datasheet specifies 1.1 gallons of water for per 55-pound bag,

[33] Additional aggregate will increase the variation from powdered form to its final color. In the case of the samples made for this thesis, the additional aggregate is approximately five grams of mica in each formula, which does not change the color significantly when broken up during the blending process in the Robo Coupe.

equivalent to 166.56 milliliter per 1.00 kilogram. Mathematical conversion was used to calculate the proper amount of water needed for each[34]:

1. 3.60 kilograms of Pale Olive

$\frac{166.56\ mL}{1.00\ kg}$ x $\frac{x\ mL}{3.60\ kg}$, x = 599.61 mL

599.61 milliliter of water is needed to mix with 3.60 kilogram of Pale Olive powder.

2. 1.20 kilogram of Light Olive Gray

$\frac{166.56\ mL}{1.00\ kg}$ x $\frac{x\ mL}{1.20\ kg}$, x = 199.87 mL

199.87 milliliter of water is needed to mix with 1.20 kilogram of Light Olive Gray powder.

3. 1.20 kilogram of Grayish Olive

$\frac{166.56\ mL}{1.00\ kg}$ x $\frac{x\ mL}{1.20\ kg}$, x = 199.87 mL

199.87 milliliter of water is needed to mix with 1.20 kilogram of Grayish Olive powder.

A Kitchenaid stand mixer was used to blend the powdered Lithomex with water. The precise amount of water was added to the stand mixer bowl using a horse syringe, then the powder was poured on top. The mix was blended at the lowest speed setting for five minutes. High speed mechanical mixing can increase the total volume by as much as 22 percent due to air entraining. Whereas slow mixing can be used to simulate

[34] The amount of water use must be precise and consistent. Too much water will lighten the color and cause shrinkage cracks. Too little water will reduce the stability of the material and result in loss of strength.

denser masonry unit.[35] The bowl was washed and dried between each mix. All three mixes reached the ideal consistency, similar to that of ice cream.

The wet mix was pressed into molds using a margin trowel immediately after they were made. All sixteen molds were initially only filled with the base color, Pale Olive. The edges and corners were filled first by pressing the material firmly to the mold with the back of the trowel in an upward motion, forming a triangle against the side. The mold was then gradually filled from the sides toward the center. Eliminating air pockets was crucial. A combination of firm compression and manual vibration techniques using the trowel were applied for this purpose. Each mold was overfilled by 1/8 of an inch to ensure the space was filled. This step was completed in roughly 40 minutes.

The natural variation in color of the serpentine stone was mimicked by applying two more colored Lithomex, Grayish Olive and Light Olive Gray in addition to the base color. After the mold was filled with base color, random pockets were removed, or crevasses were made using a leaf trowel. These voids were then filled with other colors, either lightly mixed with each other or purely on its own. All the molds were again overfilled, this time by approximately 1/4 of an inch to accommodate later tooling. This step was completed in roughly 30 minutes. The samples were left to dry for approximately two hours after this step.

[35] Hertz, “Thesis Review.”

Wet tooling began after the two-hour standing period. The purpose of wet tooling was to create a general topography of the surface. Random pockets or pits were created using the leaf trowel. Crevices were carved using the same tool. Thin veins were created by scratching the sample lightly with a dry heavy-duty scouring pad. The duration of wet tooling was approximately 60 minutes. The samples were left to dry for eighteen hours in Lime*works*.us's laboratory in a climate-controlled environment.

Dry tooling on the samples was performed eighteen hours after wet tooling. Crevices and pits were refined to appear more stone-like with a sharp carving tool with triangular head using a combination of scraping and puncturing motions. Dry tooling was completed in approximately two hours.

The samples were left to cure in the molds for six days before demolding. The demolding process was successful with minimal difficulties. The samples were left to cure on a wooden surface for 22 days until they reach full cure, a process which takes 28 days.

Cast vs. Patching

Cast composite repair mortar casts made for this thesis only had one drying surface. The other surfaces were in contact with the impermeable borders of the mold, which formed a "skin." When used as a patching material, at least one surface is exposed to air and the rest experience some vapor permeability when in direct contact with host masonry or mortar. Casting creates a "closed" sample and may influence how moisture is moving through the stone during the curing process.[36] In addition, casting often creates a layer of paste on its only exposed surface. This can be scraped off with a trowel at thumbprint-hardness to maintain a flat surface. Tooling will eliminate this issue if a textured surface is desired.

Figure 2. Composite repair mortar samples, L1, L2, and L3. (Photograph by author, 2019)

6.3 Untreated Rainbow Sandstone Samples

The Rainbow Sandstone was distributed by Stone Depot in Perkasie, PA. The stone came from a quarry in Laurel Hill, part of the Allegheny Mountains in western Pennsylvania. The test surface of the stone was determined by its bedding orientation on

[36] Hertz.

a building. Sedimentary stones should be laid with its striations parallel to grade. This surface corresponds to the thickness in the case of the sandstones used for this thesis. Stones of at least three inches in height with relative flush surfaces were selected at the distribution center for cutting. The selected stones were rinsed with tap water then treated with D/2 according to the manufacturer's instructions. The samples were cut with a wet-cutting masonry saw. Due to safety concerns, the sample tiles were cut to about 3/4 of an inch in thickness then trimmed with masonry grinder to 1/2 inch.

Properties

Color – The bulk color of the Rainbow Sandstone was identified as 10YR 6/7 (Munsell) The striations were 7.5YR 6/8 (Munsell).

Texture and topography – The stone surface was moderately rough to the touch and left a fine, sand-like residue on the fingertips. The undulating surface had a much smoother transition in height than the sharp crevices and pits of the serpentine samples.

Fabric – Individual grains were differentiable to the naked eye. Examined under a microscope, the grains were opaque with color variations from white to orangish-tan and appeared to be sub-angular. It is difficult to comment on the sorting without performing a sieve-analysis. Much of the grains were covered with a salt-like substance that shimmers under the light.

Luster – Dull.

Hardness – 6 (Mohs' Scale)

Figure 3. Untreated Rainbow Sandstone samples, R1, R2, R3. (Photograph by author, 2019)

6.4 Stained Rainbow Sandstone Samples

Same as the untreated sandstone samples, the testing surface will be the one exposed to the elements when laid correctly. While many artistic application techniques can be used to create a natural-looking surface similar to that of serpentine, however, these artistic applications may have an impact on its wear pattern during accelerated weathering. It was decided that two even, single color coats should be applied to the samples to eliminate unnecessary variables and establish a base measurement of durability through testing. Different aesthetic application techniques are discussed in a later section in this thesis.

Methodology

Like acrylic paints, Colorwash Stain can be mixed to create different colors. They cannot, however, be mixed with water as it will decrease their durability and alter their appearance. Clear Colorwash Stain can be added to increase transparency.

A Colorwash Stain formula was developed to match Munsell 10 Y 6/2 Pale Olive, the base color of serpentine. Five stock colors, Oxide Green, Yellow Ochre, Raw Umber, White, and Earth Black were selected based on color theory and under the advice of Lime*works.*us representatives. Colorwash Stain Clear, a semi-transparent white, non-pigmented stain was used to increase the transparency of the stain in order to expose the natural variation and texture of Rainbow Sandstone.

The color simulation began with measuring out ten grams of Oxide Green. Subsequently, other colors were added to the mixing container a few grams at a time while recording the precise weight until the desired hue was reached. The color was then tested on a piece of Rainbow Sandstone, as dried Colorwash Stain varies from wet. Two test coats were applied using a chip brush. While a 12-hour curing period is needed between coats, in a testing capacity, the second coat was applied as soon as the first was dry. While proper application procedures will affect the depth of penetration and bond with the substrate, it does not typically alter the color. The dried test strip was compared to the Munsell chart and the serpentine sample, if the desired shade was not reached, more colors were added to the mixing container based on color theory. This process was repeated until the color reached a satisfactory representation of the target.

The first coat of Pale Olive stain was applied to cut and cleaned sandstone panel as evenly as possible using a chip brush.[37] A second coat was applied approximately seventeen hours later. The sample panels were propped upright during the application and curing process to represent actual condition as they would be in the field. The samples were kept in a climate controlled until they reach full cure in ten days.

Figure 4. Stained Rainbow Sandstone samples, C1, C2, and C3. (Photograph by author, 2019)

[37] Same as the control samples, the stone was first washed with water then treated with D/2 according to the manufacturer's instructions.

6.5 Samples for Water Vapor Transmission Test

Five types of cylindrical disks measuring approximately 2 ¾ inches in diameter and 1 inch in thickness were created for water vapor transmission test. Each type contained a cohort of three. The types are:

1. Serpentine
2. Rainbow Sandstone
3. Half Composite Repair Mortar and Half Serpentine
4. Composite Repair Mortar
5. Stained (top surface only) Rainbow Sandstone

Methodology

Serpentine

Serpentine samples were cored with Hilti Diamond Coring Drill DD-150-U, operated by Pullman SST. Inc. crew in their Swedesboro, New Jersey office and workshop. The serpentine samples were cored from the same stones used for accelerated weathering. The cored stone was cut with a stone saw to 1-inch thick disks.

Rainbow Sandstone

Rainbow Sandstone samples were created using the same procedure as serpentine, explained above.

Half Composite Repair Mortar and Half Serpentine

In this case, the cored samples were cut to ½ inch in thickness using a stone saw and trimmed with a stone grinder, if necessary. These disks were taken to Lime*works*.us's Telford laboratory to complete the preparation. All work was performed under the assistance of Project Manager, Chris Hertz. The disks were cleaned under running tap water and gently scrubbed with a toothbrush. Using the ½ inch stone as a base, a mold was created by wrapping a piece of sheet metal, approximately 1 ¼ inches in height, tightly around the perimeter and secured with tape.[38]

1.2 kilograms of Pale Olive Lithomex was prepared using the same method explained above. The disks were sprayed with potable water immediately before application. The Lithomex was compressed against the substrate and the mold using a margin trowel. The samples were left in the mold for four days before demolding. They were left to cure in a climate-controlled environment for 28 days.

Composite Repair Mortar Sample

Composite repair mortar samples were made with the same process as above, except the base which is used to shape the mold was taped off to keep it from bonding to Lithomex. The base was removed after the samples were demolded. They were left to cure in a climate-controlled environment for 28 days.

Stained Rainbow Sandstone Sample

Two coats of Pale Olive Colorwash Stain were brushed on to each cleaned stone disk with approximately 24 hours of drying time between applications. Only the top surface (facing upwards during water vapor transmission test) was stained to accurately represent real world situation where only the exposed surface of the replacement stone would be treated. The curved side surface was not treated since it is sealed with electrical tape during the test. The samples were left to cure in a climate-controlled environment for more than ten days while they await testing.

[38] PVC pipe of the exact size was not available.

7.0 TESTING PROGRAM

7.1 ACCELERATED WEATHERING

Introduction

Accelerated weathering is a technique that artificially weathers physical samples in a laboratory setting. The samples are placed in a weatherometer, equipped with lamps to simulate UV damage, spray nozzles to simulate rain, and a heater to create different weather conditions such as condensation and temperature fluctuations. The operator can set the conditions according to ASTM standards or established industrial standards.

Standard industry practice usually runs the accelerated weathering for 1000 to 1500 hours, which simulates a few years of weathering in natural conditions. However, the accelerated weathering to natural weathering equivalent involves complicated calculations based on the known properties of the sample material, the relationship between testing conditions (i.e. temperature, irradiance, UV cycle to condensation cycle ratio, length of spray cycle). Accurate correlation can be established by performing natural weathering test of the same material.

Technology

The samples for this thesis were tested using QUV Weathering Tester (commonly called weatherometer), model QUV/SE/SO, located in the Architectural Conservation Laboratory (ACL) and operated by the Historic Preservation Department at the University of Pennsylvania.

Methodology

Preparation

The UV lamps and spray nozzles were disassembled for cleaning immediately before testing began. The lamps were wiped down with acetone. The nozzles were washed in a sonic bath for one hour. The irradiance was calibrated to the desired number. The machine was test run for about 30 minutes on UV cycle and an hour on condensation cycle to ensure proper temperatures (at least 63°C for UV cycle and 53°C for condensation cycle) and irradiance were reached. The spray function was also tested.

Sample Placement

Samples were placed vertically on large brackets with openings that cover a small section of each samples' perimeter. Four samples were placed in each bracket, separated vertically with spacers (Figure 5). The samples were secured using telephone wires. Untreated stone samples were placed on top of composite repair mortar and stained stone samples to avoid runoff of treated material (Figure 6).


Figure 5. Testing surface, facing the UVB lamps and spray nozzles. (Photography by author, 2019)

Figure 6. Samples placed in the weatherometer. (Photography by author, 2019)

Cycle Selection

The goal of accelerated weathering test is to gain an understanding of the performance parameters of the material in a harsh environment. UVB-313 fluorescent lamps were selected because they can achieve higher UV intensity than UVA lamps. Established industrial standards were considered for setting the conditions of the test. The following chart summarizes the industrial standards for UVB:

Standard	Irradiance ($Wm^{-2}nm^{-1}$)	Wavelength (nm)	Cycle Duration (hr)		Temperature (°C)	
			UV	Condensation	UV	Condensation
1	0.63	310	4	4	63±3	50±3
2	0.55	310	8	4	70±3	50±3
3	0.44	310	20	4	80±3	50±3

Table 3. Industrial standards for accelerated weathering cycles. [39]

Standard one was selected because it simulates the harshest conditions out of the three. A spray of fifteen minutes was set at the beginning of condensation cycle. The spray creates a shock to the samples from the sudden temperature change, rapidly cooling the chamber from around 63°C to 5°C.

Testing Duration

Testing duration was reduced to a total of 864 hours instead of the industrial standard of 1000 to 1500 hours due to time constrains. The samples were taken out of the weatherometer for interim inspection every 216 hours. Interim inspection included photo-documentation of the samples using a DSLR camera and color readings taken

[39] Prah, 75.

with a spectrophotometer. This step took roughly 90 minutes each time. The samples were then secured onto the brackets and placed back into the weatherometer one position to the right. The rotation of placement ensured each sample received the same amount of exposure to the lamp and spray.

7.2 PROFILE AND VOLUME CHANGE

7.2.1 3D Scanning

Introduction

Digital comparison of 3D models of the test samples created before and after accelerated weathering was used as a method of computing quantitative measurements of profile change. Scans of the samples were captured with a hand-held 3D scanner. Digital models were created using the scanner's accompanying software. The digital models were loaded onto a point cloud processing software which computes the difference between two similar digital models.

Technology

Artec 3D Space Spider

Artec 3D Space Spider is a hand-held device designed for CAD users, capable of capturing small objects with complex geometry (Figure 7). It captures image with structured light scanning by projecting light in a pattern onto the subject.[40] The angle of distortion of the light patterns are captured with cameras, analyzed, and then

[40] Artec 3D, "Space Spider Info Sheet."

transformed into three-dimensional coordinates which recreate the scanned object.[41] The scanner has a resolution up to .1 millimeter and an accuracy up to 0.05 millimeter. Detailed technical information can be found in Appendix A – Product Data.

Figure 7. Artec 3D Space Spider. (artec3d.com)

Artec Studio 13

The scanner is accompanied by 3D scanning and data processing software Artec Studio 13. The software processes the scan and creates a 3D digital model. It gives users

[41] Knicker, "3D Scanning Basics."

the option to manually align scans, which was often used in the case of creating the digital models for this thesis.

CloudCompare

CloudCompare is an open source 3D point cloud editing and processing software designed to compare dense point clouds. Two point clouds are loaded simultaneously in the software, it analyzes the coordinates and generates a color coordinated “map” accompanied by an elevation meter indicating the amount of variance.

Methodology

The target object was placed on a rotating base. The scanner was adjusted to optimal distance and position as indicated on by the software on the screen. The author scanned the object by rotating the base, and if necessary, moving the scanner around the object. However, keeping the scanner stationary usually produces better scans (Figure 8).

Three separate scans were necessary to fully capture a test sample due to its complex surface texture. One scan captured the sides, one of its top surface, and one of its bottom surface. The scans were then aligned by the author. The software processed the aligned scans and created a 360-degree 3D model.

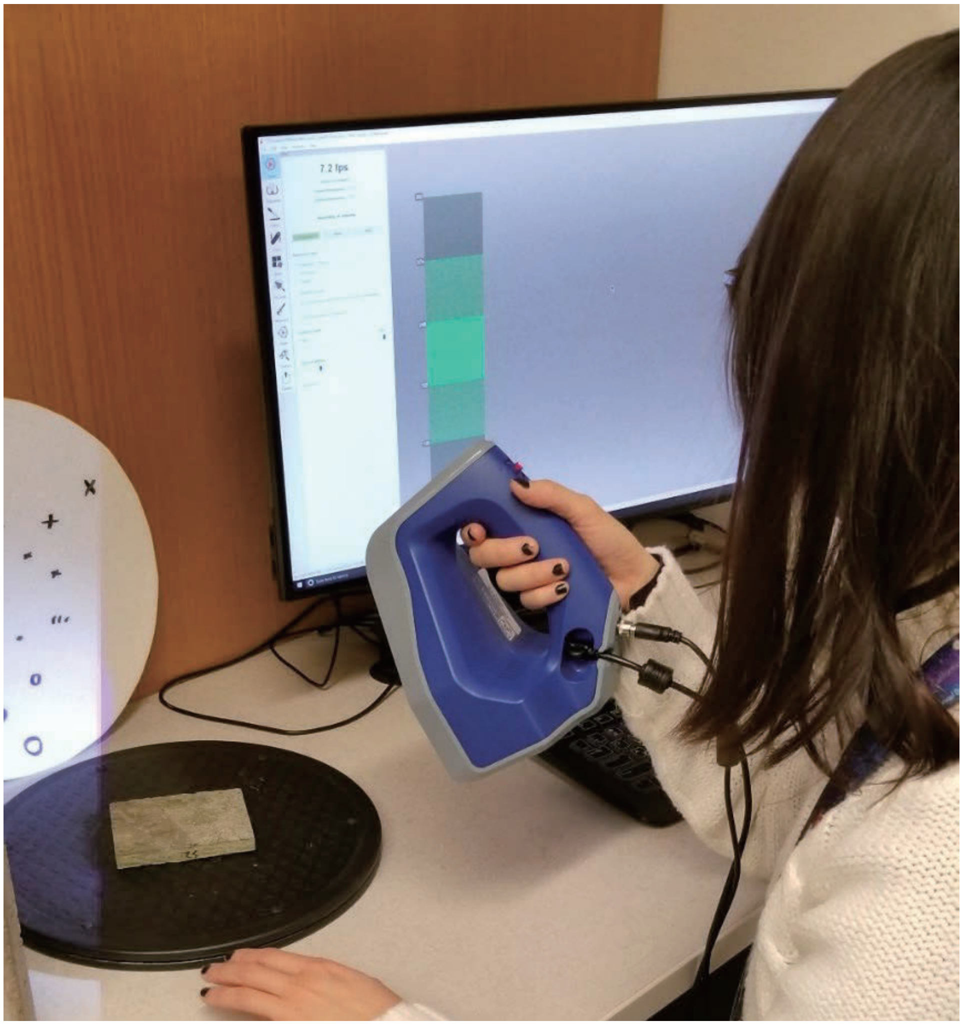


Figure 8. The author scanning a test sample using the Artec 3D Space Spider. (Photograph by Rebeca Sanchez, 2019)

A digital model was created for each sample before and after accelerated weathering. Digital models were not created at each interim inspection during accelerated weathering due to limited availability of the scanning device, it would prolong the intermission, exposing the samples to uncontrolled variables.

Accuracy

A trial scan was performed to understand the degree of accuracy. First, a flat piece of composite repair mortar sample was scanned with the Artec 3D Space Spider, followed by the creation of a digital model. Then, two squares were marked with permanent marker and measurements of five points within both squares were taken with a digital caliper, noted by points marked on the bottom surface of the sample. The surfaces of the test squares were reduced with a file and measured again at the same points (Figure 9).

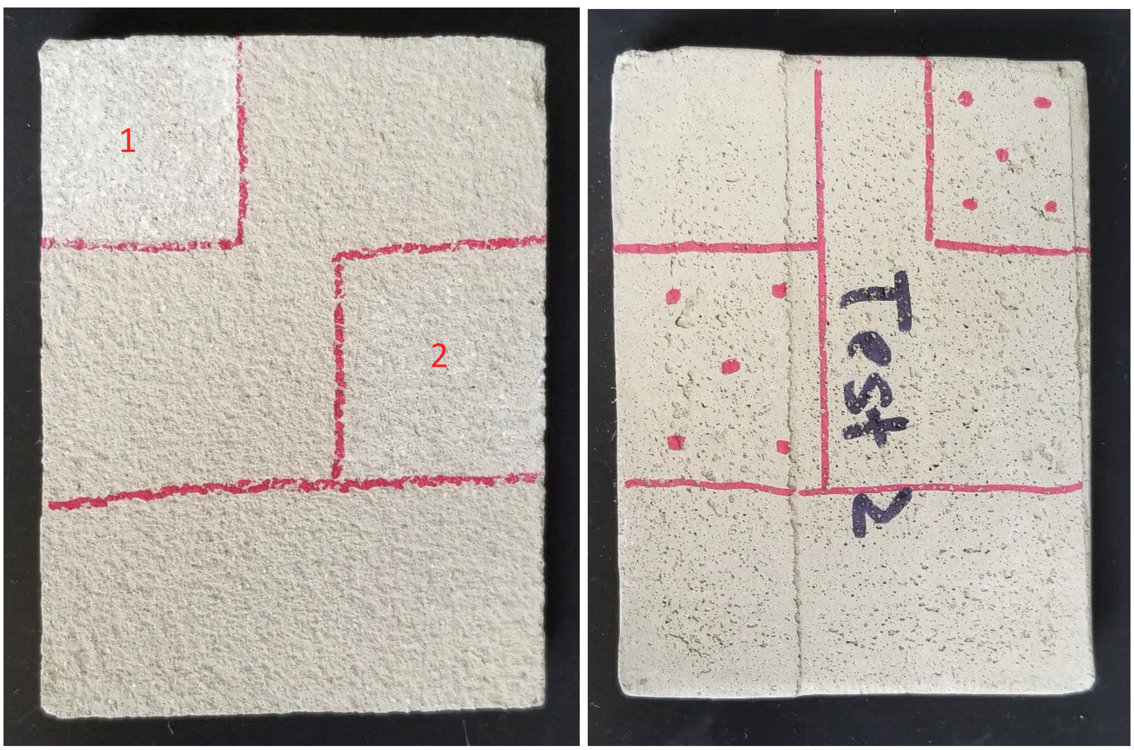


Figure 9. Trial sample for 3D scanning. Left: Front of the sample, test squares are marked with 1 and 2, where the surfaces were reduced. Right: Back of the sample, the dots in the test squares indicate where the measurements were taken. (Photograph by author, 2019)

The measurements are listed in the following table:

Test Square 1			
Location	**Measurement – Initial (mm)**	**Measurement – Reduced (mm)**	**Amount Reduced (mm)**
Upper left	12.31	12.13	0.18
Lower left	12.21	12.10	0.11
Upper right	12.39	12.07	0.32
Lower right	12.27	11.90	0.37
Center	12.23	11.91	0.32
Test Square 2			
Location	**Measurement – Initial (mm)**	**Measurement – Reduced (mm)**	**Amount Reduced mm)**
Upper left	12.37	12.27	0.10
Lower left	12.36	12.20	0.16
Upper right	12.06	12.00	0.06
Lower right	12.00	11.97	0.03
Center	12.23	12.08	0.15

Table 4. Thickness of test squares of 3D scanning test sample.

A second scan was performed. The digital models from before and after the reduction were compared using CloudCompare. The software detected changes to both test squares. The degree of change is indicated by a color scale in millimeter. The result from CloudCompare approximated the depth of surface reduction measured by the digital caliper (Figure 10).

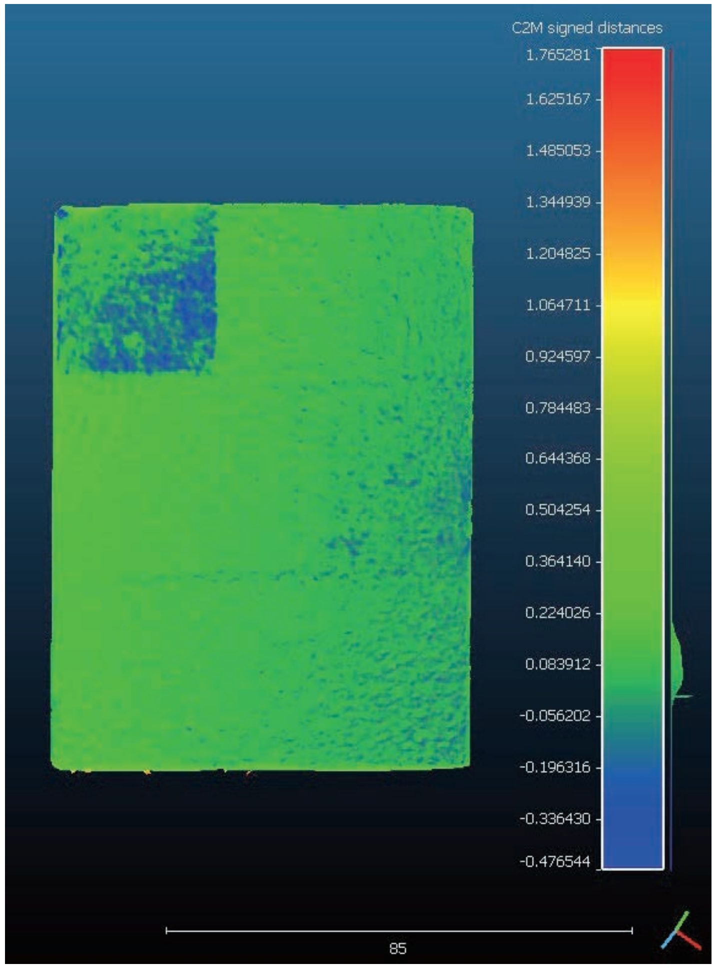


Figure 10. CloudCompare calculation shows profile reduction in dark blues. Test square 1 (top left) had reduction ranging from 0.18 mm to 0.37 mm while test square 2 had a range from 0.03 to 0.16.

There are many challenges associated with using a handheld scanning device on a complex surface. The serpentine and composite repair mortar samples contained many deep crevices or thin fissures that were difficult to fully capture. A compilation of multiple scans provided a more complete image. However, repeated scans generated too many point clouds that sometimes obscured the sharpness or “thickened” the digital model.

7.2.2 Weight Measurement

Introduction

Weight measurement is a verification method for the accuracy of profile change determined through digital model comparison discussed above. The samples were weighed before and after accelerated weathering. The amount of weight change should be similar to the degree of profile change if the digital model comparison is accurate.

Technology

Digital Scale

The samples are measured using Ohaus Adventurer, No. ARC120, digital scale to the hundredth gram.

Oven

The samples are dried in convection lab oven at approximately 60 degrees Celsius.

Methodology

The samples were dried in a convection lab oven at approximately 60 degrees for 48 hours before weighing according to procedures described under ASTM Standard C97 Section 7.1. They were weighed at the beginning and end of accelerated weathering but not at interim inspections. The limited schedule did not allow 48 hours of drying time at every inspection.

Accuracy

A few variables may affect the accuracy of the weights:

1. The samples were removed and remounted onto the brackets for the weatherometer four times during accelerated weathering. Some material loss occurred during this process; grains of material were found on the countertop where the installation took place.
2. Atmospheric pressure and humidity may influence the accuracy of the scale.
3. Moisture in samples that was not completely removed through drying.

7.3 COLOR CHANGE

7.3.1 Spectrophotometry

Introduction

Spectrophotometry is an instrumental measurement of spectral data for calculating the colors of objects. Spectral data, in this case, CIE L*a*b* readings, were measured using a spectrophotometer. The similarity of two colors were then calculated using a mathematical formula. This technique was used to compute quantitative color change of the samples after accelerated weathering.

Technology

Spectrophotometer and Software

Konica Minolta CM-2600d spectrophotometer is a handheld device used to evaluate color, relative gloss, and UV characteristics of samples. The device operates with its partner software, SpectraMagic NX, which produces graphs, color readings, and automatically calculates color differences between the “target” and “sample”.

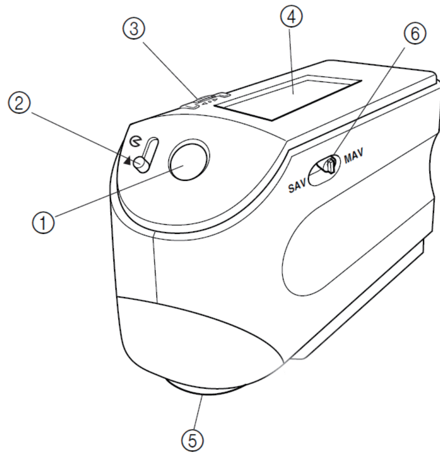
<table>
<tr><td rowspan="5">
</td><td>1. Viewfinder – used to check the position of the specimen. By sliding the lever, you can check whether the specimen is set correctly</td></tr>
<tr><td>2. Viewfinder lever – slide to open/close the viewfinder</td></tr>
<tr><td>3. Navigation wheel – turn to select an item or press to set the selected item</td></tr>
<tr><td>4. LCD display – displays the setting item and measured data</td></tr>
<tr><td>5. Specimen measuring port – port where the color measurement is taken</td></tr>
</table>

Table 5. Selected parts and functions of Konica Minolta CM-2600d spectrophotometer [42]

CIE L*a*b* Color Space

Color space, also called color model, or color system, is a mathematical model that describes the range of colors as three or four value sets. The value set points to a specific place on the coordinate designed by the system (Figure 11).[43]

[42] Konica Minolta, “Spectrophotometer CM-2600d/2500d Instruction Manual.”
[43] “Introduction to Color Space.”

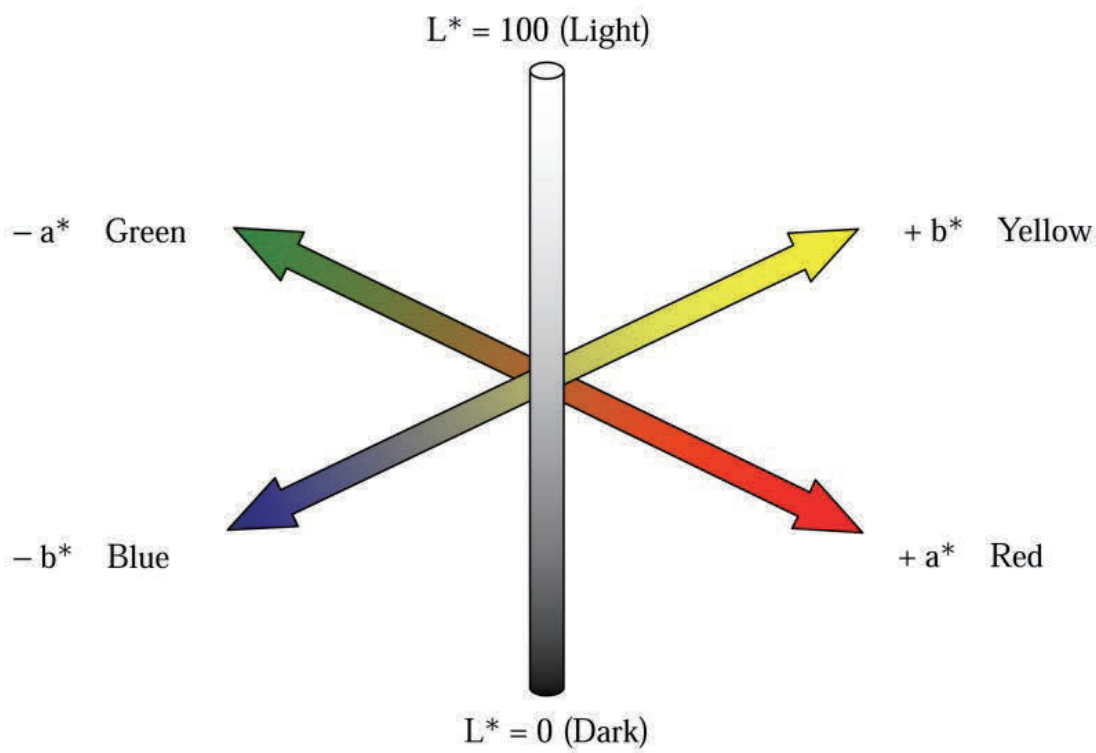


Figure 11. Three-dimensional CIE L*a*b* color space. (researchgate.net)[44]

The CIE L*a*b* color systems was used to express color measurement in this thesis. CIE L*a*b* system dedicates three values in their color space: L* range from 0 to 100, it represents lightness (pure white at 100) and darkness (pure black at 0), a* range from approximately -100 to 100, it indicates the amount of green (with negative number) and the amount of red (with positive number), b* describes the amount of blue (with negative number) and the amount of yellow (with positive number). 0 represents true gray in a* and b*.[45]

[44] "Three-Dimensional CIELAB Color Space (Adapted from Li et Al. 2005 [96])."
[45] Prah, 65

Methodology

Color readings were taken at the start of accelerated weathering (zero hour), then at the 216th hour, 432nd hour, 648th hour, and 864th hour. Color readings were taken at three locations for every sample. A template with circular cutouts indicating reading locations were created to ensure the measurements were taken at the same spot each time (Figure 12).

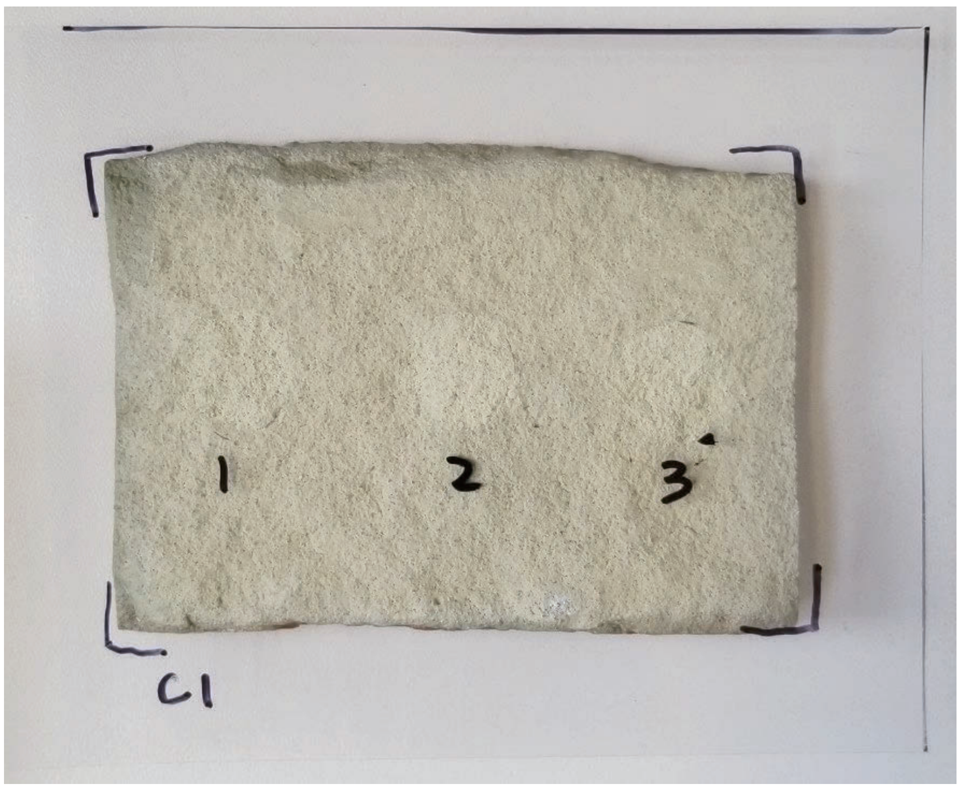


Figure 12. Test sample C1 with color reading location template.

The following table summarizes the testing parameter and device setting:

Item	**Description**
Types of Samples	4
Quantity of Samples for Each Type	3
Total Number of Samples	12
Number of Targets (sample locations) Each Sample	3
Measurement	Each measurement is an average of 5 readings
Overall Average	1 overall average from 3 measurements is given per sample
Angle of Observation	10°
Daylight Illuminant	D65
Measurement Output	SCI and SCE

Table 6. Testing parameter and device setting of spectrophotometry reading.

To take a measurement, the specimen measuring port was aligned, through the viewfinder, with the circular cutout of the template placed on top of the sample. The color reading and color change (delta E), displayed in graphs and numerical output, were generated by SpectraMagic NX. The overall average per sample after each test was charted, delta E was calculated by comparing each reading to the one taken at zero hour.

Accuracy

Measurements on uneven surfaces were challenging because the handheld spectrophotometer works best on flat surface. The spectrophotometer measures color by reflective light determined by the angle of reflection. Although a template was created to ensure the readings were taken at the same location, margins of errors occur because the device was held by the user's hand, thus it was not completely stationary. Additional challenge rose from the fact that the untreated serpentine, untreated Rainbow

Sandstone, and the composite repair mortar samples have a range of colors even in a small location. The color reading can change by as much as 3.00 units while measuring approximately the same location with a handheld device. Even though such margin of error exists, multiple readings nevertheless provided a representative, while not exact, average indicating color change.

7.3.2 Munsell

Introduction

Munsell is a color system often used by conservation professionals to assign a specific color to an item. This system name color by assigning a combination arranged in hue (purple, red-purple, red, yellow-red, yellow, green-yellow, green, blue-green, blue, blue-purple), value (0 = darkest, 10 = brightest), and chroma (0 = dull, 12 = intense). Munsell colors were assigned to each sample before and reevaluated after accelerated weathering. This process serves as another layer of verification of color change.

Methodology

Three Munsell colors were assigned to each sample, one for the dark tone, one for medium, and one for light, except the stained Rainbow Sandstone samples which received a single assigned color because they had a monochromatic coating. Each color was selected based on ASTM D1535 Standard Practice for Specifying Color by Munsell System.

Accuracy

Specifying Munsell colors to an object is subjective to the observer. There are many variables which may affect the judgment. People have different innate color perception, some can distinguish miniscule color variance while others cannot. While both color readings were taken at the same location approximately the same time of the day, slight difference in lighting can affect the perception of color, a phenomenon known as metamerism. In addition, the complex color variation within a small area of the serpentine and Rainbow Sandstone samples made them particularly challenging.

Another important variable is bias. The observer may subconsciously select a certain color. The physical state of the observer may also affect his or her judgment. Fatigue can dull one's senses.

7.3.3 Control Samples

Introduction

One sample of each type was left in a climate-controlled environment for the duration of accelerated weathering. These unweathered samples were compared to the weathered samples to establish a qualitative visualization of color change. They were observed by the author and documented using a digital single-lens reflex camera.

Methodology

The composite repair mortar control and stained stone control were created using the same method as the test samples. The Rainbow Sandstone control and serpentine control were cut from the same batch of stones as the test samples. It should be mentioned that the serpentine stones vary in color, even on different surfaces of the same stone. In this case it did not provide a good reference for color change. The unweathered control samples and their counterparts were placed side by side and documented using a DSLR camera. White balance was corrected using a gray card in Photoshop CC. No other color correction or manipulations were made to the photographs.

Accuracy

Lighting condition during the photoshoot, the lens of the camera, the monitor which the photographs are displayed or the printer if they were printed all have an unknown amount of influence over the true color of the objects. This process serves as a qualitative method of visualizing color change. Visual assessment with the unaided eye is subjective and dependent upon the individual's ability to perceive color.

7.4 WATER VAPOR TRANSMISSION

Introduction

Water vapor transmission test (water method) examines the vapor permeability of a material. Vapor permeability refers to the

> …time rate of water vapor transmission through unit area of flat material of unit thickness induced by unit vapor pressure difference between two specific surfaces, under specific temperature and humidity conditions."[46]

Water vapor transfers from one side of the material to another through voids or pores, a property known as permeability or permeance. Permeability affects how quickly a

[46] American Society for Testing and Materials, "ASTM E96 Standard Test Method for Water Vapor Transmission of Materils," 96.

material absorbs moisture or dries. In the case of this thesis, this quality is important because composite repair mortar and potassium silicate stains are both surface treatments. They must not adversely affect the natural vapor permeability of their host masonry. If their water vapor transmission rates are significantly lower than serpentine or Rainbow Sandstone, they may trap moisture inside their host masonry.

Technology

Desiccator

A desiccator is a rectangular chamber made of plexiglass containing desiccant. The chamber is sealed with three latches. It creates a controlled, dry environment to store the samples during the water vapor transmission test.

Methodology

Five types of samples in cohorts of three were tested. The types were: Rainbow Sandstone disks, stained Rainbow Sandstone disks, serpentine disks, composite repair mortar disks, and half composite repair mortar and half serpentine disks. Sample preparation method is described in Section 6.5.

The test dishes used were 250 ml plastic disposable beakers, filled with approximately 100 milliliters of deionized water. The sample disks were wrapped with a few layers of electrical tape on the curved surface until they fit tightly in the openings of the beakers. The disks were then sealed to the beaker by pouring liquid paraffin around the rim.

The test was performed according to the procedure for water method in ASTM E 96 Standard Test for Water Vapor Transmission of Materials. The test assemblies were placed in desiccators until the time of weighing. Weights were taken initially (zero hour) then at elapsed times of 30, and 60 minutes, 24 hours, 48 hours, 72 hours, 120 hours, 168 hours, and 216 hours.

8.0 OBSERVATIONS

The following observations of profile and color change were made through comparing the samples after 864 hours of accelerated weathering to their initial condition at zero hour. Water vapor transmission testing was conducted on a different group of samples which did not undergo accelerated weathering.

8.1 PROFILE AND VOLUME CHANGE

8.1.1 3D Scanning/CloudCompare

How to read the results

Figure 13 shows the results of point cloud comparsion analyzed with CloudCompare. The model of the sample is located on the left and the elevation meter on the right. The colors on the elevation meter correspond to the measured elevation in millimeters on the left side of the meter. A small scalar field indicates the bulk range of measurements with a small spike signaling the a large number of readings on that particular elevation, this is on the right side of the meter. The color-coordinated elevation is reflected on the model of the sample, similar to a topography map.

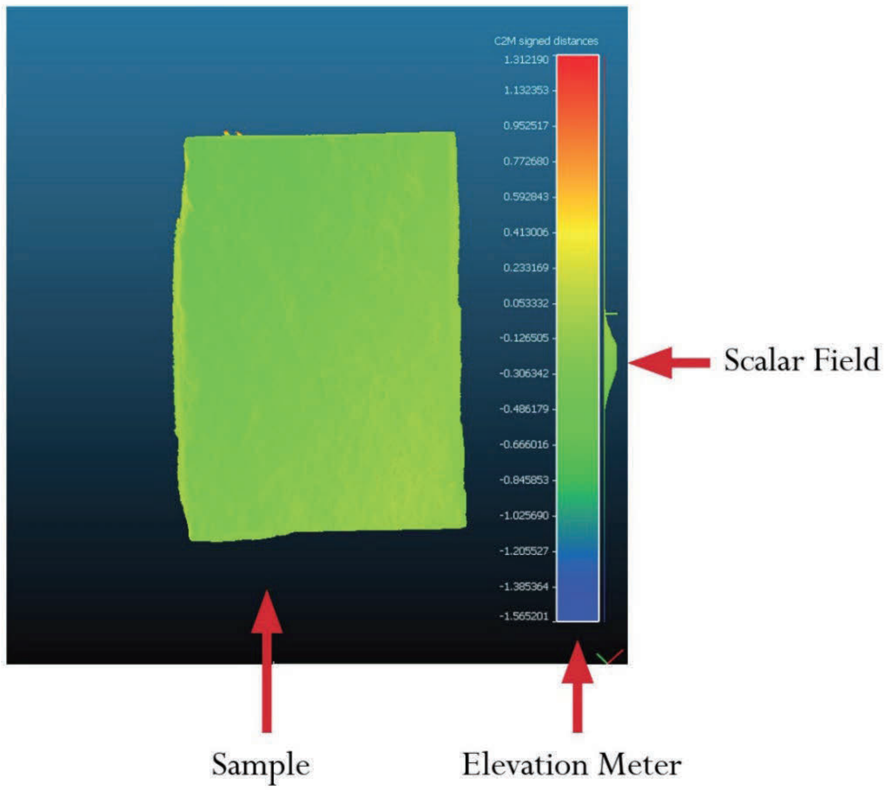


Figure 13. Results of a CloudCompare analysis.

The results show the lower right corner of the sample increased slightly in elevation, by approximately 0.05 millimeter. Elevation gain is unexpected and may indicate unanticipated interactions between the materials and the weathering conditions, experimental error, scanning variance, or some combination of these. For example, one possible source of gain could be dense point clouds from repeated scans. Another explanation may be that the sample absorbed moisture or salts were formed during accelerated weathering from chemicals in the tap water used for spray. The scan data alone is not enough to conclude the reason for elevation gain, and more experimentation would be necessary to fully understand possible sources of gain. Overall, the range fell between -0.48 millimeters to 0.04 millimeters. Most of the volume loss occurred on the top of the sample, measuring approximately -0.40 millimeter to -0.30 millimeter.

It is important to note that each elevation meter and their color assignment is unique to the sample, meaning the same shade of green will indicate different elevation for each sample. As shown below in the results for samples C1, C2, and C3, although they appear to be in similar shades of green, it does not mean they have the exact same change in elevation.

Position of the samples in weatherometer

Figure 14. Positions of sample brackets at zero hour. (Photograph by author, 2019)

Each bracket held four samples. Interim inspections occurred at 216 hours, 432 hours, and 648 hours. After each inspection, the brackets were shifted one position to the right, meaning the S1, R1, C1, and L1 would be in the position of S3, R3, C3, and L3 during 216 to 432 hours. The positions of samples on the brackets did not change.

Results

Stained Rainbow Sandstone Samples

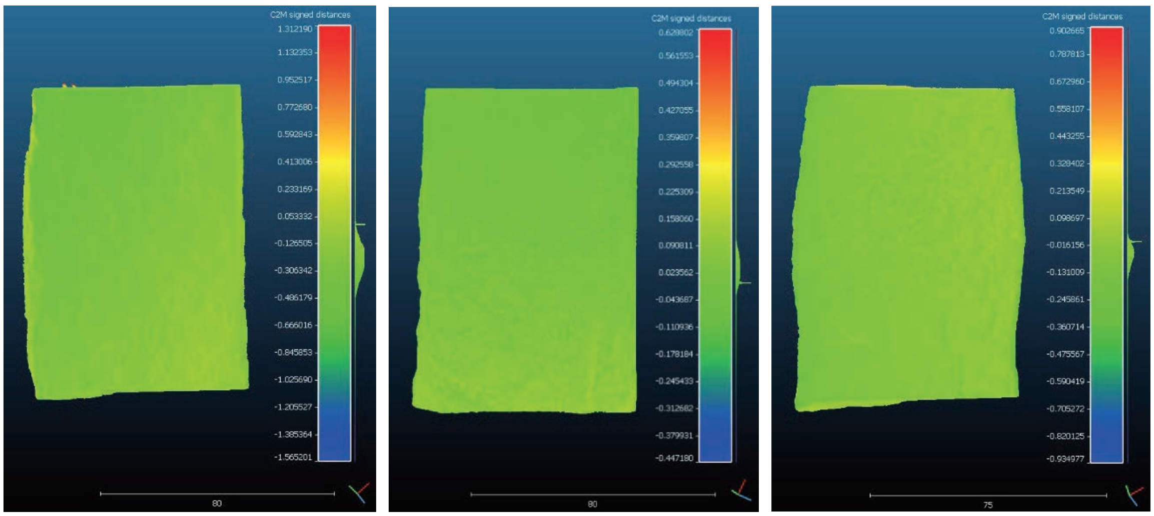


Figure 15. Results of profile change, stained Rainbow Sandstone samples, from left, C1, C2, C3. Although each model is displayed in a similar shade of green, it does not indicate the same elevation.

Sample No.	Bulk Range	Concentration of Loss	Conclusion
C1	-0.48 to 0.05	Top left	Small profile loss averaging -0.12 to -0.50
C2	-0.03 to 0.10	No significant loss detected	No significant change
C3	-0.14 to 0.05	Evenly throughout sample	Minimal loss no more than -0.14 mm

Table 7. Summary of stained Rainbow Sandstone samples test result.

Three Rainbow Sandstone samples, C1, C2, and C3, were placed in the bottom right position of each bracket in the weatherometer. All three samples showed insignificant profile loss. However, they did not have the same pattern of deterioration, possibly a result of different placement in the weatherometer.

Composite Repair Mortar Samples

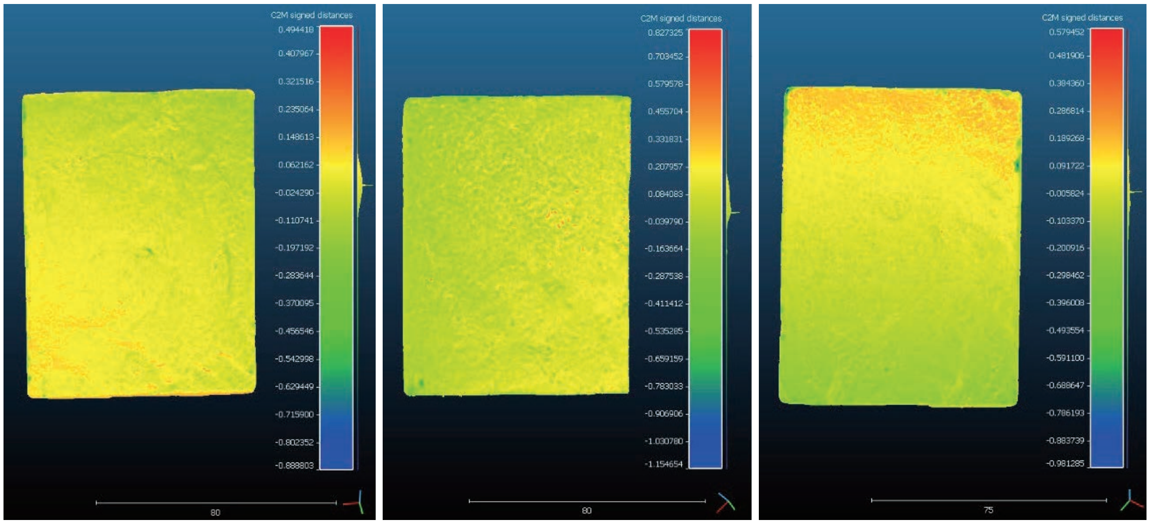


Figure 16. Results of profile change, composite repair mortar samples, from left, L1, L2, L3.

Sample No.	Bulk Range	Concentration of Loss	Conclusion
L1	-0.10 to 0.09	Top	Narrow range of measurement showing very insignificant change
L2	-0.05 to 0.17	No significant loss	Narrow range of measurement showing very insignificant change
L3	-0.18 to 0.16	Bottom	Slightly wider range of measurement showing gain on top and loss on the bottom

Table 8. Summary of composite repair mortar samples test result.

The composite repair mortar samples, L1, L2, and L3, were placed in the bottom left position on the bracket in the weatherometer. All three composite repair samples showed very insignificant profile loss. In fact, they appeared to have a slight increase in elevation. This may be caused by the aforementioned dense cloudpoints accumulated during the scans since these samples had a more complex surface texture compared to the sandstone samples. Another explanation would be the samples had slightly expanded from moisture gain or salt formation.

Untreated Rainbow Sandstone Samples

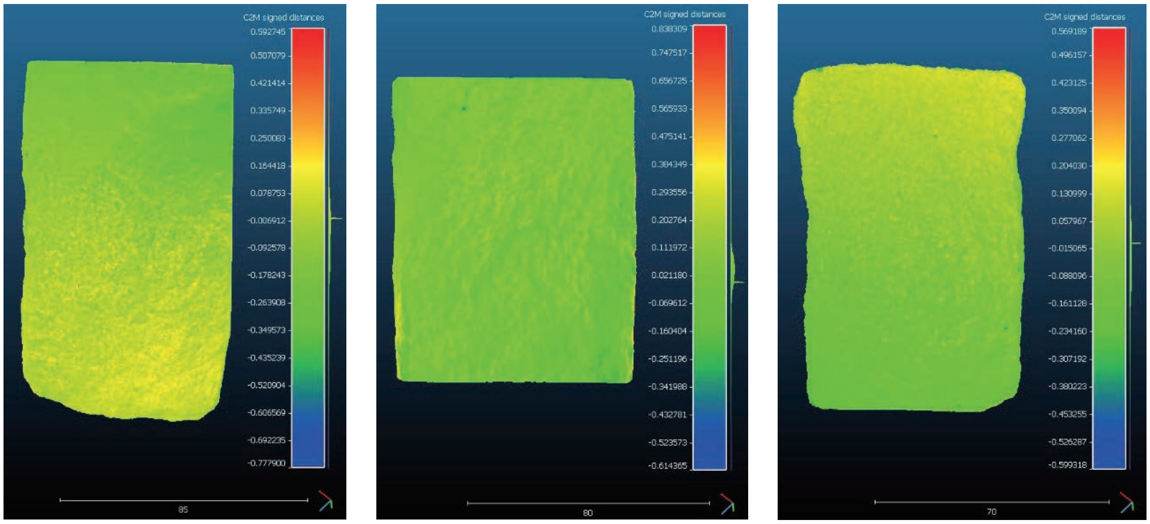


Figure 17. Results of profile change, untreated Rainbow Sandstone samples, from left R1, R2, R3.

Sample No.	Bulk Range	Concentration of Loss	Conclusion
R1	-0.20 to 0.09	Top right corner	Very small overall profile loss, almost no gain
R2	-0.05 to 0.13	Bottom right corner	Bulk of measurements fall between 0.08mm to -0.01mm, no significant change detected
R3	-0.16 to 0.11	Bottom	Large range of measurements. Small profile loss concentrated at the bottom of the sample

Table 9. Summary of untreated Rainbow Sandstone samples test result.

Overall, the three samples showed insignificant profile loss. However, there was no consistency in pattern. R1 displayed loss on top and gain at the bottom where R3 displayed the opposite. R2 was mostly consistant throughout the sample except some deeper dents along the lower right side of the sample. The inconsistancy could be a result of where they were placed in the weatherometer, where a certain location was directly in front of the spray nozzle. Neither stained nor untreated Rainbow Sandstone samples displayed significant change, however, the stained samples have weathered more evenly while the untreated samples showed localized weathering. This may be due to the crystallization of the potassium silicate network, consolidating the samples.

Serpentine

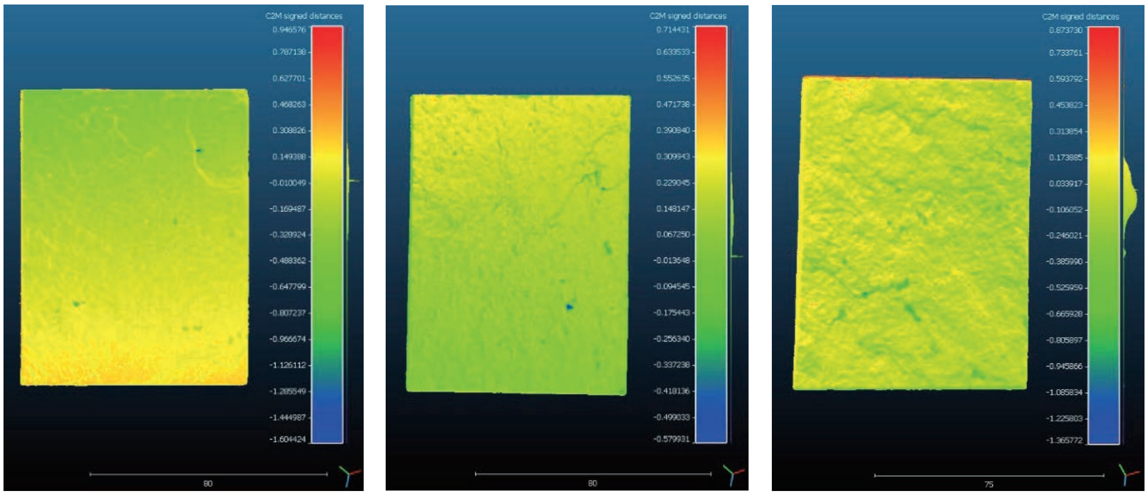


Figure 18. Results of profile change, salvaged serpentine samples, from left, S1, S2, S3.

Sampl e No.	Bulk Range	Concentration of Loss	Conclusion
S1	-0.35 to 0.21	Top	Large range of measurements showing both loss and gain in profile
S2	-0.01 to 0.27	No significant loss	Gained elevation overall
S3	-0.37 to 0.17	Right half	Very small profile loss

Table 10. Summary of untreated Rainbow Sandstone samples test result.

Three serpentine samples, S1, S2, and S3, were placed in the top left position of each bracket in the weatherometer. The cohort of serpentine samples also displayed inconsistant localized weathering. This is somewhat expected since the stone tends to have localized weak spots along veins or cleavage planes. However, they experienced roughly 0.10 to 0.20 millimeter more profile loss compared to the sandstone samples.

Summary

	Highest Elevation Loss	**Highest Elevation Gain**	**Largest Area Loss**	**Smallest Area Loss**	**Most Consisten t**	**Most Inconsistent**
Sample	Serpentine	Serpentine	Stained Sandstone	Composite Repair Mortar	Composite Repair Mortar	Serpentine

Table 11. A summary of results of all samples.[47]

Serpentine displayed the most change after accelerated weathering. They also had the largest range in elevation and the most inconsistent wear patterns. This is not surprising since case studies have shown that serpentine can display varied degrees of deterioration between stones. The relative high rise in elevation may be a demonstration of serpentine's absorptive qualities or an error due to overlapping point clouds because of samples' complex surface. The stained and unstained Rainbow Sandstone samples displayed the largest area loss. This demonstrates the sandstone is likely susceptible to erosion, therefore, any topical coating will have a reduced service life. Composite repair mortar samples were the most durable out of all. These samples displayed the least amount of elevation gain or loss, had the smallest area loss, and showed the most consistent results.

[47] Method of Calculation:
Lowest Elevation Loss: Average of elevation below zero millimeter in bulk range
Highest Elevation Gain: Average of elevation above zero millimeter in bulk range
Largest Area Loss: Estimated average of area below zero millimeter
Smallest Area Loss: Estimated average of area above zero millimeter
Most Consistent: All three samples in a cohort showing similar results
Most Inconsistent: Three samples in a cohort showing dissimilar results

8.1.2 Weight Change

The initial post-weathering measurements showed all samples except C1, C2, and C3 had gained weight. This result was perplexing. The samples were placed back into the oven for a longer period of drying, approximately 120 hours, to remove trapped moisture. The following table shows the weight of the samples:

Sample No.	Pre-Accelerated Weathering Weight (g)	Post-Accelerated Weathering Weight, 48 hours of drying (g)	Post-Accelerated Weathering Weight, 120 hours of drying (g)	Weight change, 120 hours of drying (g)
C1	209.61	209.48	209.46	-0.15
C2	235.45	235.40	235.38	-0.07
C3	193.82	193.79	193.76	-0.06
L1	169.43	171.91	171.87	2.44
L2	170.78	173.44	173.42	2.64
L3	149.27	151.92	151.83	2.56
R1	296.21	296.31	296.29	0.08
R2	256.52	256.62	256.62	0.1
R3	171.56	171.62	171.60	0.04
S1	225.69	226.29	226.23	0.54
S2	220.08	220.56	220.46	0.38
S3	227.02	227.55	227.54	0.52

Table 12. Sample weights

The sample weights decreased after 120 hours of drying compared to 48 hours, although not significantly. They still weighed more than they did before accelerated weathering. Although an exact number could not be calculated, the samples weights generally correspond to the results from the digital model comparison. Both analyses indicated the composite repair mortar samples had the largest amount of gain and the stained Rainbow Sandstone samples had the largest area loss, indicated by weight loss. The amount of weight gain was consistent in each cohort, suggesting a common phenomenon was behind it. The relatively large gain of composite repair mortar samples is vexing. Aside from previously stated potential errors, this could be the result of contaminates from the tap water used during accelerated weathering. Lithomex is less dense than the tested stones and is therefore more likely to allow contaminates to transfer into it. However, the mass and volume gain cannot be accurately explained without further testing such as petrographic analysis or scanning electron microscopy.

8.2 COLOR CHANGE

8.2.1 Spectrophotometry

The CIE L*a*b* values were calculated by averaging the three-color reading locations on each sample. The group average (i.e. Stained Sandstone Average) is the average of the cohorts. The following chart summarizes the observations:

Sample No.	Pre-Accelerated Weathering			864 Hours			
	L*	a*	b*	dE*	dL*	da*	db*
C1	48.84	-1.91	16.28	16.23	16.19	0.51	-1.10
C2	46.42	-0.67	13.81	16.06	16.01	0.53	-0.92
C3	44.06	-0.80	14.14	12.31	12.26	0.65	-0.89
Stained Sandstone Average	46.44	-1.13	14.74	14.87	14.82	0.56	-0.97
L1	44.99	-1.27	12.00	2.64	2.46	-0.33	0.79
L2	61.04	1.76	13.47	3.61	1.83	-0.13	-0.21
L3	56.85	1.66	14.51	2.01	0.58	-0.08	1.08
Composite Repair Mortar Average	54.29	0.72	13.33	2.75	1.62	-0.18	0.56
R1	60.90	1.47	12.54	4.77	0.73	0.07	2.41
R2	42.02	-0.26	14.65	5.22	0.10	0.29	4.13
R3	42.50	-1.16	15.30	3.47	-1.25	0.30	2.67
Untreated Rainbow Sandstone Average	48.47	0.02	14.17	4.49	-0.14	0.22	3.07
S1	44.40	-2.29	15.13	3.19	0.60	-2.19	1.21
S2	-1.31	15.16	9.41	2.75	0.32	-1.26	1.14
S3	0.25	14.91	6.31	3.73	-2.44	-1.22	1.29
Serpentine Average	14.44	9.26	10.29	3.22	-0.50	-1.56	1.21

Table 13. Summary of spectrophotometry results.

Stained sandstone experienced the most color change with a delta E of 14.87, with 14.82 from delta L, meaning the samples became lighter while the green-red and blue–yellow spectrum remained basically unaltered. Composite repair mortar, untreated Rainbow Sandstone, and serpentine samples showed delta E values of 2.75, 4.49, and 3.22, respectively. These were relatively small changes and can be difficult to perceive with the naked eye. The full spectrophotometry observation can be found in Appendix D – Spectrophotometry Results.

8.2.2 Color Change Evaluated through Munsell System

The following table summarizes the author's observation of Munsell color matching:

Sample No.	Pre weathering	Post Weathering	Color Change Y/N
C1	10 Y 7/2	10Y 8/2	Y
C2	10 Y 7/2	2.5GY 7/2	Y
C3	10 Y 7/2	10Y 7/2	N
L1 D	5GY 4/1	5GY 5/2	Y
L1 M	10Y 5/1	5GY 6/1	Y
L1 L	10Y 6/2	10Y 6/2	N
L2 D	5GY 4/1	5G 5/1	Y
L2 M	10Y 5/1	5GY 5/1	Y
L2 L	10Y 6/2	10Y 6/2	N
L3 D	5GY 4/1	5G 5/1	Y
L3 M	10Y 5/1	5GY 5/1	Y
L3 L	10Y 6/2	10Y 6/2	N
R1 D	7.5YR 6/8	7.5YR 6/6	Y
R1 M	10YR 7/6	10YR 7/4	Y
R1 L	2.5Y 8/2	2.5Y 8/1	Y
R2 D	7.5YR 6/8	7.5YR 6/6	Y
R2 M	10YR 7/6	2.5Y 7/2	Y
R2 L	2.5Y 8/2	2.5Y 8/1	Y
R3 D	7.5YR 6/8	7.5YR 6/6	Y

R3 M	10YR 7/6	2.5Y 7/2	Y
R3 L	2.5Y 8/2	2.5Y 8/1	Y
S1 D	10Y 4/2	5GY 4/2	Y
S1 M	10Y 6/2	10Y 5/2	Y
S1 L	5Y 5/2	5GY 6/2	Y
S2 D	10Y 4/2	5GY 4/2	Y
S2 M	10Y 6/2	10Y 5/2	Y
S2 L	5Y 5/2	5GY 6/2	Y
S3 D	5GY 4/2	5GY 4/2	N
S3 M	5GY 6/4	10Y 6/4	Y
S3 L	10Y 6/4	10Y 7/6	Y

Table 14. Summary of Munsell color assignments.

The author observed that most samples showed various degrees of color change post accelerated weathering. However, color matching to stone was extremely difficult given its complex color variation and the observation was largely subjective. In this case, this method may not be the best evaluation method of color change.

8.2.3 Color Comparison with Control Samples

Visual color comparison and photo-documentation serves as an additional qualitative observation to verify the findings of instrumental analysis. The following observations were made acknowledging the issues with color perception and bias discussed under Section 7.3. In terms of documentation and presentation, many factors, such as lighting, lens, display monitor or printer, will influence the true colors of the samples. Nevertheless, the author believes general observations can be made using this method.

Stained Rainbow Sandstone

Figure 19. Stained Sandstone Samples, C1, C2, C3, taken prior to accelerated weathering. (Photograph by author, 2019)

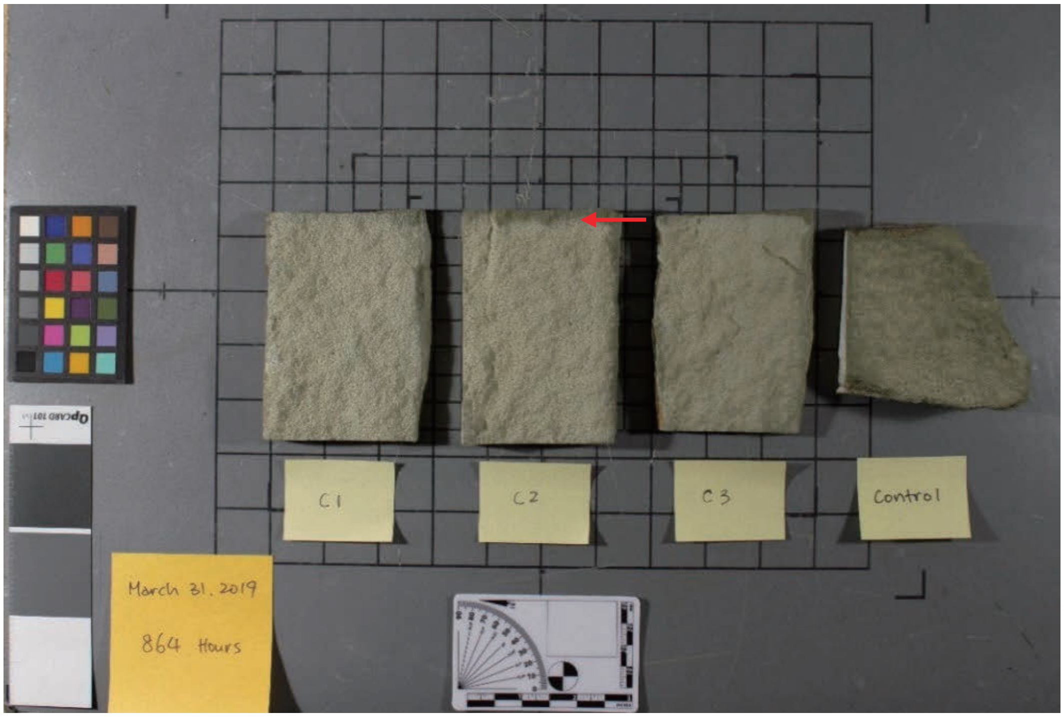


Figure 20. Stained Rainbow Sandstone Samples, C1, C2, C3, and unweathered Control, taken post accelerated weathering. (Photograph by author, 2019)

The samples visibly lightened and the color became more uniform while the pre-weathering samples displayed light and dark spots. This observation can further be confirmed with the visible difference between the protected edge (red arrow) created by the bracket and the area exposed to UV and spray.

Composite Repair Mortar

Figure 21. Composite repair mortar samples, L1, L2, L3, taken prior to accelerated weathering. (Photograph by author, 2019)

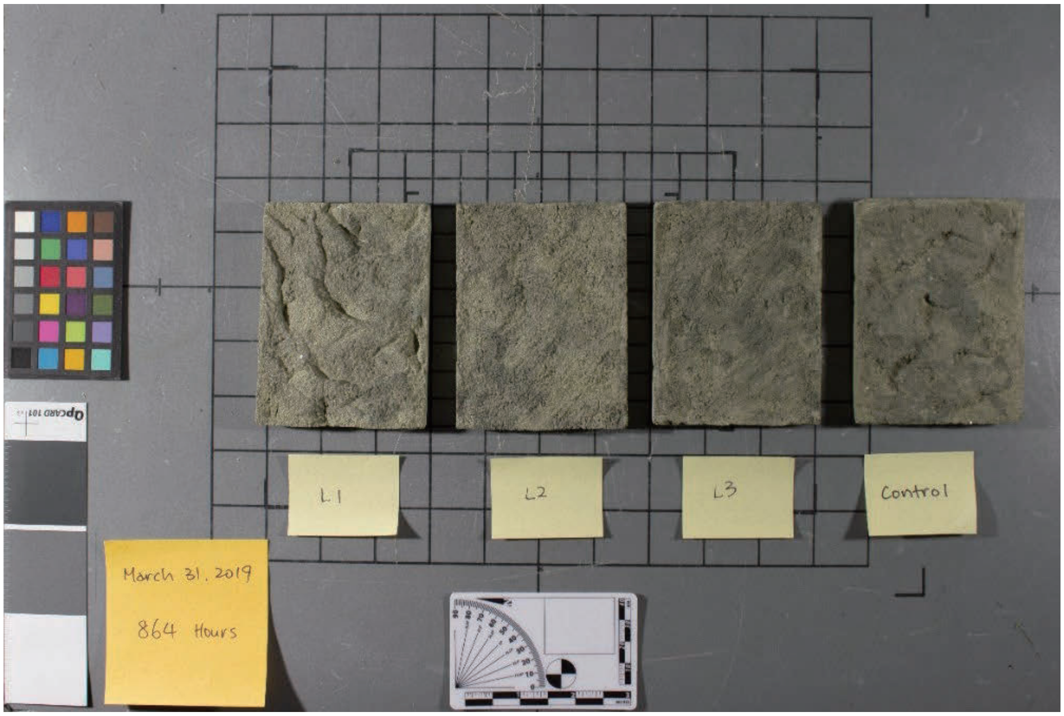


Figure 22. Composite repair mortar samples, L1, L2, L3, and unweathered Control, taken post accelerated weathering. (Photograph by author, 2019)

The lighting appears to be brighter in the pre-weathering photograph. Visual comparison did not find any distinguishable color difference between weathered samples and Control. This observation confirms the finding of spectrophotometry.

Untreated Rainbow Sandstone

Figure 23. Untreated Rainbow Sandstone samples R1, R2, R3, taken prior to accelerated weathering. (Photograph by auther, 2019)

Figure 24. Untreated Rainbow Sandstone samples R1, R2, R3, and unweathered Control, taken post accelerated weathering. (Photograph by auther, 2019)

The colors of the post-weathering samples appear to be slightly more saturated, particularly R2 and R3. This correspond to the result of the instrumental analysis, which suggested the samples darken slightly and gained a value of 3.07 in the yellow spectrum.

Serpentine

Figure 25. Serpentine samples, S1, S2, and S3, taken prior to accelerated weathering. (Photograph by author, 2019)

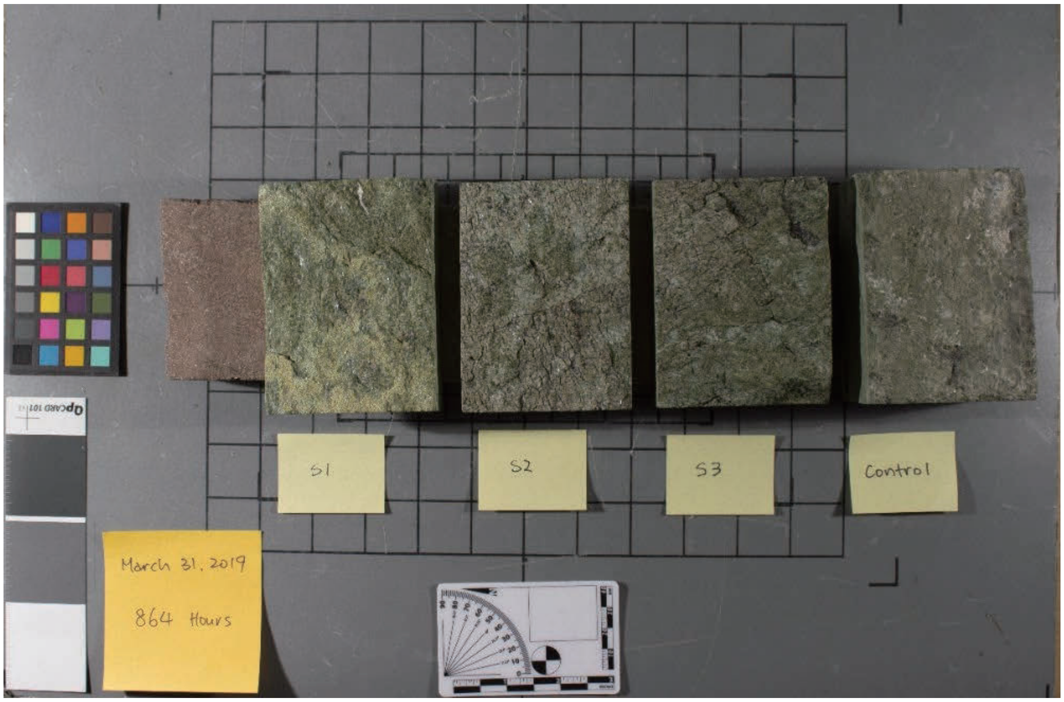


Figure 26. Serpentine samples, S1, S2, S3, and unweathered Control, taken post accelerated weathering. (Photograph by author, 2019)

Note the sample placement of S1 and S3 should be reversed in Figure 26. No distinguishable color difference between pre and post weathering samples. The result collaborates with the instrumental analysis.

8.2.4 Summary

Figure 27. All samples, from top left: C1, C2, C3, L1, L2, L3, bottom left: R1, R2, R3, S1, S2, S3 taken prior to accelerated weathering. (Photograph by author, 2019)

Figure 28. All samples, from top left: C1, C2, C3, L1, L2, L3, bottom left: R1, R2, R3, S1, S2, S3 taken post accelerated weathering. (Photograph by author, 2019)

Photo-documentation confirmed the findings of spectrophotometry. With a delta E of 14.87 in CIE L*a*b*, the stained sandstone samples were the only ones that display distinguishable color change to the naked eye. The lightening of color may be a sign of erosion for limited depth of penetration. A study by O.Buj and J. Gisbert, geologists of the Universidad de Zaragoza, Spain, suggested potassium silicate consolidant showed irregular accumulation at three millimeters below surface and a sharp decline in amount at five millimeters on a sandstone substrate.[48] The color change may also indicate the pigments used in the potassium silicate stain were susceptable to UV damage. Futher testing will be necessary to confirm these hypotheses.

[48] Buj and Gisbert, "Evaluation of Three Consolidants on Miocene Sandstone from the Ebro Basin." 6.

8.3 WATER VAPOR TRANSMISSION

The test assemblies were weighted at elapsed time of .5, 1, 24, 48, 72, 120, 168, and 216 hours. All samples showed weight gain of no more than .10 gram during the first 72 hours. This data was discarded. Weights decreased at 120 hours. The two points used to calculate water vapor transmission were 72 hours and 216 hours. Detailed information can be found in Appendix E – Water Vapor Transmission Results.

Sample	Slope	WVT (g/(h/m²))	Avg Temp (°C)	S (mmHG)	R1 - R2	Permeance (perms)
Serpentine	1.05E-02	2.74	21.34	19.05	0.22	0.64
Untreated Rainbow Sandstone	1.90E-03	0.50	21.34	19.05	0.22	0.12
Stained Rainbow Sandstone	1.50E-03	0.39	21.34	19.05	0.22	0.09
Composite Repair Mortar	2.82E-03	0.74	21.34	19.05	0.22	0.17
Half Serpentine/ Mortar	6.99E-03	1.82	21.34	19.05	0.22	0.43

Table 15. Summary of result, water vapor transmission test.

The serpentine stone had a much higher water vapor transmission rate and permeance, with almost four times higher than that of composite repair mortar. The WVT and permeance lowered by 33 percent when mortar was applied to serpentine. The author did not find any industrial standard regarding the acceptable range of WVT and permeance between a substrate and its composite repair patching. Further testing and monitoring will be necessary to determine if the composite repair mortar is suitable for patching serpentine.

The stained Rainbow Sandstone also had lower WVT and permeance but by negligible amount. The result suggested the stain is not likely to impact the natural vapor and water permeability of the stone. The composite repair mortar would be a suitable patching material for Rainbow Sandstone since it had higher WVT and permeance.

9.0 CASE STUDIES

9.1 CASE STUDY 1: COLLEGE HALL, UNIVERSITY OF PENNSYLVANIA, PENNSYLVANIA

College Hall case study focuses on a cast-stone, also called pre-cast stone or cast-concrete[49], replacement campaign for deteriorated serpentine. The project was carried out in five phases from 1990 to 2000. College Hall was selected as the primary case study because of its diverse repair methods, the amount of available archival materials, and the accessibility of interviewees. The discussion and evaluation included methodology, durability, compatibility, and overall success of the project. A list of interviewees of this case study can be found in Appendix F – College Hall Case Study.

9.1.1 Background

Building History

College Hall is a historically significant building; the first structure constructed on the West Philadelphia campus of the University of Pennsylvania.[50] The serpentine building, in Collegial Gothic style, is an iconic structure sitting behind the statue of founder Benjamin Franklin. Located on the main thoroughfare of Locust Walk and Woodland Walk, the building houses the Office of Undergraduate Admissions, Department of History, School of Arts and Sciences, and Offices of the President and Provost.

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[49] Different names were used in varies reports generated for the project
[50] "College Hall."

Built in 1871, the six-story masonry structure was designed by Thomas Webb Richards, who trained under noted Philadelphia architect Samuel Sloan and later became a professor in the School of Architecture at Penn.[51] His design embraced the poly-texture and polychromatic taste of Victorian aesthetics by juxtaposing bands and details of brown and yellow sandstone, and granite against a serpentine clad wall.[52] College Hall has been continuously occupied since its completion. The building draws attention from visitors and is greatly treasured by its occupants.[53]

Construction

The building specification created by T.W. Richards called for all exterior walls above the basement to be faced with "Serpentine Marble." The stones should be "large and flat, well bonded and bedded and hammered down solid, and in no case to be built more than 10 feet high until the mortar is well set." [54] The original wall assembly consisted of three parts. The interior was constructed with weak rubble masonry filler with small schist stones at the very centered (approximately 12 inches), mortared with an unstable clay-rich mix with little binder. The core was flanked by a face stone veneer on the exterior and hard burned brick on the interior. The face stones were jagged in the back with different thickness averaging two to six inches.[55] The face stone was laid and

[51] "Thomas Webb Richards | University Archives and Records Center."
[52] "College Hall"
[53] Knapp and Knapp, College Hall Interview with Masonry Contractor Vern Knapp and Jennifer Knapp.
[54] Richards, "Specification for the Construction of a College Building for the University of Pennsylvania on Locust St. between 34th & 36th Sts."
[55] Thomas & Newswanger Architects, "College Hall Masonry Probes."

mortared, with a thicker key extending to the back-up masonry at regular intervals but did not bond well with the inner wythe. No other anchoring system was in place.

Condition of Serpentine

Victorian color theory and the university's desire to represent its suburban setting was behind the selection of serpentine as its primary façade material. Serpentine was mistakenly identified as a stable, "non-absorptive" and "unaffected by gaseous atmosphere" in the 1890s.[56] However, the building experienced significant deterioration within a decade of its construction. The feasibility study conducted by Thomas & Newswanger Architects et al. suggested the rise of industrial pollutants had significant adverse effect on the weatherability of serpentine.[57]

College Hall originally had two towers on the east and west elevations. Studies in the 1900s determined these towers threatened the structural integrity of the rest of the building. The stones had deteriorated, and their mortar joints washed out by water due to extra exposure to weather from their position.[58] In 1913, the condition of the stone was so bad that a contractor repairing exterior found it "crumbled to dust at the least touch, block after block had to be removed and replaced by new ones." The worst

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[56] Meierding, "Weathering of Serpentine Stone Buildings in the Philadelphia, Pennsylvania, Region."
[57] Thomas & Newswanger Architects et al., "College Hall Feasability Study MTA Project 8610" 5 – 6.
[58] Thomas & Newswanger Architects et al. 43 – 44

portion was located in the east tower.[59] The west tower was demolished in 1908, followed by the east in 1929. [60]

The exterior of College Hall was covered in ivy in the 1930s and it has contributed to the stone's deterioration. Ivy was "pulling the serpentine-stone building apart block by block." After the ivy was removed, the condition of the building was described as "a big bush" by local newspaper.[61]

Early 20th Century Repairs

Despite the efforts of early repairs and demolition of the towers, water infiltration through damaged building envelope continued to plague College Hall. Water washed the loosely adhered mortar out of the rubble walls, leading to settlement and damages to the interiors.[62] Numerous sources indicate an almost continuous repair work on the exterior from 1880s. Two main methods were used to repair the damaged stones in the early 20th century: cement stucco patching and cast-stone replacement.

Cement Stucco Patches

A cementitious mixture of pigmented stucco was applied to the stone after removal of deteriorated sections. A mortar analysis performed as part of the feasibility study for Thomas & Newswanger Architects in 1986 examined samples from the east and west elevations, the results showed two different mixtures were applied.

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[59] "Stone of College Hall Crumbles with Old Age."
[60] Thomas & Newswanger Architects et al. 5
[61] "Building Melting."
[62] Ibid.

Mixture 1: The sample taken from east elevation displayed a pebble surface and had a calcium carbonate content of 7.50%, with solubles at 32.50%, and sand at 60%. The Light Grayish Olive Munsell colored stucco was color simulated with pigments rather than crushed serpentine. The chemical composition and hardness point to a Portland cement binder. Historical records dated the sample to repair campaigns between 1940 to 1960.

Mixture 2: The sample taken from west elevation displayed lumps of lime, it had a higher calcium carbonate content of 15.55%, with solubles at 38.45%, and sand at 46%. The Greenish Gray Munsell colored stucco was also tinted with pigments. The chemical composition and hardness point to a mix of lime and Portland cement binder. Records dated the sample to post-1980 repair campaigns.

A third mix containing crushed serpentine, not analyzed in this mortar analysis, was also used. This stucco patch has yellowed overtime due to the oxidation of the serpentine aggregates.[63] Even though the patching itself have weathered well, damage was introduced to the serpentine because the dense Portland cement prevents moisture from evaporating through the mortar, thus trapping moisture inside the stone.[64] Much of the cement stucco has since detached and have been repatched with a bright green stucco, a modern cement based mix applied post 2005 as a temporary solution while the west half of the building awaits the final phase of cast-stone replacement.

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[63] Thomas, College Hall Case Study Interview with Architect Marianna Thomas; Doukakis and Wentz, College Hall Interview with Keast and Hood Structural Engineers Constantine (Dean) Doukakis and Brian D. Wentz.
[64] "College Hall Restoration Exit Study. University of Pennsylvania Philadelphia, PA."

Cast-stone Replacement

In this type of repair, deteriorated serpentine was removed entirely and replaced with cast-stone veneer supported by constructed brick infill on consolidated rubble masonry. The cast-stone was made with a surface layer of crushed serpentine, acting as a color modifier. The body consisted of a cementitious binder mixed with sand and quartz aggregate.[65] This was done on College Hall at the base of one of the demolished towers in 1929 as well as the west elevation of Logan Hall, a building of similar design with serpentine face stones.

9.1.2 1986 – 2000 Cast-stone Replacement Campaign

A large-scale renovation campaign designed by Thomas & Newswanger Architects spanned 14 years from pre-design to completion. The scope of this five-phased project included the repair of exterior building envelopes, roofing, penetrations such as windows and doors, structural systems, interior finishes, and other interior modifications. The multi-phase project began with pre-design around 1986, the construction spanned a period of ten years from 1990 to 2000. Thomas & Newswanger Architect, main correspondent for the project, was hired through a competitive bidding process in 1986.[66] The project team was made up of numerous specialty consultants and contractors. Relevant information to this thesis includes the work performed by structural engineers from Keast & Hood, cast-stone manufacturer George Krier,

[65] Thomas & Newswanger Architects et al., 8
[66] Thomas, College Hall Case Study Interview with Architect Marianna Thomas.

Masonry Chemist Dr. Seymour Z. Lewin, and masonry contractor Masonry Preservation Group.

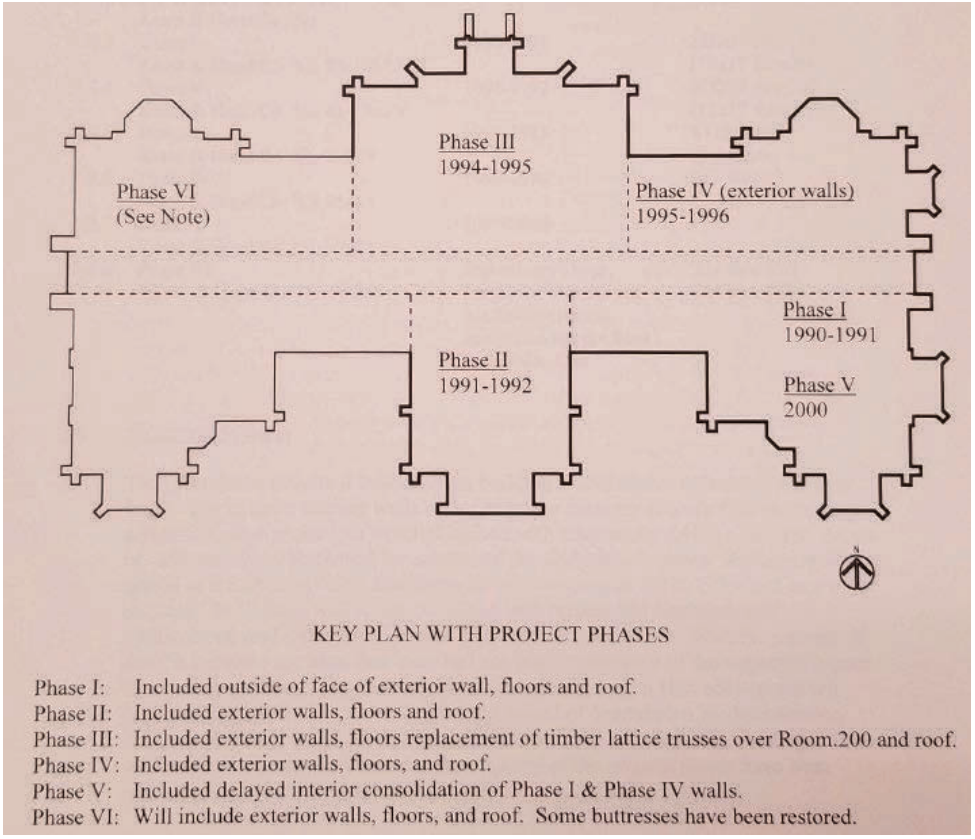

Figure 29. College Hall project key plan with project phases. Phase VI has yet to begin construction at the time of writing, May 2019. (Courtesy of Keast & Hood, 2005)

Summary of Stone Conservation Survey, 1986

A survey of exterior masonry elements on both College Hall and Logan Hall, including serpentine, cast-stone, and various stucco mixes, was performed by Dr. Seymour Z. Lewin of New York University. Analytical methods were x-ray diffraction supplemented with petrographic microscopy, scanning electron microscopy, and wet chemistry as needed.

The serpentine contained quartz, phlogopite, dolomite, and calcite minerals. The study identified freeze-thaw cycles impact on the water content within the stone as the primary agent of deterioration, causing the stone to crack, spall, and crumble away. Additional adverse effect from acid rain created differential color alterations. The exposed area showed more noticeable yellowing than protected sections.

The cast-stone elements made with Portland cement and coarse aggregates were in good condition. In comparison, the stucco patches of the lime variety have weathered poorly. Wet-dry cycles washing out the lime binder in addition to degradation to gypsum from air pollutants caused the stucco to detach.

Challenges

Conditions assessment in 1986 indicated light to severe deterioration of building stones, depending on the species. Both mica schist and sandstone had localized bowing or spalling but were otherwise in good condition. The serpentine, on the other hand, experienced severe spalling on much of its surface. The project team was also concerned with asbestos inclusions and the soundness of the wall assembly. Masonry probes were used to evaluate the conditions of the wall and to determine a safe method of removing the serpentine.[67] Four probe holes measuring approximately 12 square feet were opened on the exterior provided a view into the wall assembly. It was described as "bonded construction" of rubble core and load bearing face stones. Keast & Hood Structural Engineers advised caution when removing the serpentine, as it may have caused

[67] Thomas & Newswanger Architects et al., 6 - 10

structural instability such as disintegration of the inner-most small stone rubble course. Shoring was suggested as a mitigation; however, the project team was concerned that a shift in load may destabilize the entire wall assembly. If the serpentine were to be removed, the inner rubble masonry cores alone would have to bear the load with support from the interior of the building.[68]

On the other hand, the type of masonry construction and varying thickness of face stone was challenging for the cast-stone replication. Since the cast-stone is too hard for extensive field cutting, each must be cast to an exact thickness resembling the serpentine it is replacing, and this dimension is not known until the serpentine is removed. The other recommended solution was the construct a uniformed brick back-up wall to ease the logistics of casting the replacements.[69]

Due to these complications, the team instead considered the feasibility of consolidating the serpentine by consulting Dr. Lewin over chemical consolidation. He suggested testing a silicate consolidant in-situ for a period of one year or laboratory accelerated weathering. However, such treatment may only last five to ten years and will require regular inspection.[70] In addition, replacement using a similar colored stone was tested in-situ; however, the stone did not blend in well with surrounding because of its darker color and greater reflectance.

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[68] Keast & Hood Co., "Structural Investigation: College Hall." 35 – 42.
[69] Ibid.
[70] Thomas & Newswanger Architects, "College Hall Masonry Probes."

Other Conditions

Other conditions noted in the report were localized settlement deformation from building loads, the safety of old fire escape on the east elevation, water infiltration, structural concerns with wood joists, wrought iron girders, and floor trusses, and deformed window and door frames.[71]

Prototype Wall Restoration

A test reconstruction was performed in the summer of 1987, with the intention to study the conditions of the masonry construction and develop strategies for full scale repair. The project took place from the south-central pavilion to the south elevation. With the intention to preserve as mush serpentine as possible, the stones were sounded, and the deteriorated material was removed. Different mixtures of stucco varying in color, texture, and composition were applied on the reduced serpentine.[72]

Composite Repair

During the initial preservation/stabilization phase in 1989, composite repair was tested to determine its feasibility as a restoration method. All serpentine stones were sounded, and where suitable, the stone was reduced to sound surface and patched with Jahn, a composite repair mortar manufactured by Cathedral Stone Products. The "unsound" serpentine (locations were the stone was detached from back-up masonry)

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[71] Keast & Hood Co., 127
[72] Ibid. 127

was removed. The voids were filled with brick and the surface recreated with composite repair mortar.[73]

Cast-stone Replacement

Ultimately, cast-stone replacement was selected as the best method of repair based on its success on Logan Hall and College Hall during previous campaigns.[74] It was also recommended by Dr. Lewin in his report, stating the "pristine appearance of these building facades[75] can be regained by the skillful use of pigmented cast stone" and further emphasized that it is "the only practical one."[76] In addition, the project team made further discovery of the severity of serpentine deterioration. Patching with composite repair mortar would have limited service life as the host masonry continue to decay.

The university contracted cast-stone manufacturer George Krier to "produce models that replicate the natural stone."[77] The product criteria were specified as:

> …High in compressive strength (in excess of 6000 psi,) low porosity, color-fastness, absence of air bubbles, cracks and other imperfections…good match of color, texture, and bonding patterns.[78]

The cast-stone was cast in molds made with a rigid wooden perimeter and a latex mold with the original tooling of the serpentine on the bottom. The surface texture was created by casting the latex on tooled plaster models to make negative imprints. Krier

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73 Keast & Hood Co., "University of Pennsylvania College Hall Construction Chronology Plus Interior & Exterior Assessments with Proposed Remediations." 6 – 8.
74 Thomas, College Hall Case Study Interview with Architect Marianna Thomas.
75 Referring to College Hall and Logan Hall
76 Lewin, "Stone Conservation Survey: College and Logan Halls, University of Pennsylvania."
77 Thomas & Newswanger Architects, "Study Phase Meeting Memoradum No. 2."
78 Thomas, "College Hall: A Team Approach to Restoration."

tested several methods and mixtures but they did not meet the durability or aesthetic standards. The final product was made by scattering mica flakes and liquid pigments made from stable metal oxides on the latex mold then filling it with green concrete. A manufactured green sand made from basalt was used to improve the vibrancy and saturation of the green tone. The cast-stone product underwent accelerated weathering, compression, water absorption, and freeze/thaw before it was approved for installation.[79]

The full formula was as follows[80]:

Cement: ASTM C150, Type II, low alkali cement

Fine Aggregates: ASTM C33, manufactured green sand consisting of ground Cardiff Green basalt stone.

Coarse Aggregates: ASTM C33, No. 2 crushed Cardiff Green Basalt, nominally passing through 3/8" sieve.

Pigment: ASTM C979, inorganic mineral oxide pigments, colorfast, alkaliproof.

Admixtures: Acrylic polymer and modifiers, "Acryl 60" as manufactured by Thoro System Products.

Water: potable

The team decided to match the tooling of the cast-stone to its original finish instead of the weathered surface. They believed this method followed the standard set by traditional in-kind replacement and would better restore the original appearance as

[79] Ibid.
[80] Ibid.

intended by the architect. The cast-stone surface had a hatched patterned outline dressed with tooth chisel, while the mottled field pattern was carved with pointed (Figure 30).[81]

Figure 30. Detail of cast-stone with recreated original tooling. (Photograph by author, 2019)

The original ashlar coursed serpentine had a wide range of dimensions. Making an exact replication of each stone was unfeasible giving the size of the building. The project team worked together to find a solution. The masonry contractors traced the layout of the serpentine on the wall. Then, full-size cartoons were made to plan the layout. From this, Krier devised a method that is both practical while still representative of the original pattern. A family of stone with vertical increment of two inches and horizontal increments of three or four inches were created for the flat surfaces of the exterior. They were placed in such a way that is both a repeat of a regular pattern but also resembled the original layout of the serpentine (Figures 31 and 32). Special

[81] Ibid.

dimensions were made for irregular areas such as the chimney or near openings. As of 1991, 49 different size of casts were produced.[82]

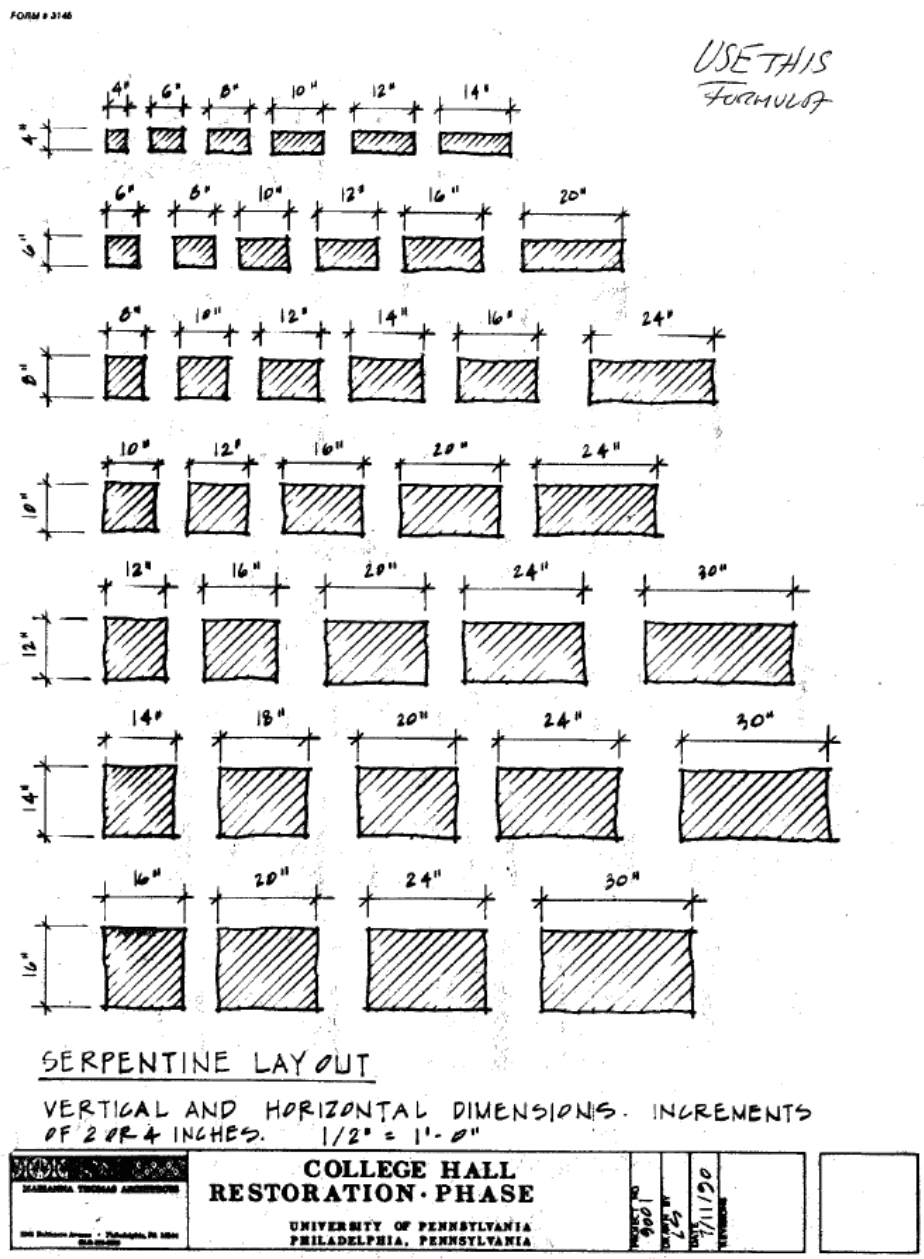

Figure 31. Krier's plan for cast-stone dimensions. (Courtesy of Architectural Archives, UPenn)

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[82] Ibid.

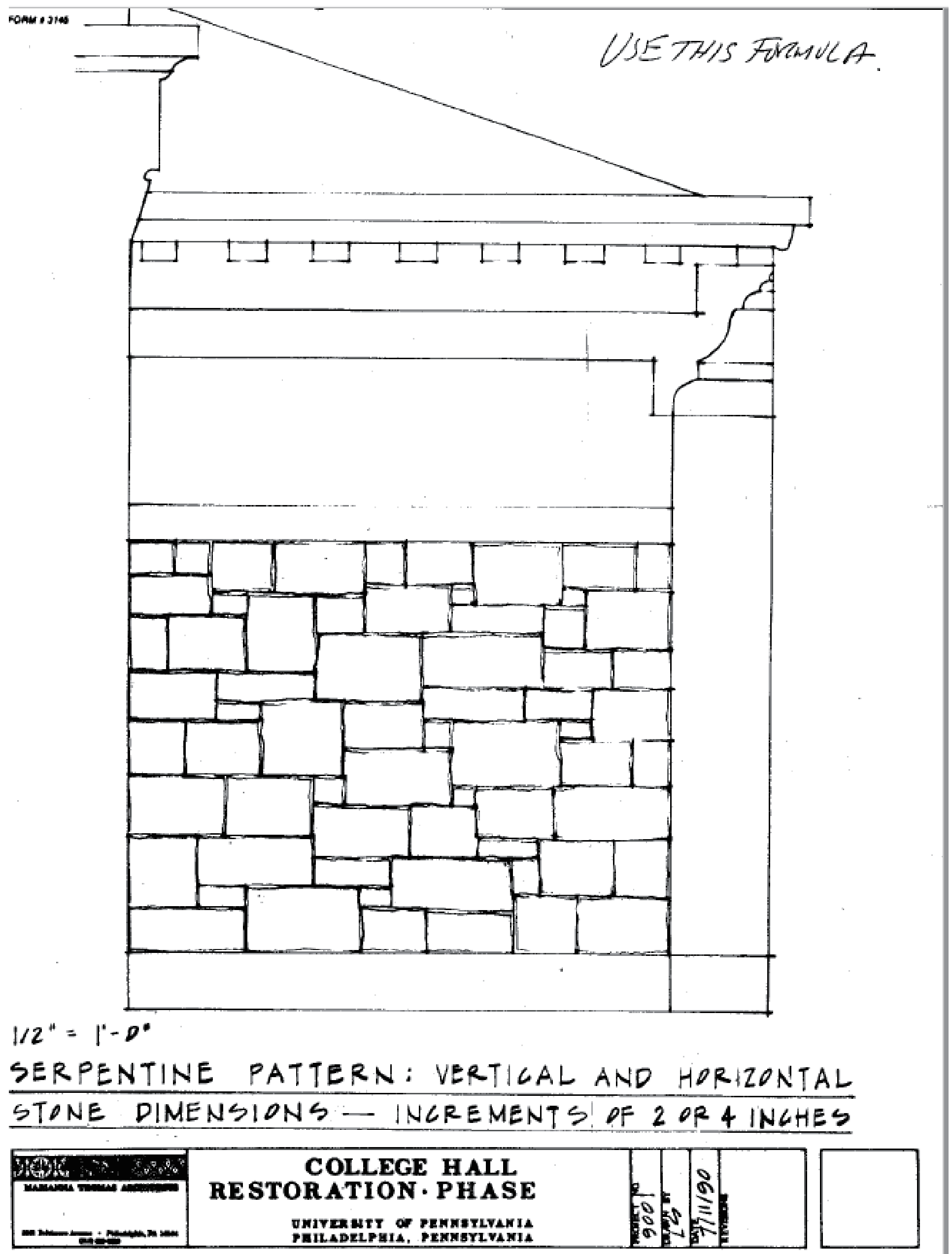

Figure 32. Krier's layout of serpentine pattern. (Courtesy of Architectural Archives, Upenn)

Installation

Masonry Wall Reinforcement

Before work could began on the serpentine replacement, the back-up masonry needed to be stabilized to ensure the structural integrity of the building. Previous field investigation showed extensive loss of "mud mortar" in the inner-most rubble core. "Mud mortar" is a mix that contains clay, mud, with large amount of aggregate, and little binder. The mortar provided little adhesion and support and the wall remained standing from good stone to stone contact.[83] The deterioration created a hazardous working condition for the masons. There were incidents where pieces of rubble core rushed out of the void when a serpentine face stone was removed. This required a suitable method of consolidation where new mortar can be injected deep into the voids of the rubble core. The project team adopted a "pneumatically applied dry-packing procedure". First the remaining "mud mortar" was removed mechanically by chipping hammer then air blasted. The dry-packing was delivered by a "gun like" propeller that launched two jets of materials simultaneously, one of dry Portland cement and sand mix and the other water or wetting agent solution. The materials combine upon impact and fill up the voids or joints. This method was deemed appropriate by the project team and applied where necessary prior to the installation of cast-stone.[84] The cementitious mixture enhanced the stone matrix by filling the voids from mortar loss. The

[83] Doukakis and Wentz, College Hall Interview with Keast and Hood Structural Engineers Constantine (Dean) Doukakis and Brian D. Wentz.
[84] Keast & Hood Co., "University of Pennsylvania College Hall Construction Chronology Plus Interior & Exterior Assessments with Proposed Remediations." 8 – 9

consolidation also strengthened the back-up wall, enabling the installation of cast-stone anchors. The extra strength also served as additional structural support that enhanced overall safety of the building.[85] Once the wall assembly was consolidated with this method, the masons no longer experienced perilous destabilization when removing the serpentine.[86] On areas where dry-packing consolidation was not possible, the stones were removed and infilled with bricks.[87]

Installation of Cast-Stone Replications

The cast-stone replications were produced in Krier's workshop then delivered on site, ready to be installed. Keast & Hood Structural Engineers developed a special stainless-steel anchor which was embedded in the mortar joint to support the cast-stone. It had a broad, corrugated end about four inches in length, one and a half inches in width and a quarter of an inch in thickness welded onto a threaded rod approximately five and a half inches long with a diameter of half of an inch. The corrugated section was placed underneath the cast-stone, which was four inches thick, while the threaded rod tied into the backup masonry.[88]

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[85] Doukakis, "UPenn Thesis, College Hall Case Study Review."
[86] Knapp and Knapp.
[87] Keast & Hood Co., 11
[88] Doukakis and Wentz.

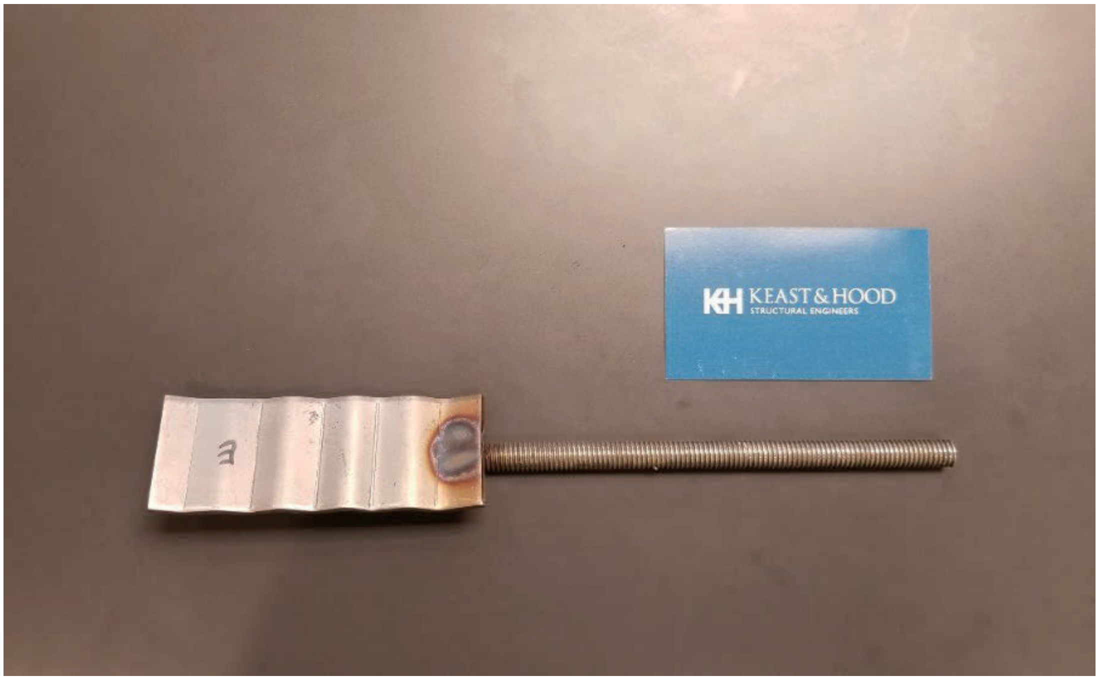

Figure 33. Anchor used to install cast-stone on College Hall, Keast & Hood Collection. (Photograph by author, 2019)

The stone was installed manually onto mortared back-up and bedding of a mix that contained four parts sand, one-part cement (from Mexico), and one-part lime. The largest pieces of cast-stone weighed about 50 pounds. The installation process was simple and was accomplished without major issues.[89]

9.1.3 Current Conditions

College Hall Project Phases I – V spanned from 1990 – 2000. The renovation oversaw the replacement of most serpentine stone from the north central pavilion to south central pavilion among other repairs. Phase VI, which has yet to begun, will

[89] Knapp and Knapp.

include cast-stone replacement of serpentine using the similar method as explained above on the west elevation and the western portions of north and south elevations.[90]

As College Hall awaits the convening of Phase VI, the serpentine on the un-renovated sections of the building continues to deteriorate. Keast & Hood conducts bi-annual visual inspections since 2013 to update the buildings general conditions and identify areas which need immediate intervention. Areas of spalls are either left untreated, scarified if it is not over pedestrian traffic, or patched with a green stucco as a temporary repair.

The author conducted a survey of the exterior serpentine repairs on February 2019 from ground level assisted by binoculars. The conditions are documented with a digital single-lens reflex camera. The purpose of this survey is to 1) identify the previous repairs: stucco patching, composite repair, and cast-stone replacement 2) assess each repair's current condition 3) assess College Hall's overall condition. The survey can be found in Appendix F – College Hall

9.1.4 Conclusion of College Hall Case Study

Overall, the project was deemed a success by all parties interviewed. They were very satisfied with the cast-stone replacement. The material has weathered well with only a few minor spalls or cracks. The building façade has a cohesive appearance (except for the west portion awaiting Phase IV) and maintains its character defining feature – a polychromatic design featuring green serpentine stone.

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[90] Keast & Hood Co.

The author agrees with Dr. Lewin's assessment that cast-stone is the only "practical" solution to the conditions present on College Hall. Given the size and scope of the project, the replacement must be cost-effective and durable. Being an iconic building on the university campus, it must meet high aesthetic standards. The building was placed on the National Register of Historic Places in 1978 and the architect's polychromatic color scheme of contrasting gray and green stone was listed as part of the statement of significance.[91] Therefore, it is important to maintain the building's green color. Cast-stone replacement is the only cost-effective material that meets all these criteria. It allowed rapid, mass production yet still maintained variations in color and size combinations. The material showed little sign of deterioration after more than 20 years. And the replacement appropriately restored the architect's design intent. Where entire section was replaced with cast-stone, it looks like a natural stone building when viewed from 20 feet and beyond, which is the standard used by the Cast Stone Institute of America for a passing cast-stone repair. Replacement with another green stone may have met the aesthetic standards, but it would have been be much more expensive. Each stone would have been transported to the site, fitted, cut, installed, and then individually tooled. It would also prolong the schedule of construction, which is not desirable for a busy university building that must remain operational during construction.

[91] University City Historical Society, "College Hall."

Alternative Repair Methods

An important purpose for the case studies is to assess if Repair No. 1 and Repair No. 2 are appropriate alternatives for these projects.

Compatibility with Repair No. 1: Composite Repair Method

Composite repair mortar cast as a replacement for cast-stone is not an appropriate alternative repair method for College Hall. Although composite repair mortar can be cast and used as a unit replacement in some cases, its compressive strength does not meet College Hall specification of 6000 psi. Due to the severity of the serpentine deterioration, a wholesale patching repair may only have a limited service life. Any remaining serpentine will continue to deteriorate from acid rain and the composite repair mortar patching will fail as its substrate fails.

Compatibility with Repair No. 2: Mineral Stain Method

The author asked all interviewees if they will consider Repair No. 2 as an alternative repair method. In general, it is possible if the material meets the criteria of the project. Keast & Hood expressed the material must have good durability. Marianna Thomas expressed the stone should be similar in weight and able to be tooled, she was also concerned with the aesthetic quality – whether the coating would be a flat color, or can variation be achieved while maintaining the natural texture of the stone. Tom Ewing was also concerned with the aesthetic quality of the replacement. It should not look "mass produced" or like "plastic". On a different note, Ewing expressed that shop-produced replacements have cost saving advantage since environmental protection in the field is expensive. Vern Knapp stated that the replacement must meet the structural engineer's requirements.

Meeting the Aesthetics Requirement

Under the premise that a suitable replacement stone meeting the criteria stated in Section 5.2 is available, potassium silicate stain can be worked to closely mimic the original stone under a skilled artisan. A skill artisan is a conservation technician who is trained by the manufacturer or other professional institution in the application of the stain. The technician should also have a good understanding of material's properties and limitations. However, high standard of aesthetic quality cannot be quickly produced in such way as the cast-stone replacement. The technique is similar to that of creating a watercolor painting, mixing colors and using different application technique. The artisan must tool and paint each stone individually. High demand for detail will cost more time. On the other hand, a replacement for a stone which is largely uniform in color, such as a brownstone, two coats of a single color may be sufficient to create a satisfactory resemblance.

Meeting the Durability Requirement

Test results suggested that potassium silicate stain is susceptible to color change either from erosion or UV degradation of the pigments. This method would be inappropriate for a complete replacement project for a building as large as College Hall. The stone may need to be retreated every decade or two, which is not cost-beneficial for the building owner. It would also hinder operations for a busy institutional building.

9.2 CASE STUDY 2: RECITATION HALL, WEST CHESTER UNIVERSITY, PENNSYLVANIA

Recitation Hall (Figures 34 – 37) is the oldest building on the main campus of West Chester University, Pennsylvania. The 1892 building undergone a large-scale composite repair mortar patching restoration of its serpentine face stone from 2010 to 2011, which will be the focus of this case study.

This case study is compiled from a phone interview with conservator Lorraine Schnabel of Schnabel Conservation L.L.C., who conducted a stone conditions assessment and proposed treatment recommendations, and a joint in-person interview and site visit with Rodney Lukens, retired Project Manager of West Chester University, masonry restoration contractor Gregory Hess, Ralph Hart, and Cody Wilson of Caretti Restoration & Preservation Services L.L.C. (Caretti), and Van Burriss, Manufacturer's Representative for composite repair mortar supplier, Conproco. Project documentation and report were provided by Schnabel L.L.C. and West Chester University Facilities Design and Construction Department. Construction photographs were provided by Caretti. The author performed a brief survey of the building in March 2019.

Figure 34. Primary elevation of Recitation Hall, facing north. (Photograph by author, 2019)

Figure 35. Recitation Hall, west elevation. (Photograph by author, 2019)


Figure 36. Recitation Hall, south elevation. Looking northwest. (Photograph by author, 2019)


Figure 37. Recitation Hall, east elevation. (Photograph by author, 2019)

9.2.1 Background

Building History

Recitation Hall was built in 1892, it is the oldest surviving original building in West Chester University. It is centrally located on campus in an area called "The Quad" or Quadrangle, which received a Historic District designation on the National Register of Historic Places around 1981. This 12.6-acre area is the university's original campus.[92] Recitation Hall was commissioned as the university grew with increased enrollments. The building was designed by a West Chester native architect, T. Roney Williamson, as a modest, utilitarian Collegiate Gothic building due to budget limitation.[93]

West Chester University built exclusively with serpentine, a local stone quarried just a few miles away, for the first 55 years of the university's establishment. Recitation Hall was one of six serpentine buildings constructed on West Chester University campus around late 19th century to early 20th century: Ruby Jones Hall (1899) (Figure 38), the Old Library (1904)(Figure 39), Old Main (c.1976), Old Gymnasium (1889), and Green Gables (1892). Old Main, Old Gymnasium, and Green Gables have since been demolished when their functions outgrew the buildings. As the oldest serpentine building (also the oldest in overall) of the university, Recitation Hall has significant value.[94]

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[92] Webster, "West Chester Uni District Nomination"
[93] Ibid.
[94] Ibid.

Figure 38. Ruby Jones Hall (1899), one of three remaining serpentine building in West Chester University. East elevation. (Photograph by author, 2019)

Figure 39. Old Library (1904), one of three remaining serpentine building in West Chester University. West elevation. (Photograph by author, 2019)

Construction

Recitation Hall is a three-story university building of roughly 13,000 square feet. It was constructed as a monolithic rubble wall with serpentine as face stone and Indiana limestone as trims and details.[95] The interior rubble is made up with many types of stone. They were likely stones that did not meet the standards of face stone. As seen in the basement, some parts of the wall were infilled with bricks or concrete blocks. However, the exact configuration of the wall is not known. The serpentine face stone range in size and shape. The thickness varies from two to twelve inches. The stones were quarried and bedded in random orientation. Thicker stones at irregular intervals tied the face stones to the backup masonry.[96]

[95] Ibid.

[96] Lukens et al., Recitation Hall Interview with Rodney Lukens, Gregory Hess, Ralph Hart, Cody Wilson, and Van Burriss.

Figure 40. Exposed back-up rubble masonry wall during the repair campaign. (Courtesy of Caretti Restoration & Preservation Services, L.L.C., 2011)

Figure 41. Parts of the back-up masonry were infilled with brick; it is not known if they are original or from subsequent repairs. (Courtesy of Caretti Restoration & Preservation Services, L.L.C., 2011)

Figure 42. Section of exposed wall in the basement of Recitation Hall showing different types of stone, bricks, and concrete blocks. (Photograph by author, 2019)

9.2.2 Recitation Hall Serpentine Repair Campaign

Summary

The repair campaign for Recitation Hall was initiated around 2008 to address the deterioration of the face stones. An initial survey suggested removing roughly 75 percent of the serpentine and replace them with cast-stone. However, later conditions survey and consultations with Schnabel and Caretti generated an alternative solution. Many of the stones were in good condition after the surface deterioration was removed. West Chester University decided that a composite repair mortar patching will allow them to retain the largest amount of original serpentine and best preserve the integrity of the building. Construction began in the summer of 2010 and was completed fifteen months later.

Condition of Serpentine

The serpentine used to construct Recitation Hall was quarried from Brinton's Quarry, only a few miles from site.[97] Petrographic study showed the serpentine contained antigorite, chlorite, chromite, and minimal amounts of carbonate. The chlorite minerals are susceptible to acid hydrolysis, where magnesium detaches from the crystal lattice and form other compounds, such as magnesium salts. Magnesium salts are hygroscopic, they draw moisture from air, which accelerates deterioration of the stone.[98]

Figure 43. Pre-construction photograph of east elevation, Recitation Hall. Note the deteriorated stones below the third story window sills and on the gable. (Courtesy of Caretti Restoration & Preservation Services, L.L.C., 2010)

[97] Lukens et al.

[98] Schnabel Conservation L.L.C., "Stone Conservation Assessment for Recitation Hall Serpentine." 13

Figure 44. Stone underneath window sills are generally in worse condition. Note the dark stains formed from moisture accumulation. (Courtesy of Caretti Restoration & Preservation Services, L.L.C., 2009)

Summary of Stone Conservation Assessment

Schnabel Conservation L.L.C conducted a stone conditions assessment in August 2008 as part of the pre-construction evaluation aimed to develop treatment recommendations including the conservation of original serpentine and patching with composite repair mortar. This assessment included a stone by stone evaluation through sounding and petrographic study of serpentine thin sections.[99]

Sounding survey was performed on all the exterior serpentine except for a single inaccessible below-grade area. Sound stone gives a "bright ring" when tapped, and

[99] Schnabel Conservation L.L.C. 1

deteriorated stone makes a "dull thud or snapping sound." The color of serpentine may also suggest the condition of the stone. The green stones tend to be deteriorated while the stones that formed a yellow crust are more likely to be sound.[100] Schnabel's report categorized the result and recommendations as follows:

> 1**. Face-off:** loose flakes of stone were observed on or could be dislodged from the surface (leaving a convex or planar surface relative to the wall face) but the stone gave off a ringing sound.
>
> 2. **Repair:** discrete parts of the stone were deteriorated, but the balance was sound. This condition was applied almost exclusively to stones at the window jamb stones, stones at the corners of the building, and at lintel stones where the bottom or top of the stone only was unsound. Repair of these shaped stones could represent a cost savings over replacement due to their two finished faces.
>
> 3. **Replace:** this condition was assigned not only to any stone that sounded dull, but also to stones that were eroded beyond the face of the wall, or that would have such an eroded surface if the loose material were removed.
>
> 4. **Sound:** no action required.[101]

[100] Ibid. 2
[101] Ibid. 2 - 3

Figure 45. Detail photography showing the yellow crust on top of the serpentine, retaining its original tooling. The green stone has largely lost the crust with some remaining on the edges, it shows visible signs of erosion. (Courtesy of Schnabel Conservation L.L.C, 2008)

The deterioration of serpentine began as a gradual loss of its surface layers, starting with its tooled surface. Stones near limestone sills or other adverse conditions such as open joints or cracks were in worse condition. Proximity to limestone may have led to gypsum formation in serpentine from dissolved calcium runoff combined with sulfur in the atmosphere. However, further testing such as X-ray diffraction or chemical analysis would be necessary to confirm this hypothesis. In other cases, the stones had inherent cracks or may have been cracked during the tooling process and allowed water to gain access, which accelerated their deterioration. Other cracks appeared adjacent to mortar joints, which may have been caused by water trapped in pointing mortar.[102]

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[102] Ibid. 3

Recommendations

Schnabel recommended four methods to eliminate water infiltration and to restore and preserve the serpentine stone: 1) remove the existing raised ribbon joint and restore the original narrow ribbon joint. 2) remove loose surface, which tend to trap moisture, 3) redirect water flow from limestone wash courses and sills by installing drip edge, 4) replace or repair badly deteriorated stone to allow effective water movement across the building's surface, with the options being replace in-kind, replacement with cast stone, or patch repair. Schnabel further suggested that the stone and brick rubble wall back-up are uneven in thickness and structural remediation may be necessary.

Proposed Methods

Schnabel's report suggested three repair or replacement methods:

Replacement in-kind

A potential source for quarried serpentine, commercially called Verde Antique, a "serpentine marble", is available from the U.S. Vermont Verde Antique L.L.C in Rochester, Vermont. The company quarries and fabricates the stone as a polished slab for decorative use.[103] The stone is advertised as having the "hardness and durability of most granite…low absorption rate and high flexural strength."[104] The physical and chemical properties of this potential replacement stone should be tested for compatibility. A compatible stone should have near identical mineralogical composition,

[103] Ibid. P. 14

[104] Vermont Verde Antique L.L.C, "Vermont Verde Antique Architectural Information Kit." 3

absorption rate, strength, and can be tooled to a similar finish.[105] Visually, the Verde Antique appears darker and contains much larger number of veins and mica than serpentine.

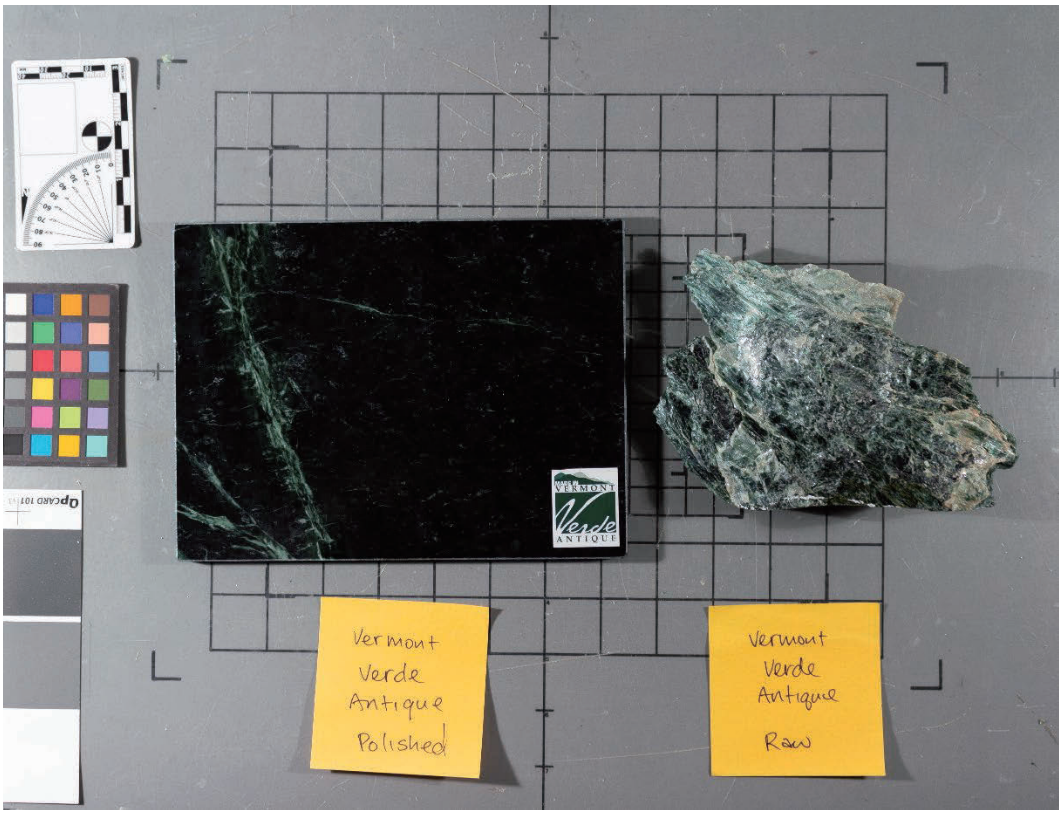


Figure 46. Vermont Verde Antique samples received from manufacturer. Left: polished, Right: unprocessed. (Photograph by author, 2019)

[105] Schnabel Conservation L.L.C., 13

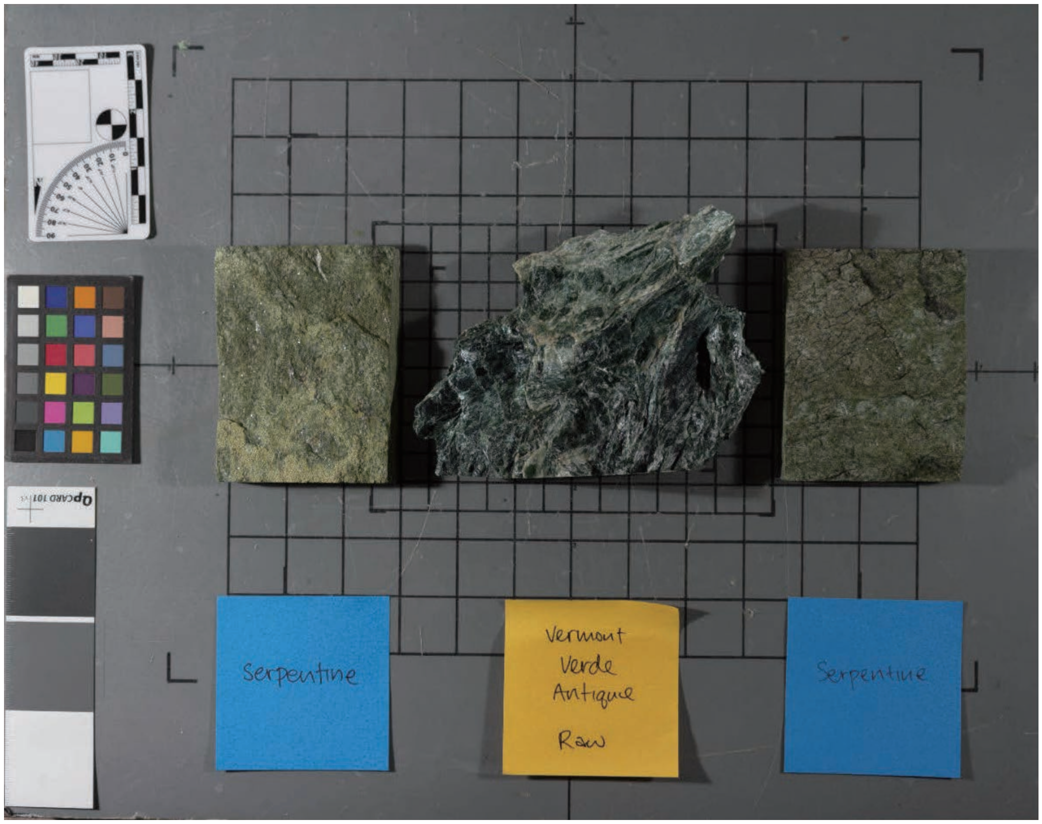
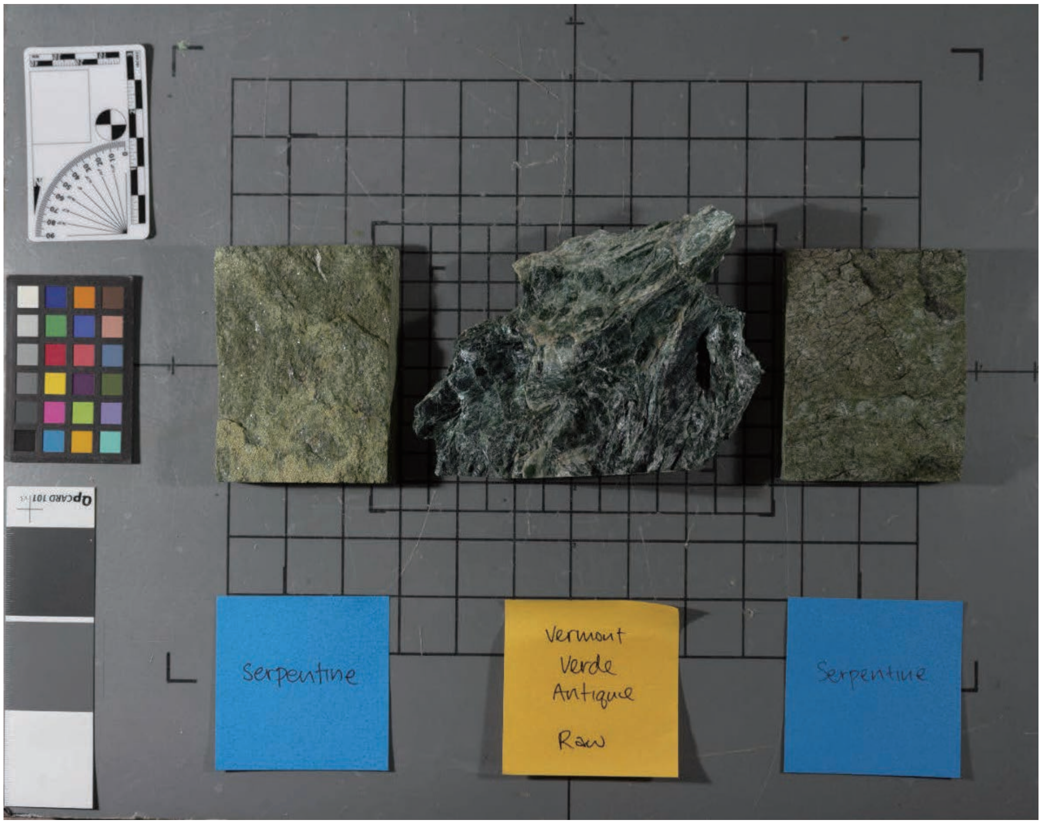


Figure 47. Unprocessed Vermont Verde Antique (center) compared to serpentine samples retrieved from Woodland Presbyterian Church in Philadelphia (left and right). Vermont Verde Antique appears much darker and contains many veins. (Photograph by author, 2019)

Replacement with Cast-Stone

Cast-stone replacement was discussed extensively under College Hall Case Study. In the case of Recitation Hall, the challenges came from localized replacements. For one, the dimensions of original stone varied greatly, it would be necessary to make many custom molds and may require onsite fabrication. In addition, it would be difficult to match each replacement to its surrounding masonry given their complex color. The



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Patching with Composite Repair Mortar

Composite repair mortar had been used on Recitation Hall in the past, however, with limited visual success. Schnabel cautioned against fading pigments and surface erosion of the material. There was further concern for bonding strength associated with the absorption quality of the substrate. Patching material would fail if the substrate was not properly prepared or lack satisfactory absorption. Past patching repairs on the building showed various degree of degradation, however, the cause of deterioration cannot be confirmed without testing.[107]

Selection of Repair Methods

There was a brief discussion to replace all serpentine with cast-stone, however, given that most stones are in good condition, the university decided to preserve as much as they can. Localized unit cast-stone replacement was considered for the project. However, the mock-ups did not meet the aestheticc standards. There were many pits left by air pockets of entrained air on the cast-stone's surface.[108]

After consultation with Caretti, the university selected to use composite repair mortar as the primary treatment. This allowed the building to retain much of its original fabric, which has significant historic value. Stones beyond repair were replaced with

[106] Schnabel Conservation L.L.C., 13 - 14
[107] Ibid. 14
[108] Lukens et al.

serpentine salvaged from other builidngs on campus.[109] The project team made the decision to preserve the current weathered appearance instead of restoring the original prestine condition. The team believed this to be the more honest approach, acknowledging that aged building will look different.[110]

Material

The composite repair mortar used on this project, Matrix (Mimic) was supplied by Conproco Corporation. Matrix is a Portland cement based mortar, advertised as having low shrinkage, durable, salt resistant, and breathable.[111] The product can be tooled at thumbprint hardness. Different application technique will alter the color of the finish. A smooth surface will appear lighter than a rough surface because the texture affects how light is reflected.[112]

The mortar is stored in powdered form. When ready for application, water is added at 1:4 or 1:4.5 water:powder ratio. The wet mix was applied, usually by trowel, onto clean, surface saturated dry masonry substrate.[113] Full technical data can be found in Appendix A – Product Data.

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[109] Ibid.
[110] Ibid.
[111] Conproco Corporation, "Matrix_PDB."
[112] "Conproco » FAQ – Stone Repair."
[113] Conproco Corporation, "Matrix_PDB."

Published Technical Data[114]

Category	Reference	Description
Base		Portland Cement
pH	Wet Mix	> 12
Water/Dry Material Ratio	Wet Mix	0.20
Dry Bulk Density	ASTM C188	92 pounds per cubic foot
Setting Time by Vicat Needle	ASTM C191	240 minutes
Percent Air-pressure Method	ASTM C231	4 percent
Water Absorption	ASTM C140	11 percent
Water Vapor Transmission	ASTM E96	5.2 perms
Length Change	ASTM C157	<500 µstrains at 28 days
Modulus of Elasticity	ASTM C469	2.6 x 10^6
Slant Sheer Bond Strength-Epoxy	ASTM C882	1800 psi
Compressive Strength	ASTM C109	7 Days: 2900, 28 Days: 3000
Tensile Strength	ASTM C307	7 Days: 300, 14 Days: 480, 28 Days: 560

Table 16. Published data of Matrix.

Construction

Exterior restoration focused on serpentine repair started in the summer of 2010 to accommodate the University's schedule. The crew worked through the winter with heating and weather protection.[115]

Substrate Preparation

Proper preparation of substrate has a direct effect on the longevity of the repair. The masons cut back the deteriorated surface until sound stone was reached. This can sometimes be difficult because serpentine is friable, special caution was taken to avoid

[114] Ibid.
[115] Lukens et al.

accidentally removing good stone.[116] Water is sprayed on the stone right before application of the composite repair mortar for the substrate to reach surface saturated dry.

According to Schnabel, consolidation was not perfomed because the stone was in good condition after the exfoliated surface was removed, and consolidants on the market cannot achieve the necessary depth of penetration needed to be meaningful.[117]

Application of Composite Repair Mortar

The complex color and texture of existing serpentine required advanced application technique. Color matching was performed in-situ using two methods. A selection of four semi-custom color composite repair mortar: Yellow Serpentine, Serpentine, Dark Serpentine, and Golden Chester, supplied by Conproco, was available for field mixing. The material came in dry powdered form. The masons mixed the pigmented powder until a desired color is reached, add water, and apply onto the substrate. Another method was to mix several different colors with water separately, then apply onto the substrate by compressing them tightly against one another into a desired appearance.[118] A gradual transition of color can be achieved by sliding the trowel back and forth between two colors.

The composite repair mortar was applied in lifts of two to three inches at a time. Deeper repairs were reinforced with stainless steel pins. Tooling was applied when the

[116] Ibid.
[117] Schnabel, Recitation Hall Interview with Architectural Conservator Lorraine Schnabel.
[118] Lukens et al.

mortar reaches thumb print hardness. The biggest challenge for the project team was to achieve consistent tooling across the board. Each mason had one's own idea of how the finished product should look. Different tools were used according to the mason's preference.[119]

Figure 48. Serpentine patching in progress, stainless steel pins were inserted for additional structural support at areas of major loss. (Courtesy of Caretti Restoration & Preservation Services, L.L.C., 2011)

[119] Ibid.

Figure 49. New face recreated with composite repair mortar. The joints were later pointed with Type O mortar. (Courtesy of Caretti Restoration & Preservation Services, L.L.C., 2011)

Figure 50. Stainless steel pins embedded in epoxy were used to provide additional support to keep the composite repair mortar in place. (Courtesy of Caretti Restoration & Preservation Services, L.L.C., 2011)

9.2.3 Current Condition

The author conducted a brief site survey accompanied by Lukens, Hess, Hart, Wilson, and Burriss in March 2019, eight years after the project was completed. The goal of this survey is to assess the condition and quality of the patching, inspect the exposed rubble masonry wall in the basement, and to make general observations. The conditions were recorded by a digital single lens reflective camera. The conditions survey is in Appendix G – Recitation Hall

9.2.4 Conclusion of Recitation Hall Case Study

The Recitation Hall repair project received the Preservation Alliance for Greater Philadelphia Grand Jury Award in 2012. The Project Manager Lukens was very satisfied with the finished product. Hess said it was a successful, portfolio building project for Caretti. It was a success for Conproco as well, both client and contractor were satisfied with the product. Currently, composite repair mortar patching is in good condition with limited, sporadic spalls or cracks. The project team expects the repair to last at least 50 years. [120]

[120] Ibid.

Figure 51. North elevation pre-construction. (Courtesy of Caretti Restoration & Preservation Services, L.L.C., 2010)

Figure 52. North elevation, eight years after restoration campaign. (Different lighting and weather conditions may alter the appearance of color between the two photographs.) (Photograph by author, 2019)

Alternative Repair Methods

Like College Hall case study, interviewees were asked for their opinion on the appropriateness of Repair No. 1 and Repair No. 2 for Recitation Hall project.

Compatibility with Composite Repair Method

This project is a demonstration that composite repair method is feasible as a primary treatment for a medium to large size building such as Recitation Hall. The conditions of the patches should be continuously monitored for the next few decades to assess the longevity of the repair. However, the composition of composite repair mortar may vary from Portland cement based, lime based, or others. Their longevity and weatherability may vary. Proper installation practice and the underlying conditions of the buildings will also impact the durability of the repair. Readers should keep in mind that failure in one project may not necessarily mean the method or a particular product is flawed. It is necessary to determine the exact cause of failure in order to perform an unbiased assessment.

Compatibility of Mineral Stain Method

The author asked all interviewees if they will consider mineral stain method as an alternative repair method. Burriss voiced concern for the durability of mineral stains. A stained is a topical treatment and may only reach a depth of a few millimeters, depending on the absorptiveness of the stone and the product itself. The color will fade as the surface of the stone erodes. Burriss stated that Conproco's mineral stain product has a service life expectancy of approximately fifteen years. Using this method as an alternative means setting the owners up for a maintenance cycle. Lukens confirms that such situation is undesirable for building owners. He prefers repairs that can last for 50 years or more. Hess expressed that different stones will have different absorption and water transmission rates; the material must be studied for its suitability to the building and its durability. Overall, the members of the joint interview agreed that patching repair allows the building to retain more of its original fabric.[121] Schnabel also expressed concerns about the durability and stability of a mineral stain coating. Furthermore, she said if one can find a replacement stone with similar texture to the original stone, then the stained substituted can look very similar.[122]

Meeting the Aesthetics Requirement

This section follows the same reasoning stated in College Hall case study. An appropriate substitute stone can be worked to closely resemble its surrounding under skilled hands. However, high aesthetics demand will require longer duration of labor.

Meeting the Durability Requirement

Test results suggested that potassium silicate stain is susceptible to color change either from erosion or UV degradation of the pigments. The stone may need to be retreated every decade or two, which is not cost-beneficial for the building owner. The goal of Recitation Hall project was to implement a durable, low maintenance repair

[121] Ibid.
[122] Schnabel.

method. Repair No. 2 does not meet this goal. It would also hinder operations for a busy institutional building.

9.3 CASE STUDY 3: ST. FRANCIS OF ASSISI CHURCH, STAUNTON, VIRGINIA

St. Francis of Assisi Church is a Gothic Revival Catholic church built in 1895. From 2015 to 2016, the building undergone an extensive renovation which replaced 100 percent of its serpentine face stone with green granite. This case study was compiled from a phone interview with structural engineer Rex Cyphers of WDP & Associates, the firm which performed structural engineer service and designed the project. Other sources included newspaper articles and documentation of the project on WDP and the parish's websites.

9.3.1 Background

Building History

The parish of St. Francis of Assisi was founded in 1845 due to the increase of Catholic population in Virginia. A smaller church was built in 1850. The current church was commissioned to house the increasing congregation in the late 1880s and was officially completed in 1895. The building was designed by parishioner Thomas J. Collins in the "English Gothic" style. Collins was an active participant in the revival movement who also designed many other monumental buildings in the region. The spiritual goal of the architectural movement was described as "to lead the beholder to mystically reach towards the heights of Heaven."[123]

[123] "St. Francis of Assisi Catholic Parish, Staunton, Virginia."

Original Construction

The masonry walls were faced with serpentine stone from Chester County, Pennsylvania except the less visible east elevation. A story suggested that the greenstone was chosen to honor the Irish parishioners who made up the majority of the congregation.[124] The serpentine face stone had an average thickness of eight inches, it was on top of a triple-wythe back-up wall. The wythe immediately behind the serpentine consisted of rubble stone with brick infill, followed by two more stable wythe of masonry, then lathed and plastered on the interior. The serpentine face stone was load bearing, it carried lateral load and the weight of the roof.[125]

9.3.2 Exterior Renovation Campaign

Summary

St. Francis of Assisi Church undergone an extensive renovation project which replaced all of its serpentine face stone from 2015 to 2016 at a cost of $3.2 million. The project team was made up with general contractor Lantz Construction, masonry contractor Rugo Stone, and consulting engineer WDP & Associates.[126]

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[124] "St. Francis of Assisi Catholic Parish, Staunton, Virginia."

[125] Cyphers, St. Francis of Assisi Interview with WDP & Associates Rex Cyphers.

[126] Neil, "St. Francis of Assisi, Staunton, Rededicated | The Catholic Virginian."

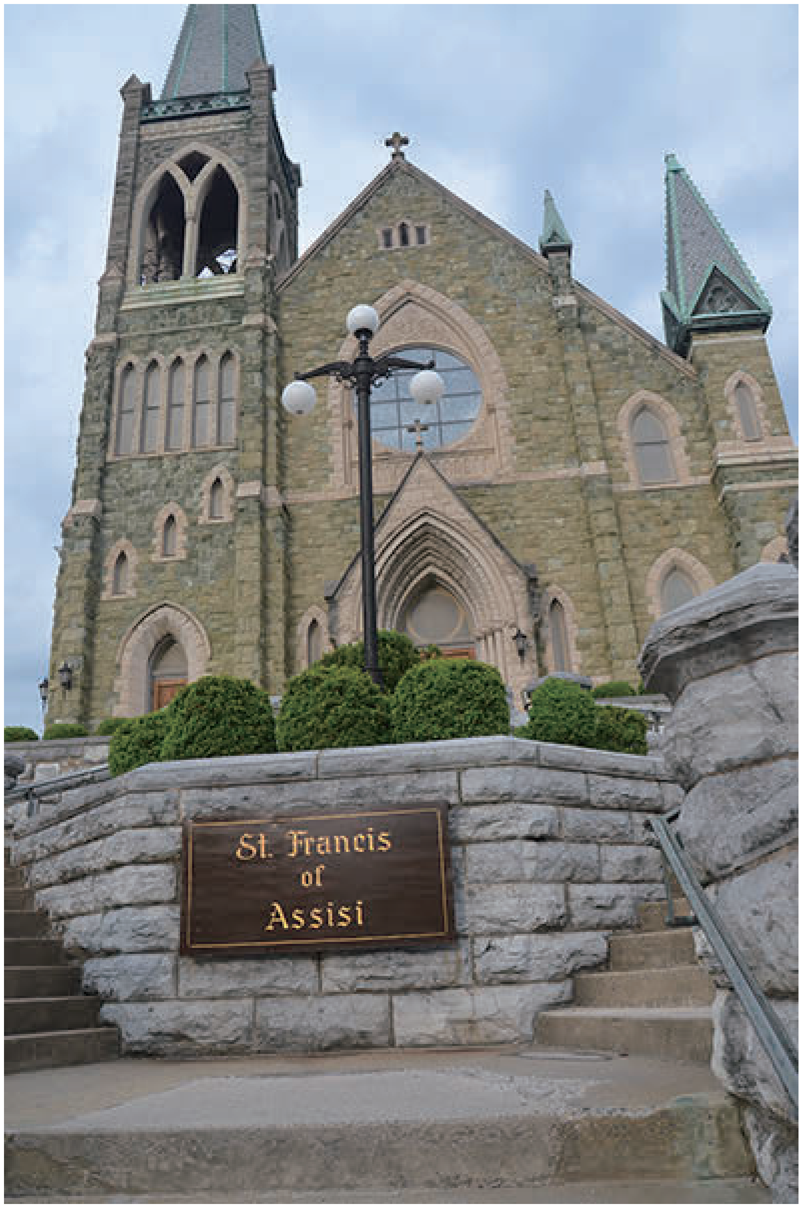

Figure 53. Pre-construction photograph of St. Francis of Assisi. (stfrancisparish.org)

Condition of Serpentine

WDP performed a complete stone survey of the building. The result indicated much of the serpentine was in bad condition. The deterioration was due to a combination of weathering from age and how the stone was oriented. Serpentine is weak at its cleavage plane, it separates easy due to water infiltration and general weathering. Severe delamination occurred where the cleavage plane is laid parallel to the surface.[127]

Figure 54. Close-up of the original serpentine displays extensive delamination and spalling. (stfrancisparish.org)

Selection of Repair Methods

The primary consideration for the project was durability and the client's desire for a green natural stone. The congregation felt that it was an important character defining feature for the church.[128] The feasibility of consolidation was briefly considered; however, test results suggested the stone was not a good candidate for the treatment to

[127] Cyphers.
[128] Peters, "St. Francis Gears up for the Great Reveal."

be effective. Other repairs were possible, but they had limited service life. As a result, the project team and client determined that 100 percent replacement with a substitute stone would best provide long term stability.[129]

Property tests such as hygrothermal analyses were performed to guide the selection of substitute stone. Green granite (Figure 55) showed the most potential. In addition, the quarry had the capability to provide stones which suited the specifications of the project.[130]

Figure 55. Replacement green granite panels are tooled on the surface to resemble natural stone. (August 2015, stfrancisparish.org)

[129] Ibid.
[130] Ibid.

Construction

In order to replicate the original pattern of the stone courses, the project team laser-scanned the building and numbered each stone. The main challenge of the project was to ensure structural stability during serpentine removal while keeping the church occupied. A phasing plan was developed by studying where and how much stone can be removed at a time. Therefore, the repair was carried out sporadically around the building instead of rebuilding from the bottom up.[131]

Both the serpentine face stone and the immediate brick infill behind it was removed and replace with four-inch-thick granite (Figure 55). Since the replacement granite is about four inches thinner than the serpentine, the granite was reinforced with glass fiber reinforced polymer (GFRP) bars. They are said to be advantages over steel reinforcement due to their higher tensile strength, and insusceptibility to corrosion.[132] At the same time, the inner wythes were repointed and stabilized as necessary. Removed brick infills were rebuilt with replicated bricks.[133] An exterior bracing system was installed as additional support since the thickness of the walls were reduced. These steel columns are anchored through the exterior stone to resist out of plane loads and support the weight of the roof.[134]

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[131] Ibid.

[132] "St. Francis of Assisi Facade Investigation & Replacement, Staunton, VA," WDP & Associates, February 12, 2015, https://www.wdpa.com/projects/st-francis-assisi-facade-investigation-replacement-staunton-va.

[133] Cyphers, St. Francis of Assisi Interview with WDP & Associates Rex Cyphers.

[134] "St. Francis of Assisi Facade Investigation & Replacement, Staunton, VA."

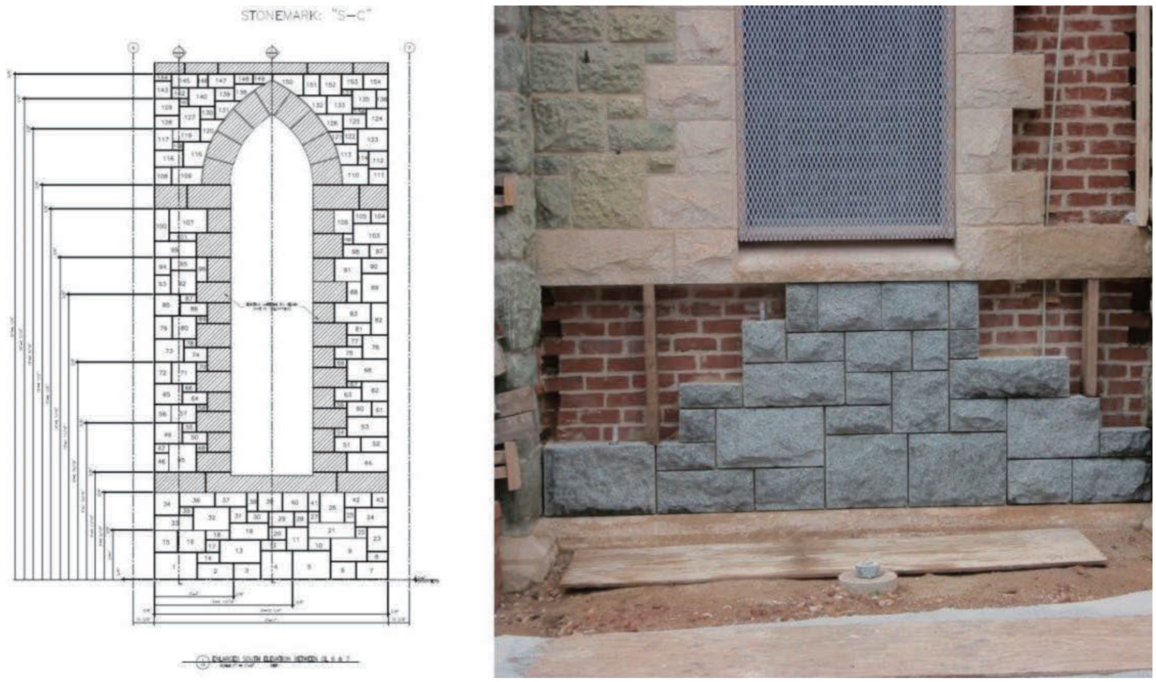


Figure 56. Left: drawing showing the numbered stone and its layout. Right: replacement green granite laid according to the shop drawing with the reconstructed brick wythe behind it. (wdpa.com)

Figure 57. Scaffolding around the church were designed to allow entry to the church during construction. The plastic covering serve as weather protection and safety precaution. (July 2015, stfrancisparish.org)

9.3.3 Conclusion of St. Francis of Assisi Church Case Study

The year-long restoration project of St. Francis of Assisi received the 2016 MIA+BSI: The Natural Stone Institute Pinnacle Award of Merit in Renovation/Restoration and the Heritage Preservation Award from the Historic Staunton Foundation in January 2018.[135] Newspaper articles about the project lauded it as a great success, the church and its congregation appeared to be satisfied with the new appearance of their building.


Figure 58. Close-up of the principal façade after the renovation. (wdpa.com)

Alternative Repair Methods

[135] "St. Francis of Assisi Facade Investigation & Replacement, Staunton, VA."

Compatibility with Composite Repair Method

Similar to the case of College Hall, composite repair mortar is likely not strong enough as a substitute for structural stone. In addition, it does not satisfy the church's desire for natural stone replacement.

Compatibility with Mineral Stain Method

Meeting the Aesthetic Requirement

While stained stone is technically a stone replacement, but it may not fit the church's idea of a natural stone since they are artificially colored. If another appropriate natural stone is available and the building requires a full replacement, it makes little sense to substitute one that need additional labor of staining.

Meeting the Durability Requirement

Analysis showed that the intensity of the color of the mineral stain coating will lighten over time. Depending on the weatherability of the stone substrate, the mineral stain coating will be lost completely once the top surface which the stain penetrated has eroded. The building will need a complete reapplication once the service life expires. It would not meet the goal of a 100 plus year repair with minimal maintenance.

10.0 CONCLUSION

10.1 PRODUCT EVALUATION

10.1.1 Composite Repair Mortar – Lithomex

Performance

All evaluations determined the lime-based composite repair mortar, Lithomex, is a good performance material. It displayed the least amount of profile loss both in depth and area, averaging .11 millimeters and less than 43 percent area loss out of the three samples tested. It also had the least amount of color change, averaging a delta E of 2.75 in CIE L*a*b* color spectrum. However, water vapor transmission test indicated that it had lower WVT and permeance than serpentine. Lithomex's average WVT was at 0.74 $g/(h/m^2)$ and permeance at 0.17 perms compared to serpentine's 2.74 $g/(h/m^2)$ and 0.64 perms. The half Lithomex and half serpentine assembly had an average WVT of 1.82 $g/(h/m^2)$ and permeance of .43 perms. Ideally, the patching material should be equal or more water and vapor permeable than its substrate. It is not known if this amount of lowered permeability will have an adverse effect on serpentine.

Appropriate Use

Composite repair mortar is appropriate for small scale patching, such as sporadic material loss, to large scale stone repair of a medium sized building as demonstrated by Recitation Hall. The material has the aesthetic ability to blend in well with its host masonry under skilled hands. It can be casted as unit replacement if determined to be appropriate by a structural engineer. Testing is required to verify if the cast lime-based composite repair mortar has the adequate strength to carry out the load bearing functions of the original stone.

10.1.2 Potassium Silicate Stain - Colorwash Stain

Performance

It should be reemphasized that the performance of Colorwash Stain is affected by its substrate. In the case of Rainbow Sandstone, it experienced very little profile loss, comparable to that of the unstained samples. However, it showed visible color change, averaging a delta E of 14.87. The stain has become much lighter after 864 hours of accelerated weathering. The product may have poor depth of penetration due to the sandstone's low porosity, or the pigments may not be UV stable. Water vapor transmission test indicated that Colorwash Stain does not significantly impact Rainbow Sandstone's natural vapor permeability. Stained Rainbow Sandstone's average WVT is 0.39 g/(h/m^2) and permeance at 0.09 perms compared to untreated Rainbow Sandstone's 0.50 g/(h/m^2) and 0.12 perms.

Appropriate Use

Stained substitute stone is appropriate for small scale unit replacement, especially at a highly visible location. The substitute stone can be made to blend in well with its surrounding masonry (Figure 59). However, the color of the stain will lighten relatively quickly overtime and will need to be re-stained every few years. This prohibits the material to be used for a large-scale replacement due to maintenance cost. In addition, substitution for stones with complex color demands highly skilled craftsman and time to recreate. This may be a deterrent for some projects.

Figure 59. Top left: Stained Rainbow Sandstone using varies application technique and multiple custom simulated colors. Top right: Stained Rainbow Sandstone with two coats of monochromatic green. Bottom: natural serpentine. (Photograph by author, 2019)

On the other hand, its natural loss of color may be ideal for some applications when an impermanent treatment is desired. The material is often used to conceal slightly discolored patching or Dutchman repair. It can also be used to treat newly quarried in-kind replacement, as they will often appear dissimilar to the aged stone on the building.

10.2 REPAIR SELECTION

The first steps to any repair campaign are understanding the building's condition and setting a goal for the project. Understanding the building conditions and developing appropriate treatments will increase the longevity of any stone repair or replacement.

Oftentimes, underlying problems such as ground water or roof water infiltration are major contributors to stone deterioration. These issues must be mitigated first. Setting a goal for the project will serve as guide for selecting the appropriate stone repair method. These are some questions to consider:

- What is the primary concern of the project?
    - Budget
    - Schedule
    - Durability
    - Aesthetics
    - Authenticity
- What are the aesthetic goals?
    - Cohesive appearance
    - Distinguishable repairs
- What is the preservation philosophy?
    - Preserve as much of original material as possible
    - Longevity of the building comes first, material can be substituted
    - Must use natural stone

Repair Method Evaluation

The following evaluation is made based on test results or case studies. These only serve as general observations. It is essential to consult appropriate professionals such as structural engineers and architectural conservators to thoroughly evaluate and test the suitability of repair methods considered for each project.

Method	Evaluation Method	Pros	Cons
Cast-stone	College Hall case study	• Highly durable • Appropriate for large scale or 100 percent replacement ○ Can achieve cohesive appearance • Reversible	• Is a substitute material • May not be compatible with original stone, if they were retained

Portland cement-based composite repair mortar	Recitation Hall case study	• Durable
		• Aesthetically flexible
		  ○ Can achieve cohesive appearance with host masonry
		  ○ Can be a distinguishable repair from host masonry
		• Versatile
		  ○ Appropriate for small scale patching
		  ○ Appropriate for limited unit replacement (must be approved by structural engineer)
		  ○ Appropriate for large scale repair
		• Can retain original stone
		• Reversible
			• Is a substitute material
			• Not appropriate for 100 percent replacement
			• Higher demand in labor skill
			
			Unknown:
			• Compatibility with host masonry
			• Color stability

Natural stone substitutio n	St. Francis of Assisi case study	• Is a natural stone, although not in-kind • Can be durable (must be confirmed with testing) • Appropriate for 100 percent replacement • Can be used for unit replacement (must be approved by structural engineer)	• May not match original stone, if they were retained • May have higher cost than 100 replacement with cast-stone
Natural hydraulic lime-based composite	Testing	• Durable • Color stable • Aesthetically flexible	• Is a substitute material • Not appropriate for 100 percent replacement

repair mortar		○ Can achieve cohesive appearance with host masonry ○ Can be a distinguishable repair from host masonry • Versatile ○ Appropriate for small scale patching ○ Appropriate for limited unit replacement (must be approved by structural engineer) ○ Appropriate for large scale repair • Can retain original stone • Reversible	• Higher demand in labor skill
Mineral stain on substitute stone	Testing	• Is a natural stone, although not in-kind • Aesthetically flexible ○ Can achieve cohesive appearance with host masonry ○ Can be a distinguishable repair from host masonry • Appropriate for limited unit replacement (must be approved by structural engineer) • Somewhat reversible (by natural erosion)	• Not color stable • Relatively short service life • Not appropriate for 100 percent replacement • Higher demand in labor skill

Table 17. Summary of pros and cons of all methods evaluated.

Summary

The following chart serve as an overview of findings in this thesis.

Method	Appropriate for	Aesthetic Goals			Durability	Labor Skill
		Cohesive Appearance	Distinguishable Repair	Natural Stone Substitution		
Cast-Stone	Complete replacement	Yes	N/A	No	100+ years	Moderate
Cement-based Composite Repair Mortar	Small to large scale patching Limited unit replacement	Yes	Yes	No	50+ years	Moderate to high, depends on the application
Natural Substitute Stone	Complete replacement and unit replacement	Yes with complete replacement	Likely	Yes	Depends on the stone	Moderate
Lime-based Composite Repair Mortar	Small to large scale patching Limited unit replacement	Yes	Yes	No	50+ years	Moderate to high, depends on the application
Stained Substitute Stone	Limited unit replacement Conceal patching or Dutchman	Yes	Yes	Somewhat	approx 15 years	Moderate to high, depends on the application

Table 18. Summary of Findings.

11.0 RECOMMENDATION FOR FURTHER TESTING

The following recommendations for further testing will yield a more comprehensive evaluation of all the factors which may impact the durability of a repair.

11.1 COMPOSITE REPAIR MORTAR

Bond Strength of Lithomex on Different Stones - Bond strength is affected by the porosity and surface texture of the host masonry. Poor bond strength will likely lead to detachment.

Accelerated Weathering of different products – Lime-based, Cement-based, or other composition may impact the performance of a composite repair mortar.

Impact of Vapor Transmission between Portland cement-based product and Lime-based product – Portland cement is known to be less vapor permeable than most stone. This test aims to evaluate if Portland cement-based products adversely affect the natural vapor permeability of a stone.

Cause of swelling/weight gain – petrographic study or scanning electron microscopy to examine the presence of contaminants as potential cause.

Range of acceptable vapor and water permeability difference – additional research and natural weathering of Lithomex patching on serpentine may determine if the lowered WVT and permeance would cause deterioration to the stone.

11.2 POTASSIUM SILICATE STAIN

Depth of Penetration – since potassium silicate stain bonds directly to its host masonry, depth of penetration has a direct effect on the durability of the coating. This test can establish a more accurate expected service life of the product.

Accelerated Weathering on Different Stones – potassium silicate stain's performance is directly related to its host masonry since the porosity of the stone impacts the depth of penetration. This test can establish a more accurate expected service life of the product on different host masonry.

Impact of Different Application Technique on Durability – different application techniques (i.e. brush on vs. spray on) can be used to achieve aesthetic appearance. It is important to understand of they will impact the service life of the product.

Impact of Ultraviolet Light on Pigments – spectrophotometric analysis indicated a significant lightening of the color. This test will determine if the lightening is a result of pigment degradation from ultraviolet light.

Bibliography

Section 1

None

Section 2

Brown, Kathryn Elizabeth. "Assessment and Evaluation of Consolidation Methods on Serpentine Stone at the 19th Street Baptist Church, Philadelphia, PA." Theses (Historic Preservation), University of Pennsylvania, 2013.

Dorchester, Jane Elizabeth. (2001).*The Evolution of Serpentine Stone as a Building Material in Southeastern Pennsylvania: 1727-1931*. (Master's Thesis). University of Pennsylvania, Philadelphia, PA.

Farndon, John. *Illustrated Guide to Rocks & Minerals*. Lorenz Books, 2018.

Upton, Dell, and John Michael Vlach, eds. *Common Places: Readings in American Vernacular Architecture*. Athens: University of Georgia Press, 1986.

Section 3

Chaux et Enduits de St Astier. "Raw Materials & Production of St Astier Pure and Natural Hydraulic Lime," 2016. http://www.stastier.co.uk/nhl/info/pdfs/Raw_Materials_and_Production_of_NHL.pdf.

Henry, Alison, and Jill Pearce, eds. *Stone Conservation: Principles and Practice*. Shaftesbury: Routledge, 2015.

Holmes, Stafford, and Michael Wingate. *Building with Lime*. Revised Edition. Practical Action Publishing, 2002.

Lime*works*.us. "Colorwash Stain for Masonry Technical Data Sheet." Accessed March 16, 2019. https://limeworks.us/wp-content/uploads/2017/06/ecologic-colorwash-data-sheet.pdf.

Prah, Araba (2017). *A Performance Evaluation and Assessment of Mineral Silicate Coatings for the Restoration of the Exterior Concrete at Jackson Lake Lodge*. (Master's Thesis). University of Pennsylvania, Philadelphia, PA.

Section 4

Chaux et Enduits de St Astier. "Raw Materials & Production of St Astier Pure and Natural Hydraulic Lime," 2016. http://www.stastier.co.uk/nhl/info/pdfs/Raw_Materials_and_Production_of_NHL.pdf.

"KEIM History - Keimfarben." Accessed February 23, 2019. https://www.keim.com/en-gb/about-us/keim-history/.

Holmes, Stafford, and Michael Wingate. *Building with Lime*. Revised Edition. Practical Action Publishing, 2002.

Henry, Alison, and Jill Pearce, eds. *Stone Conservation: Principles and Practice*. Shaftesbury: Routledge, 2015.

Lime*works*.us. n.d. "Colorwash Stain for Masonry Technical Data Sheet." Accessed March 16, 2019. https://limeworks.us/wp-content/uploads/2017/06/ecologic-colorwash-data-sheet.pdf.

Lime*work*s.us. n.d. "St-Astier-Lithomex-Technical-Data-Sheet.Pdf." Accessed April 25, 2019. https://limeworks.us/wp-content/uploads/2017/06/st-astier-lithomex-technical-data-sheet.pdf.

Section 5

None

Section 6

Hertz, Chris. "Thesis Review," April 8, 2019.

Section 7

American Society for Testing and Materials. "ASTM E96 Standard Test Method for Water Vapor Transmission of Materials," 2000.

Artec 3D. "Space Spider Info Sheet," n.d. https://www.artec3d.com/files/pdf/Space-Spider-Booklet-EURO.pdf.

"Introduction to Color Space." Accessed March 30, 2019. http://www.arcsoft.com/topics/photostudio-darkroom/what-is-color-space.html.

Knicker, Mike. "3D Scanning Basics: How Structured Light Scanning Works." Accessed April 2, 2019. https://info.qpluslabs.com/blog/3d-scanning-basics-how-structured-light-scanning-works.

Konica Minolta. "Spectrophotometer CM-2600d/2500d Instruction Manual." Accessed March 30, 2019. https://sensing.konicaminolta.us/uploads/cm-2600d-2500d_instruction_eng-519q17w94r.pdf.

Prah, Araba (2017). *A Performance Evaluation and Assessment of Mineral Silicate Coatings for the Restoration of the Exterior Concrete at Jackson Lake Lodge*. (Master's Thesis). University of Pennsylvania, Philadelphia, PA.

"Three-Dimensional CIELAB Color Space (Adapted from Li et Al. 2005 [96])." ResearchGate. Accessed March 30, 2019. https://www.researchgate.net/figure/Three-dimensional-CIELAB-color-space-adapted-from-Li-et-al-2005-96_fig3_26547925.

Section 8

Buj, O, and Gisbert, J. "Evaluation of Three Consolidants on Miocene Sandstone from the Ebro Basin." In *Proceedings of the International Conference on Heritage, Weathering and Conservation, HWC 2006*, 2:741–747, 2006.

Section 9

"Building Melting." *The Philadelphia Inquirer*, July 15, 1974.

"College Hall." University of Pennsylvania Facilities and Real Estate Services, December 20, 2012. https://www.facilities.upenn.edu/maps/locations/college-hall.

"College Hall Restoration Exit Study. University of Pennsylvania Philadelphia, PA." Philadelphia, PA: University of Pennsylvania, September 4, 1991. Facilities and Real Estate Services.

Conproco Corporation. "Matrix_PDB.Pdf." Accessed March 29, 2019. http://conproco.com/wp-content/uploads/2015/11/Matrix_PDB.pdf.

"Conproco » FAQ – Stone Repair." Accessed March 29, 2019. https://conproco.com/professional-tips-stone-repair/.

Cyphers, Rex. St. Francis of Assisi Interview with WDP & Associates Rex Cyphers. Phone interview, January 25, 2019.

Doukakis, Constantine (Dean). "UPenn Thesis, College Hall Case Study Review," April 5, 2019.

Doukakis, Constantine (Dean), and Brian D. Wentz. College Hall Interview with Keast and Hood Structural Engineers Constantine (Dean) Doukakis and Brian D. Wentz. In person interview, January 24, 2019.

Keast & Hood Co. "Structural Investigation: College Hall," June 8, 1988. Supplemental Reports. Archive of Marianna Thomas Architects. "University of Pennsylvania College Hall Construction Chronology Plus Interior & Exterior Assessments with Proposed Remediations." Philadelphia, PA: University of Pennsylvania, June 1, 2005. BLDG 95. Facilities and Real Estate Services.

Knapp, Vern, and Jennifer Knapp. College Hall Interview with Masonry Contractor Vern Knapp and Jennifer Knapp. In person interview, February 25, 2019.

Lewin, Seymour Z. "Stone Conservation Survey: College and Logan Halls, University of Pennsylvania." Department of Chemistry, New York University, 1986. Archive of Marianna Thomas Architects.

Lukens, Rodney, Gregory Hess, Ralph Hart, Cody Wilson, and Van Burriss. Recitation Hall Interview with Rodney Lukens, Gregory Hess, Ralph Hart, Cody Wilson, and Van Burriss. In person interview, March 11, 2019.

Meierding, Thomas C. "Weathering of Serpentine Stone Buildings in the Philadelphia, Pennsylvania, Region: A Geographic Approach Related to Acidic Deposition." In *Special Paper 390: Stone Decay in the Architectural Environment*, 390:17–25. Geological Society of America, 2005. https://doi.org/10.1130/0-8137-2390-6.17.

Neil, Steve. "St. Francis of Assisi, Staunton, Rededicated | The Catholic Virginian," May 23, 2016. https://www.catholicvirginian.org/?p=1392.

Peters, Laura. "St. Francis Gears up for the Great Reveal." The News Leader, March 17, 2016. https://www.newsleader.com/story/news/local/2016/03/16/st-francis-gears-up-great-reveal-catholic-church-renovation/81824458/.

Richards, T.W. "Specification for the Construction of a College Building for the University of Pennsylvania on Locust St. between 34th & 36th Sts.," 1871. Archive of Marianna Thomas Architects.

Schnabel Conservation L.L.C. "Stone Conservation Assessment for Recitation Hall Serpentine," September 19, 2008.

Schnabel, Lorraine. Recitation Hall Interview with Architectural Conservator Lorraine Schnabel. In person interview, February 8, 2019.

"St. Francis of Assisi Catholic Parish, Staunton, Virginia." Accessed April 10, 2019. http://stfrancisparish.org/tour.html.

"St. Francis of Assisi Facade Investigation & Replacement, Staunton, VA." WDP & Associates, February 12, 2015. https://www.wdpa.com/projects/st-francis-assisi-facade-investigation-replacement-staunton-va.

"Stone of College Hall Crumbles with Old Age." *Telegraph*, September 15, 1913.

Thomas & Newswanger Architects. "College Hall Masonry Probes," February 23, 1987. Supplemental Reports. Archive of Marianna Thomas Architects. "Study Phase Meeting Memorandum No. 2," February 8, 1989. Supplemental Reports. Archive of Marianna Thomas Architects.

Thomas & Newswanger Architects, Clio Group, Inc., Keast & Hood Company, Dr. Seymour Z. Lewin, Archway Contracting Company, Inc., Robert E. Linck, and Arena & Company, Inc. "College Hall Feasibility Study MTA Project 8610.Pdf," December 1986. Archive of Marianna Thomas Architects.

Thomas, Marianna. "College Hall: A Team Approach to Restoration," December 12, 1991. Supplemental Reports. Archive of Marianna Thomas Architects. College Hall Case Study Interview with Architect Marianna Thomas. In person interview, March 4, 2019.

"Thomas Webb Richards | University Archives and Records Center." Accessed March 6, 2019. https://archives.upenn.edu/exhibits/penn-people/biography/thomas-webb-richards.

University City Historical Society. "College Hall." College Hall, University of Pennsylvania. Accessed March 23, 2019. http://uchs.net/HistoricDistricts/collegehall.html

Vermont Verde Antique L.L.C. "Vermont Verde Antique Architectural Information Kit," n.d., 5.

Webster, Richard J. "West Chester Uni District Nomination" February 17, 1981.

<u>Section 10</u>

None

<u>Section 11</u>

None

Appendix A – Product Data

001-11/2018-ENG

Professional 3D scanning solutions

Artec 3D

Industrial design and manufacturing / Healthcare
Science and education / Art and design

CERTIFIED Solution Partner
SOLIDWORKS

Artec 3D

Offices

2, rue Jean Engling,
Luxembourg, L-1466

2880 Lakeside Drive, #135,
Santa Clara, CA 95054, USA

info@artec-group.com
www.artec3d.com


Artec Eva and Space Spider:
The perfect package for mass production, industrial design & more
Artec Eva and Space Spider are the ideal 3D scanners for professional use. Unrivalled in their scanning quality, they are proven to scan fast and in very high resolution, while being easy to use.
Very high resolution
Create a quick, textured and accurate scan of medium to large surface areas with Eva, and use Artec Space Spider to scan small areas, capturing intricate detail with minute precision.
Artec 3D
GIGABYTE

A tried and tested product used in a wide range of industries

Artec Eva and Space Spider are used in countless industries, including quality control, the automotive industry, medicine, heritage preservation, computer graphics, design, forensics, education, reverse engineering and architecture.

Artec Studio professional 3D data processing software

Scan with Artec Studio advanced 3D data processing software for editing data fast and effectively using Artec's unparalleled algorithms. Then export the results into a wide range of formats: OBJ, PLY, WRL, STL, AOP, ASCII, Disney PTX, E57, XYZRGB, CSV, DXF, XML

Use models in a wide range of software:

AUTODESK. SOLIDWORKS Geomagic blender

Artec Eva and Space Spider:

New possibilities for forward thinking industries

From rapid prototyping to quality control, CGI to heritage preservation, the automotive industry to forensics, medicine and prosthetics to aerospace, Artec Eva and Space Spider are used to customize, innovate and streamline a wide range of different industries.

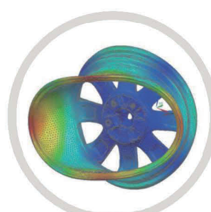
In focus: Reverse engineering

Test and redesign a part without manufacturing defects using 3D scan data.

Scan your object fast and with high accuracy

Create your 3D model using Artec Studio algorithms

Export to simulation software



Analyze how the object reacts under specific conditions

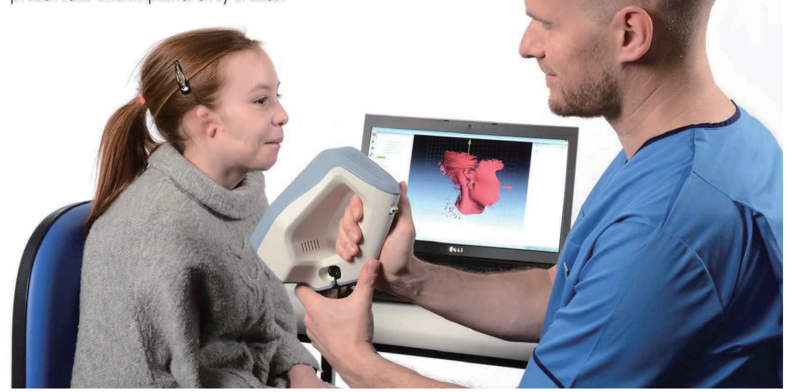
In focus: CGI

Digitally capture a person or object to create a 3D CG model for use in visual effects.

Artec Eva and Space Spider are widely used in the entertainment industry, including by TNG Visual Effects, who have provided their 3D scanning services to blockbuster films such as Twilight: Breaking Dawn 1 & 2 and Man of Steel.

In focus: Orthotics and Prosthetics

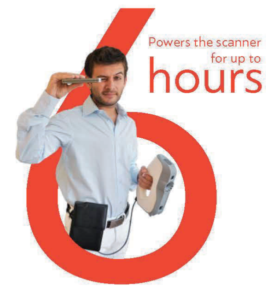
Use Artec Spider to capture the geometry of ears with precision so as to design custom implants for patients with ear deformities. Artec Spider is well-suited for digitizing the deeper surfaces within the ear canal as well as the area between the ear and the head. With the help of an Artec 3D scanner, surgeons can rest assured that they'll never have to approximate models for the prosthetics and implants they create.



3D scanning has never been so portable

Artec handheld 3D scanners are compatibile with both lightweight laptops and tablets, making for the best all round user experience. Plus with the Artec battery pack, which gives up to 6 hours scanning time, you really can take Artec scanners anywhere, capturing objects right in the field.

Artec battery pack



Compatible tablets & lightweight laptops*

Tablets: Microsoft Surface Pro 4, Surface Pro 3, Wacom Mobile Studio Pro 13" & 16" i7 512 GB, Wacom Cintiq Companion 2
Lightweight laptops: Dell XPS 15, HP Omen, HP ZBook 15 G3 Mobile Workstation, Gigabyte P34G v2

**These models have been tested and verified by Artec, however other lightweight options may also be available.*

Artec Eva and Space Spider:

What you need to know

Extremely versatile

Scan a broad range of objects with Artec Eva and Space Spider. Use Eva for medium to large objects and Space Spider for small objects

Fast and accurate

Eva scans fast, capturing and simultaneously processing up to two million points per second with up to 0.1mm accuracy

Speed and precision

Artec Space Spider processes up to one million points per second and produces images of extremely high resolution *(up to 0.1 mm)* and superior accuracy *(up to 0.05 mm)*

Target free

No object preparation needed. Start scanning from the word go

Easy integration

Integrate Artec Eva or Space Spider into your own scanning system using Artec Scanning SDK

Portability

Lightweight and battery compatible, you can take Artec scanners anywhere. The Artec battery pack provides power for up to 6 hours of scanning

Safe to use

Artec scanners employ structured light technology and are totally safe for scanning people

Tablet compatibility

Scan with a tablet for greater mobility

Real-time scanning

Frames are automatically aligned in real time

High resolution

Scan in brilliant colour and high resolution *(Eva up to 0.5mm, Space Spider up to 0.1 mm)*

3D video mode

Scan a moving object and record a real-time 3D video

Bundling

Several scanners can be bundled together and synced to scan larger objects automatically

Artec Studio 13

Revolutionary 3D scanning and data processing software

Enjoy the smartest, easiest and most effortless scanning ever with Artec Studio 13

Easy 3D scanning with Artec Studio 13

Creating 3D scanning masterpieces requires smart and powerful software to capture, process, analyze and edit data.

Now anyone can achieve professional results with the most comprehensive and straightforward 3D scanning software on the market today.

- User-friendly and intuitive interface for smooth, expertly guided 3D scanning
- Quick and easy start-up process. No special positioning requirements, just point and shoot
- Artec Studio 13 software is compatible with tablets as well as 3D sensors, and together with the battery pack for the 3D scanner, you can easily create professional scans anytime and anywhere
- Get high quality scans every time with a smart tracking system that ensures correct movement of the scanner and object capture
- Stop or pause scanning and continue exactly from where you left off, with the smart auto-continue feature
- Achieve equally great results using both manual and Autopilot modes

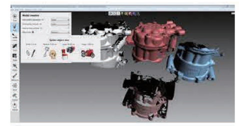
Smart, fast and automated post-processing

What was once tricky and time consuming for new and inexperienced users is now a thing of the past.

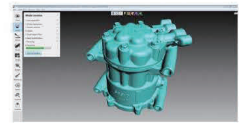
Making accurate 3D models
has never been so straightforward

Introducing AUTOPILOT – the smartest and most advanced post-processing mode ever. Create professional 3D objects in just a few clicks

Autopilot. An essential tool for beginners, a time saver for experienced users

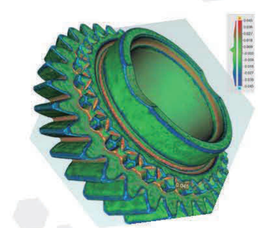


Answer a few easy questions about the object you have scanned, including its size, geometry and texture. All the questions are illustrated with clear examples.



Based on the info provided, Autopilot automatically chooses the right algorithms and settings to create the best possible result.

Fast and accurate application of automatically selected settings for all the processing stages: Creates a high precision 3D model in no time.



Thorough analysis in Artec Studio

- Get all the needed measurements, including the surface size and the volume of your model
- Compare your scans and models
- Annotate your 3D object

Export files to CAD in one click

- Export scanned model to CAD software with just one click
- Export files to 3D Systems' Design X software
- Effortlessly export your 3D model directly to SOLIDWORKS in seconds

EXPORT YOUR MODEL TO A WIDE RANGE OF POPULAR SOFTWARE

AUTODESK. SOLIDWORKS Geomagic blender

Eva

Artec's fastest structured-light 3D handheld scanner

Space Spider

Metrological device for superior precision

Long-term repeatability in data capture

Automatic temperature stabilization

Artec Studio 13
Ultimate

For use with Artec 3D scanners and 3rd party sensors*

Artec Studio 13
Professional

For use with all Artec 3D scanners

All Artec handheld scanners come with a USB cable and power cord.

**Compatible sensors: Kinect for Windows V1 & V2, Intel RealSense F200 (IVCAM), R200 (DS4) & SR300, PrimeSense Carmine, ASUS Xtion, XYZprinting 3D scanner.*

Where to buy
Artec Scanners

Find Artec Eva and Space Spider in stock at over 110 distribution centers worldwide.

www.artec3d.com/where_to_buy

Global support, training and integration

offered by every distribution center and online by Artec's dedicated support team.

Optional extras:


Battery pack


Shoulder bag


Hard carry case

Artec Scanning SDK free to download

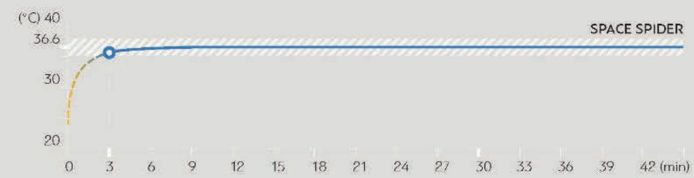
www.artec3d.com/3d-software/sdk

<table>
<tr><th></th><th>EVA</th><th>SPACE SPIDER</th></tr>
<tr><td>Ability to capture texture</td><td colspan="2">Yes</td></tr>
<tr><td>3D resolution, up to</td><td>0.5 mm</td><td>0.1 mm</td></tr>
<tr><td>3D point accuracy, up to</td><td>0.1 mm</td><td>0.05 mm</td></tr>
<tr><td>3D accuracy over distance, up to</td><td colspan="2">0.03% over 100 cm</td></tr>
<tr><td>Texture resolution</td><td colspan="2">1.3 mp</td></tr>
<tr><td>Colors</td><td colspan="2">24 bpp</td></tr>
<tr><td>Light source</td><td>flash bulb</td><td>blue LED</td></tr>
<tr><td>Working distance</td><td>0.4 – 1 m</td><td>0.2 – 0.3 m</td></tr>
<tr><td>Linear field of view, H×W @ closest range</td><td>214×148 mm</td><td>90×70 mm</td></tr>
<tr><td>Linear field of view, H×W @ furthest range</td><td>536×371 mm</td><td>180×140 mm</td></tr>
<tr><td>Angular field of view, H×W</td><td colspan="2">30 x 21°</td></tr>
<tr><td>Video frame rate, up to</td><td>16 fps</td><td>7.5 fps</td></tr>
<tr><td>Exposure time</td><td colspan="2">0.0002 s</td></tr>
<tr><td>Data acquisition speed, up to</td><td>2 million points/s</td><td>1 million points/s</td></tr>
<tr><td>Multi core processing</td><td colspan="2">Yes</td></tr>
<tr><td>Dimensions, H×D×W</td><td>261.5×158.2×63.7 mm</td><td>190×140×130 mm</td></tr>
<tr><td>Weight</td><td colspan="2">0.85 kg / 1.9 lb</td></tr>
<tr><td>Power consumption</td><td>12V, 48W</td><td>12V, 24W</td></tr>
<tr><td>Interface</td><td colspan="2">1 x USB 2.0, USB 3.0 compatible</td></tr>
<tr><td>3D mesh formats</td><td colspan="2">OBJ, PLY, WRL, STL, AOP, ASCII, PTX, E57, XYZRGB</td></tr>
<tr><td>3D point cloud formats</td><td colspan="2">BTX, PTX</td></tr>
<tr><td>Formats for measurements</td><td colspan="2">CSV, DXF, XML</td></tr>
<tr><td>Processing capacity</td><td colspan="2">40 million triangles / 1GB RAM</td></tr>
<tr><td>Supported OS</td><td colspan="2">Windows 7, 8 or 10 – x64</td></tr>
<tr><td>Minimum computer requirements*</td><td>i5 or i7 recommended, 12Gb RAM</td><td>i5 or i7 recommended, 18Gb RAM</td></tr>
<tr><td>Calibration</td><td colspan="2">no special equipment required</td></tr>
</table>

*Please refer to www.artec3d.com for detailed hardware requirements.

Space Spider

Warm up period for achieving maximum accuracy

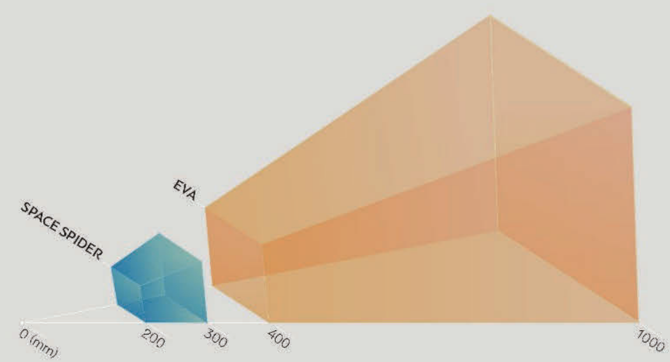


To achieve the very best results, every measurement tool is usually tuned to the conditions of a particular use case. Space Spider, however, keeps its precision in a wide range of temperatures and adjusts to the conditions in only 3 minutes, saving you precious time.

temperature range for achieving maximum accuracy

Field of view

of Artec Scanners



Colorwash Stain for Masonry

Technical Data Sheet

Interior & Exterior Silicate Dispersion
Paints & Stains for Concrete, Stone, Bricks, Concrete Block,
Lime and Cement Mortar, Plaster, and Drywall

Last Modified: Jul 21, 2015

Properties

Ecologic™ Colorwash Stain is a highly durable Silicate Dispersion Stain for interior and exterior use. It is breathable, anti-microbial, mildew resistant, non-combustible, flame retardant, washable & bonds by soaking into the surface. Cures by petrifying and molecularly bonding to masonry substrates.

Ecologic™ Colorwash Stain is 96% mineral-sourced in a water-base. It is odorless within hours (zero VOCs) and displays all the properties of natural stone (i.e, it is water-vapor permeable.) It does not blister or peel, is water-repellent, and has a life expectancy of 20 plus years.

Not suitable for:
Wood (not stable), plastic, metal (non-absorbent), floors (mechanical abrasion) and gypsum plaster (not chemically neutral).

Where to use it

Ecologic™ Colorwash Silicate Dispersion Stain can be used on rigid, absorbent, mineral-based, chemically neutral wall surfaces. Ideal are mineral-based surfaces such as concrete, lime & cement plaster (stucco), unglazed brickwork and even old powdery stucco after it has been solidified by a mineralizing coat of Ecologic™ Waterglass Primer & Consolidant.

Color

White and 11 full-tone colors, all colors come as solid stains, but can be diluted down with Ecologic™ Colorwash Stain clear to a semi-transparent or fully transparent coating. The color brilliance of transparent stains can be increased by painting them over a light undercoat of Ecologic™ Potassium Silicate Paint. Custom tinting is available for minimum order quantities.

Coverage

Approx. 320 – 360 sq ft. per 1 gallon (4 liter) (varies depending on surface type, pretreatment, and dilution)

Drying Time

Depending on temperature and relative humidity, dry to touch after approx. 1 – 2 hrs, but allow at least 12 hours for thorough drying before re-coating.

Colorwash Stain for Masonry

Technical Data Sheet

Interior & Exterior Silicate Dispersion
Paints & Stains for Concrete, Stone, Bricks, Concrete Block,
Lime and Cement Mortar, Plaster, and Drywall

Application

Stir well before use. Do not use if the working (air + substrate) temperature is below 41ºF (5ºC) or above 100.4ºF (38ºC). Apply by brush, roller, or airless sprayer depending on surface roughness.

Cleaning	Wash tools with warm water and soap immediately after use.
Storage	Keep containers tightly sealed in a cool, dry, and frost-free place. Shelf life is 24 months in unopened containers.
Safety	Keep containers tightly sealed. Keep out of reach of children. Do not empty into drains or water sources, but let dry and discard solid leftovers with regular garbage. Use goggles and protective gear when working over-head.
Ingredients	Water, potassium silicate, earthen & mineral pigments, pure acrylate stabilizer, ammonium solution, polysaccharide, cellulose, sodium-phosphonate, fatty acid defoamer, hydrophobing agent.

General Preparation

Surfaces must be rigid, absorbent, and chemically neutral or alkaline, dry, clean, and free of dust, oily residues, and grease. Remove any loose plaster and make good with alkaline absorbent filler. Old coats of latex and alkyd paints must be removed completely in order to restore surface absorbency. Protect adjacent glass, metal, ceramic, etc against splatters and remove unavoidable splatters immediately with water.

Note:
Silicate Paint products are slightly alkaline. ***(pH = 8.5 – 9.0)***

Old Lime & Cement Stucco, highly absorbent Mineral Surfaces – Outdoors

Solidify powdery, sanding mineral surfaces such as mortar, stucco, adobe, concrete, or old unglazed brickwork with one conditioning coat of Ecologic™ Waterglass straight. Ecologic™ Waterglass is available as an opaque to semi-transparent coating. Details to be discussed with our sales staff.

Concrete, Mortar, Stucco, etc. – Outdoors

On new concrete etc. make sure surfaces are fully cured, i.e. min. 30 days old at time of painting. Remove any oily residues such as form release agents, etc.
On old cleaned / restored concrete use 1 coat diluted with up to 10% Ecologic™ Waterglass plus 1 coat undiluted.

Colorwash Stain for Masonry

Technical Data Sheet

Interior & Exterior Silicate Dispersion
Paints & Stains for Concrete, Stone, Bricks, Concrete Block, Lime and Cement Mortar, Plaster, and Drywall

Tinting Ecologic™ Colorwash Stain

In small quantities: Full tone Ecologic™ Colorwash Stain can be mixed to create different shades. For added depth of color and less transparency they can be added by creating a paste with Ecologic™ Waterglass and thoroughly mixing.

To increase transparency, add Colorwash Clear (00). Pigment content should not exceed 15% by weight. For more brilliant color shades use semi-transparent tinted Ecologic™ Colorwash Stain over a white base of Ecologic™ Potassium Silicate for both indoor and outdoor applications

In large quantities: Custom-tinting is available with a minimum volume requirement.

Mix thoroughly with an electric drill mixer (2500 RPM) or equivalent. Do not use other manufacturers' tints or pigments with Silicate Paints, since they may be silicate-resistant, or not sufficiently lightfast.

conproco®

Matrix

Trowel applied, cementitious repair mortar, formulated to be compatible with the color and physical properties of parent material.

WHERE TO USE
Repair and reconstruct natural and cast stone, terracotta, and brick. Unique on-site color matching by trained, certified technicians.

Performance Characteristics

Low shrinkage
- Maintains integrity of repair, resists cracking.

Thermal compatibility
- Prevents delamination due to temperature change.

Durable
- Resistant to weathering action, excellent freeze/thaw stability and abrasion resistance.

Very low permeability
- Resistant to deicing salts, chloride, and chemical attack, and environmental pollution.

Breathability
- Will not cause damage to structure by restricting moisture vapor flow.

Shaveable
- Recreate sharp edges and architectural details.

Single component
- Easy to batch in less than full pail quantities.

On-site color matching
- Great matches, no wait for factory samples.

Surface Preparation

- Remove loose and deteriorated material, laitance, dirt, dust, oil and any surface contaminants that will inhibit proper bond.
- Saw cut edges with a diamond blade at a 90° angle to eliminate feather edging. Avoid polishing the edges, as this will inhibit bond.
- Avoid bruising or micro cracking during surface preparation. Refer to ICRI Surface Preparation Guide 03732.
- Repair zone must be a minimum of 1/2 inch deep, of simple geometry, with no complex edge conditions.
- Avoid long narrow repairs; these have a greater tendency to crack.
- Apply *Conpro Start* where a consolidant is of benefit.
- Saturate substrate with clean water, (saturated surface dry/SSD), with no standing water during *Priming* or *Application*.
- Remove concrete from corroded steel and several inches beyond to expose non-corroded steel.
- Provide a 3/4 inch clearance between the concrete and steel.
- Damaged reinforcing steel should be inspected by a qualified engineer and appropriate action taken.

Priming

Stone, Terracotta and Concrete
- Prime the prepared substrate including all edges with a bond coat of *Matrix*. Work the bond coat into the substrate to ensure intimate contact and establish bond. The repair mortar must be applied into the plastic bond coat. If the bond coat dries, remove and re-apply.

Embedded Metal and Steel
- Remove all scaling rust from embedded metal and steel.
- Apply *ECB* anti-corrosion coating.

Mixing

- Measure Matrix powder and water to achieve a 4 to 4.5 parts powder to 1 part water ratio (or approximately 1 gallon per 50 lb unit of Matrix).
- Pour measured water into a clean container suitable for mixing.
- Place 1/2 of measured Matrix into mixing container with water and mix until uniform. Add remaining 1/2 Matrix to the mixing container and mix until fully blended to a uniform, lump free consistency.
- Mechanically mix using a low speed drill (400 - 600 rpm) and mixing paddle or mortar mixer.
- Additional water may be added to achieve desired consistency for placement of the Matrix. Over watering the mix will affect final color.
- For multiple batches, the additional water should be added in a uniform fashion to avoid color shift.
- Insufficient water will not hydrate the material and it will not achieve full strength. Mix only as much material as can be placed in 15 - 20 minutes.
- Do not over mix, as this will entrain excess air.
- Do not re-temper, this will affect color.

Application

- At the time of application, surfaces should be saturated surface dry/ damp (SSD) but hold no standing water.
- Follow instructions for *Priming*.
- Force the material against the edges of the repair, working from right to left or left to right.
- Over-build repair zone by 1/4 inch.
- Shave to final form with Mitre Rod up to 2 hours (longer in cold temperature) after application.
- Do not overwork the finish.

Curing

- Ensure repair zone stays properly hydrated. This may vary depending on ambient conditions. If hydration is not maintained, the repair may flash dry and not achieve full strength. Refer to ACI 308R-01 for detailed curing recommendations. If the repair is inaccessible, tape polyethylene over area to retain moisture. Do not allow polyethylene to contact the material.
- Protect repair from direct sunlight, wind, rain and frost during curing period.

Clean Up

- Clean tools and equipment with water immediately after use. Cured material must be removed mechanically.

Matrix

Theoretical Yield

Yield per Pail	Repair Depth	Square Feet
0.5 cubic feet	1/2 Inch	12.00
0.5 cubic feet	1 Inch	6.00
0.5 cubic feet	1.5 Inches	4.50
0.5 cubic feet	2 Inches	3.00

Product Handling

Packaging
- 5 gallon plastic pails – 50 lbs.

Shelf Life
- 18 months when properly stored.

Storage
- Transport and store in cool, clean, dry conditions in unopened containers.
- High temperature or high humidity will reduce shelf life.

Limitations

- Do not apply unless substrate and ambient temperature can be maintained at a minimum of 40°F for 24 hours. Refer to ACI Cold Weather Application Guidelines.
- Cold mixing water and low temperature will retard set. Hot water and high temperature will accelerate set.
- Protect application from precipitation and high wind for at least 24 hours.
- Do not add more water than specified.
- Do not re-temper, as this will affect color.
- Avoid overworking material during placement as this will affect color and cause surface checking.
- Do not allow polyethylene or burlene to touch surface while curing as this will cause whitening of the material.

Health and Safety

- Product is alkaline.
- Do not ingest.
- Avoid breathing dust.
- Avoid contact with skin and eyes.
- Refer to Material Safety Data Sheet (MSDS) for additional information.

First Aid

- In case of skin contact, wash thoroughly with soap and water.
- For eye contact, flush immediately with a high volume of water for at least 15 minutes and contact a medical professional.
- For respiratory problems, remove person to fresh air.

Disposal

- Dispose of material in accordance with local, state or federal regulations.

Technical Data

Physical state and appearance		Dry, pigmented powder		
Base		Portland cement		
pH	Wet mix	>12		
Water/dry material ratio	Wet mix	0.20		
Dry bulk density	ASTM C188	92 lbs./ft.^{3}		
Setting time by vicat needle	ASTM C191	240 minutes		
Percent air – pressure method	ASTM C231	4%		
Water absorption	ASTM C140	11%		
Water vapor transmission	ASTM E96	5.2 perms		
Length change	ASTM C157	<500 µstrains @ 28 days		
Modulus of elasticity	ASTM C469	2.6 x 10^6		
Slant shear bond strength – epoxy	ASTM C882	1800 psi		
		7 Days	**14 Days**	**28 Days**
Compressive strength – psi	ASTM C109	2900		3000
Tensile strength – psi	ASTM C307	400	480	560

conproco®

17 PRODUCTION DRIVE, DOVER, NEW HAMPSHIRE 03820
TELEPHONE 800.258.3500 • FAX 603.743.5744 • WEB ADDRESS www.conproco.com

Artec 3D

Ideal 3D scanner for CAD

Precision at your fingertips

Enhanced 3D scanner featuring improved accuracy system

Developed for the International Space Station

Space Spider

€19,700

Includes 2 year warranty

Designed specifically for CAD users who require absolute precision, Artec Space Spider is ideal for additive manufacturing, reverse engineering, quality control and mass production. Together with Artec Studio software, it is a powerful tool for engineers and industrial designers of every kind.

Objects to 3D scan

Artec Space Spider is perfect for capturing small objects with complex geometry, sharp edges and thin ribs. Scan objects such as molding parts, PCBs, keys or coins, or even a human ear, use a wide range of measurement and editing tools to work with your data and export it to CAD software.

Designed for space, great for Earth

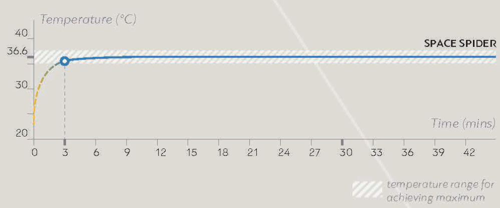
Artec Space Spider was developed to spec for use on the International Space Station. Artec was asked to create a new version of the award-winning Artec Spider which could be relied on to provide the most accurate and stable scanning results in the space station's tough environment for months and months on end – and at speed. The result is the fastest, most reliable precision 3D scanner yet.

Long-term repeatability

Featuring new, higher grade electronics and a dramatically faster warming period, with temperature stabilization at 36.6 °C, Space Spider is a robust 3D scanner which provides long term repeatability and accuracy in its measured data in a broad spectrum of environmental conditions.

Saves you time

To achieve the very best results, every measurement tool is usually tuned to the conditions of a particular use case. Space Spider, however, keeps its precision in a wide range of temperatures and adjusts to the conditions in only 3 minutes, saving you precious time.



Speed and precision

Processes up to 1 million points per second AND produces extremely high resolution (up to 0.1mm) and superior accuracy (up to 0.05mm).

Two-year warranty

Artec Space Spider is here and ready for the long haul. In fact, it's so stable and reliable that we offer a two-year guarantee.

Portability

Extremely light, weighing in at 0.85 kg (1.9 lb) and battery compatible. This means you can really take Artec Space Spider anywhere, even to space!

Target free

No need to stick targets all over your object, just point and shoot.

High resolution and detailed texture

Scan in brilliant color and high resolution (up to 0.1mm).

Real-time scanning

Scan at 7.5 frames per second. Frames are automatically aligned in real-time.

Safe to use

Artec Space Spider uses LED lights and is totally safe to use for scanning both children and adults.

Easy integration

Integrate any Artec 3D scanner into your own customized scanning system using Artec Scanning SDK.

Applications

Artec Space Spider is the perfect solution for rapid prototyping and manufacturing, as well as healthcare, the automotive industry, aerospace, quality control, heritage preservation and graphic design.

www.artec3d.com

Artec 3D

Space Spider specifications

Ability to capture texture	Yes
3D resolution, up to	0.1 mm
3D point accuracy, up to	0.05 mm
3D accuracy over distance, up to	0.03% over 100 cm
Warm up period for achieving maximum accuracy	3 minutes
Texture resolution	1.3 mp
Colors	24 bpp
Light source	blue LED
Working distance	0.2 – 0.3 m
Linear field of view, HxW @ closest range	90 mm x 70 mm
Linear field of view, HxW @ furthest range	180 mm x 140 mm
Angular field of view, HxW	30 x 21°
Video frame rate, up to	7.5 fps
Exposure time	0.0002 s
Data acquisition speed, up to	1 000 000 points/s
Multi core processing	Yes
Dimensions, HxDxW	190 x 140 x 130 mm
Weight	0.85 kg / 1.9 lb
Power consumption	12V, 24W
Interface	1 x USB 2.0, USB 3.0 compatible
Output formats	OBJ, PLY, WRL, STL, AOP, ASCII, PTX, E57, XYZRGB
Output format for measurements	CSV, DXF, XML
Processing capacity	40 000 000 triangles / 1GB RAM
Supported OS	Windows 7, 8 or 10 – x64
Minimum computer requirements	I5 or I7 recommended, 18 GB RAM
Warranty	2 years

www.artec3d.com

001-02/2017-EURO-ENG

DATASHEET

Lithomex

Stone repair and restoration mortar

Specially formulated repair mortar based on Pure Natural Hydraulic Lime and aggregates for the repair or simulation of masonry, brick or stone.

Mixing and use:

Can be mixed manually or mechanically in a typical mortar mixer or with a whisk, adding approximately 1.1 gals water per 55 lbs bag of Lithomex used. Mix well for 3-5 minutes. Adjust final water content carefully to consistency required.
For small quantities mixed by hand, add just sufficient water to make a semi dry crumbly consistency, beat vigorously for a few minutes and carefully add a few drops of water at a time until desired consistency is achieved. (8 oz water to 3lbs Lithomex)
The application surface must be clean, free from dust and oils. On porous surfaces, ensure that suction is controlled by pre-wetting and apply Lithomex before this is fully dry. Never apply to surfaces that are over saturated or have standing water. Lithomex can also be applied on metal lath.

For application on dense impervious materials, please consult us.

The minimum thickness is ¼" (can be dressed or cut back to a feather edge when set).
For projection / moulded work, greater than 4" it may be necessary to pin and dowel.
Applied in thin layers it can be built out to 4" over a working day.
Applied in layers of up to 2" in one pass.
Lithomex is suitable for all types of casting.

Always dampen application areas. The mortar should be well pressed back in place..

Support where necessary with wires, anchorages, stainless steel fixings or formers, etc.

Simulation of stone / brick features, rough finishes, false joints etc. can be made approximately 5 hours from application (in damp cold weather up to 24 hours).
Shaping and forming of details can be carried out for up to 2 - 3 days after placing by scraping to profile or level with metal tools, such as the edge of a trowel or steel float however most shaping and finishing work can be done within 24 hours.
Fine finishes are achieved either by troweling at time of initial setting or by fine carborundum paper after the material is sufficiently hard (usually 7 days)

Carving, using appropriate tools, requires waiting up to a week or more depending on the weather conditions.

DATASHEET

Lithomex

Stone repair and restoration mortar

Where ashlar masonry or very finely jointed masonry has had considerable damage to the arises, flush finishing in Lithomex with a false struck joint is the ideal solution.

If building details are damaged and require repair prior to the façade being lime washed or painted, Lithomex will readily accept lime washes and paints.

On rendered areas Lithomex can be used to form decorative stone or brick features such as mouldings and cornices.
Lithomex's unique qualities allow it to be tooled, shaped and carved even weeks after the final set has taken place. This affords sufficient time to achieve the very highest standard of work with the best quality reproduction.

Technical Data

Bulk density: (kg/m^3) : 1325 â€“ 1360
Granulometry: from 0.8 to 0.08mm
Consumption: 1.6 to 1.7 kg. per m^2 per mm. of thickness

Setting time (in water with no surcharge): start -- 1h30min / end â€“ 2h30min. Tests on paste (water addition 18.7%)

.

Tests on hardened mortar (water addition at 18.7%)

Capillarity	2.06 gr.cm^2. √2 min	**LOW**	tested at 28 days
Water permeability	0.25 ml.m.day	**LOW**	tested at 28 days
Vapour permeability	0.75 gr.m^2.hour.mmHg	**VERY HIGH**	tested at 28 days

	Tensile Strength PSI	**Compressive** Strength PSI	**Elasticity** Moduli MPa	**Shrinkage** mm.m
7 days	319	899		0.81
28 days	346	1052	7690	0.85

The above details are given for information purposes only. Final dosages and application should be checked with our technicians. The Factory reserves the right to alter specifications.

VERMONT Verde ANTIQUE

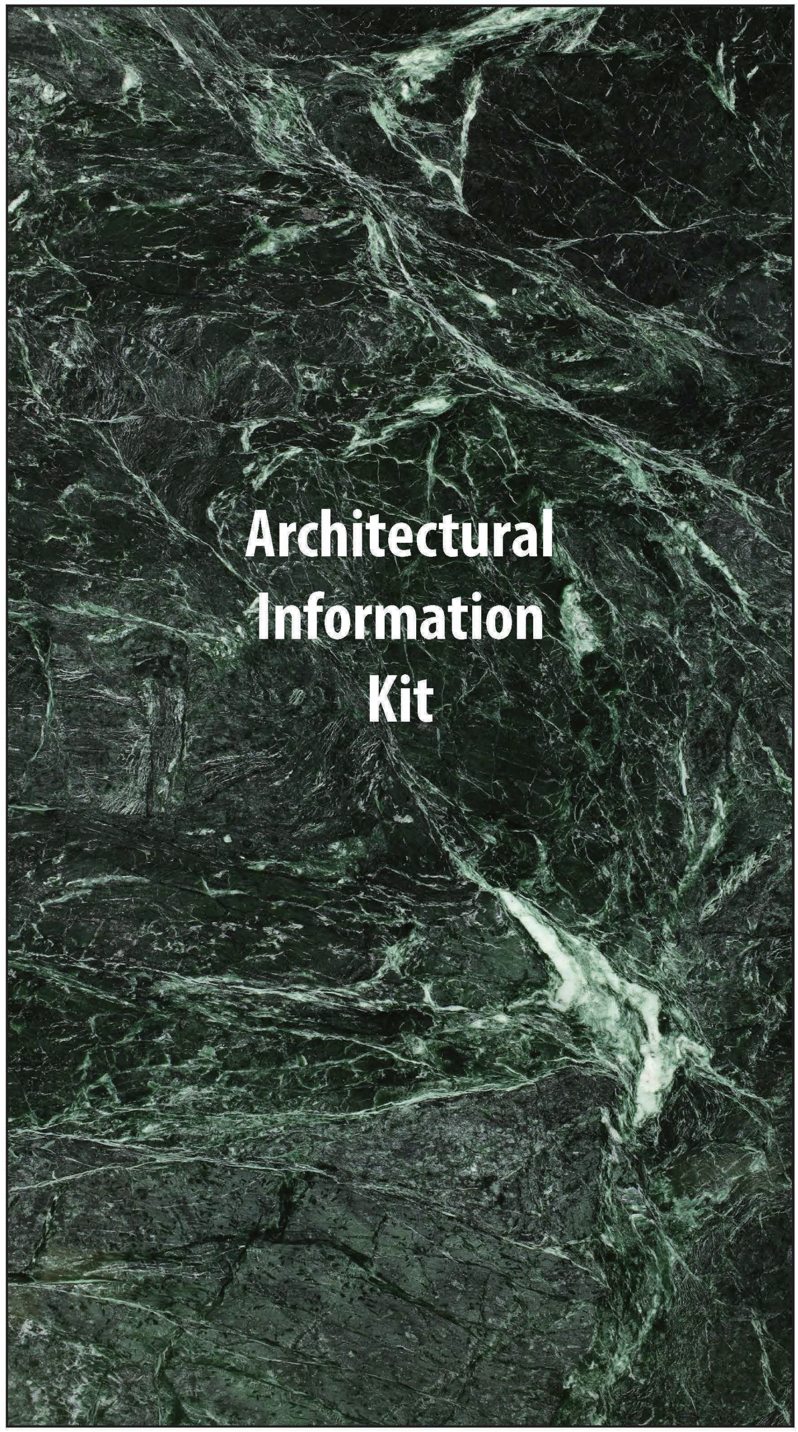
World's Finest Serpentine Stone

Single Source Serpentine

Cut-to-Size Stone

Worldwide Usage

Historical Usage



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Architectural Information Kit

Notable Installations

Recent Projects

Baseball Hall of Fame, Cooperstown, NY
The Battery, San Francisco, CA
East Texas Medical Center, TX
Federal Courthouse, Buffalo, NY
GM Building / Trump International, New York, NY
Rutland Regional Medical Center, Rutland, VT
333 West Wacker Drive, Chicago, IL
7 World Trade Center, New York, NY

A Few of Many Older and Historical Projects

745 7th Avenue, New York, NY
Atkinson Building, Los Angeles, CA
Blair Building, Chicago, IL
Bloomer Building, Rutland, VT
British Columbia Power Commission Building, Victoria, BC
Cartier, New York, Toronto, Phoenix, Boston, Hawaii, Houston
Chittenden Block, Rutland, VT
Conrad National Bank, Kalispell, MT
Equitable Federal Savings and Loan, Lancaster, OH
First National Bank and Trust, Lima, OH
Fountain Theater, Cincinnati, OH
Hall of Administration, Los Angeles, CA
Home Baking Company, St. Mary's, OH
Houston Light and Power Building, Houston, TX
Lincoln Centre, Minneapolis, MN
MacLean Hunter Publishing Building, Toronto, Ontario
NASDAQ Exchange, New York, NY
National Realty Company, Jackson, MI
New England Tel & Tel, Springfield, MA
New York State Capitol, Albany, NY
Northwestern National Life Insurance Building, Minneapolis, MN
Rochester Methodist Hospital, Rochester, MN
Security People's Trust Company, Erie, PA
Union Planters Bank & Trust Company, Memphis, TN
United States Post Office and Court House, Montpelier, VT
University of Vermont Library, Burlington, VT
Vermont State Office Building, Montpelier, VT
Verrazano Narrows Bridge Monument, Staten Island, NY
Wabash Federal Savings and Loan, Terre Haute, IN
Wayne State University, McGregor Memorial, Detroit, MI
Women's Federal Savings and Loan, Cleveland, OH

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Technical Specifications

Technical Information	English	Metrics	Test Method
Absorption by Weight,%	0.15	0.15	(C97)
Density, Lbs/Ft3 (Kg/m3)	179	2,867.3	(C97)
Compression Strength, psi (MPa)	26,124	180.29	(C170)
Abrasion Resistance, Hardness	110	N/A	(C241)
Flexural Strength, psi (mpa)	4178	33.37	(C880)

Geology

Vermont Verde Antique while having the "look" of marble is actually a "serpentine" and classified as a hydrous magnesium silicate. With the hardness and durability of most granite, and its low absorption rate and high flexural strength, it is an excellent choice for both interior and exterior uses.

Serpentine is a major rock forming mineral and is found as a constituent in many metamorphic and weathered igneous rocks. Serpentine's structure is composed of layers of silicate tetrahedrons linked into sheets; this structure is what gives Verde Antique its high flexural strength rating.

Vermont Verde Antique is the commercial name for the serpentine "marble" derived from highly sheared ultramafic rocks that have been rewelded and metasomatized by the process of serpentinization. These ultramafic bodies are now recognized as segments of ancient oceanic crust that became part of the eastern North American continent during the Taconian orogeny. This is considered to be middle Ordovician in age, around 450 million years ago.

More deformation and metamorphism took place during the Acadian orogeny around 360 million years ago. This may have resulted in the polishable Vermont Verde Antique serpentine.

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LEED Rating Information

Under *Energy and Atmosphere* Vermont Verde Antique could positively impact the energy efficiency of a building with its high thermal mass helping to regulate temperature changes.

In the *Materials and Resources* category Vermont Verde Antique's quarry generates almost no waste rock; from the largest block to the smallest piece, everything is now used. We are in fact now utilizing some of the older historic "waste" piles in present projects. Another possibility is that as the building's life cycle is completed the durability of Vermont Verde Antique will allow for its reuse on other projects.

Our quarry and processing plant are ideally located for projects being completed in the Northeast. Our *500 mile local radius* covers all of New England and extends to such cities as New York, Philadelphia, Washington, Pittsburgh and Cleveland.

In the *Innovation and Design* category Vermont Verde Antique could contribute to the performance of the building by helping to reduce life cycle costs in such areas as durability, mold resistance and improved air quality.

We operate both our marble quarry and processing facilities in an environmentally sensitive manner and take pride in our place and commitment to the communities where we live and work.

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Single Source Serpentine

Cut-to-Size Stone

Worldwide Usage

Historical Usage

Architectural Information Kit

Fabrication Capabilities: Cut-to-Size Stone and Much More

The Vermont Verde Antique serpentine stone processing/fabrication facility located in Barre, Vermont employs a staff of experienced craftsmen and can professionally complete any job from residential kitchen or bath countertops to the largest commercial custom cut-to-size work.

Our equipment includes:

- (Three) 3.5 meter blade saws capable of cutting the green slabs to any thickness for custom jobs and unique needs
- A twelve-head line polisher, one of the few in North America, able to produce finishes such as polished, honed and brushed
- A large wire saw with the capacity to cut slabs 16'x8'
- A contour wire saw for curved work and other intricate projects
- Numerous gantry bridge saws for custom cut-to-size jobs

Having our own facility gives our clients a big advantage by being able to select from our large inventory of serpentine slabs and blocks stored inside our 40,000 square foot building for year-round viewing.

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info@vtverde.com
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Appendix B – Formulas

deGruchy's LIME WORKS™.us

Makers of ecologic® Brand Mortar & Plaster For Historic Restoration and Green Building

Phone: 215-536-6706
Fax: 215-536-2281

3145 State Road, Telford, PA 18969

www.LimeWorks.us

Quality Control Worksheet

Recipie Source:	Recall	Number of Batches:	1
Product:	Lithomex	Batch Size:	1
Formula:	LMML-1000	Waste:	0%
Size:	Quart	Output:	Size Change
Company/Customer:			
Project:			
Date:	1/15/2019		
Lot Number:			

Checklist Field	
Provide Formula:	
Verify Formula:	
Measure Base Material(s):	
Measure Pigment(s):	
Blend/Mix (5 min.):	
Take Sample :	
Verify Sample Accuracy:	
Print Labels:	
Apply Labels:	
Package Product:	

Recipie for 1 (Qt) Quart Container.		
Lithomex	1.229	kg
Inclusions Mica	4.980	g
Pigment Black 330	3.630	g
Pigment Yellow 918LO	7.560	g
Pigment Green (Gn)	4.525	g
Total Weight:	1.251	kg

Notes:

Serpentine color to match Munsell 10Y 6/2 (Pale Olive)

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Fax: 215-536-2281
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www.LimeWorks.us

Quality Control Worksheet

Recipie Source:	Recall
Product:	Lithomex
Formula:	LMML-1001
Size:	Quart
Company/Customer:	
Project:	
Date:	1/15/2019
Lot Number:	

Number of Batches:	1
Batch Size:	1
Waste:	0%
Output:	Size Change

Checklist Field	
Provide Formula:	
Verify Formula:	
Measure Base Material(s):	
Measure Pigment(s):	
Blend/Mix (5 min.):	
Take Sample :	
Verify Sample Accuracy:	
Print Labels:	
Apply Labels:	
Package Product:	

Recipie for 1 (Qt) Quart Container.		
Lithomex	1.201	kg
Inclusions Mica	4.865	g
Pigment Black 330	10.195	g
Pigment Yellow 918LO	7.390	g
Pigment Green (Gn)	22.020	g
Pigment Downtown Brown 2005	4.300	g
Total Weight:	1.249	kg

Notes:
Serpentine to match 10Y 4/2 (Grayish Olive)

deGruchy's LIME WORKS™.us — Makers of ecologic® Brand Mortar & Plaster For Historic Restoration and Green Building

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Quality Control Worksheet

Recipie Source:	Recall		Number of Batches:	1
Product:	Lithomex		Batch Size:	1
Formula:	LMML-1002		Waste:	0%
Size:	Quart		Output:	Size Change
Company/Customer:				
Project:				
Date:	1/15/2019			
Lot Number:				

Checklist Field	
Provide Formula:	
Verify Formula:	
Measure Base Material(s):	
Measure Pigment(s):	
Blend/Mix (5 min.):	
Take Sample :	
Verify Sample Accuracy:	
Print Labels:	
Apply Labels:	
Package Product:	

Recipie for 1 (Qt) Quart Container.				
Lithomex		1.228	kg	
Inclusions Mica		4.990	g	
Pigment Black 330		6.010	g	
Pigment Yellow 918LO		7.985	g	
Pigment Green (Gn)		2.030	g	
Pigment Downtown Brown 2005		1.020	g	
Total Weight:		1.250	kg	

Notes:
Serpentine to match 5Y 5/2 (Light Olive Gray)

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Fax: 215-536-2281

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Formula Worksheet

Recipie Source:	Custom		Number of Batches:	1
Product:	Silazur		Batch Size:	1
Formula:	SILML-1004		Waste:	0%
Size:	Sample		Output:	Size Change
Company/Customer:				
Project:				
Date:	1/15/2019			
Lot Number:	Melissa Thesis			

Custom Checklist	
Provide Formula:	
Verify Formula:	
Measure Base Material(s):	
Blend/Mix (5 min.):	
Take Sample :	
Verify Sample Accuracy:	
Print Labels:	
Apply Labels:	
Package Product:	

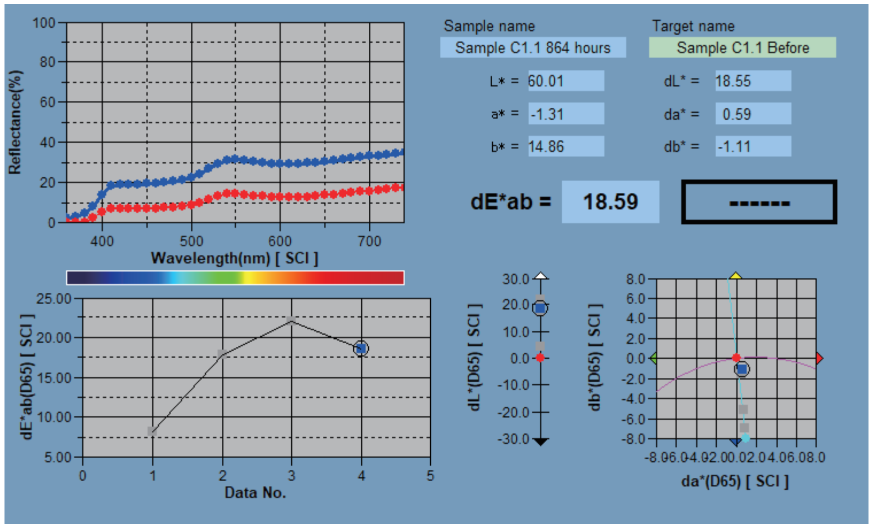
Recipie for 1 Sample.				
Silazur 30 Yellow Ochre		4.005	g	
Silazur 50 Oxide Green		10.000	g	
Silazur 80 Raw Umber		14.940	g	
Silazur 00 White		24.880	g	
Silazur 90 Earth Black		4.535	g	
Silazur Clear		75.400	g	
Total Weight:		133.760	g	

Notes:
Simulation to match bulk color of serpentine sample

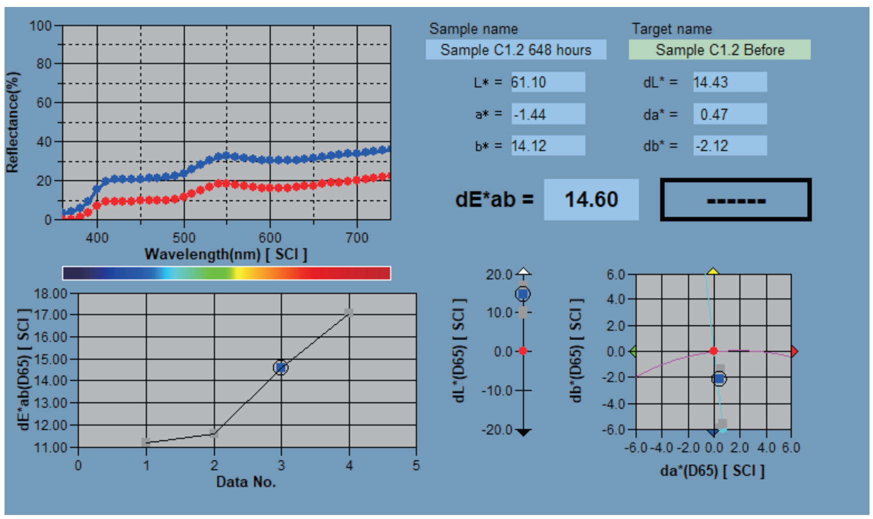
Appendix C – Summary of Testing Program

Testing Program	Purpose	Testing Location	Duration	Reference
Pre-weathering weight	To determine weight change	ACL	48-hour prep, 15 minutes weighing	
Pre-weathering spectrophotometry	To determine color change	ACL	2 hours	ASTM E1164
Pre-weathering Munsell	Additional verification for color change	ACL	2 hours	ASTM D1535
Pre-weathering 3D Scanning	To determine surface profile change	Materials Library	8 Hours	
Accelerated weathering	To determine durability	ACL	864 hours (36 days)	ASTM G147, ASTM G151, ASTM G154
Interim Inspection	Rotation sample position, record color change	ACL	Every 216 hours	ASTM E 1164
Post-weathering weight	To determine weight change	ACL	48-hour prep, 15 minutes weighing	
Post-weathering spectrophotometry	To determine color change	ACL	2 hours	ASTM E1164
Post-weathering Munsell	Additional verification for color change	ACL	2 hours	ASTM D1535
Post-weathering 3D scanning	To determine surface profile change	Materials Library	8 hours	
3D model comparison	To determine surface profile change	Any	4 hours	
Water Vapor Transmission	To determine water vapor transmission rate and permeance	ACL	10 days	ASTM E96

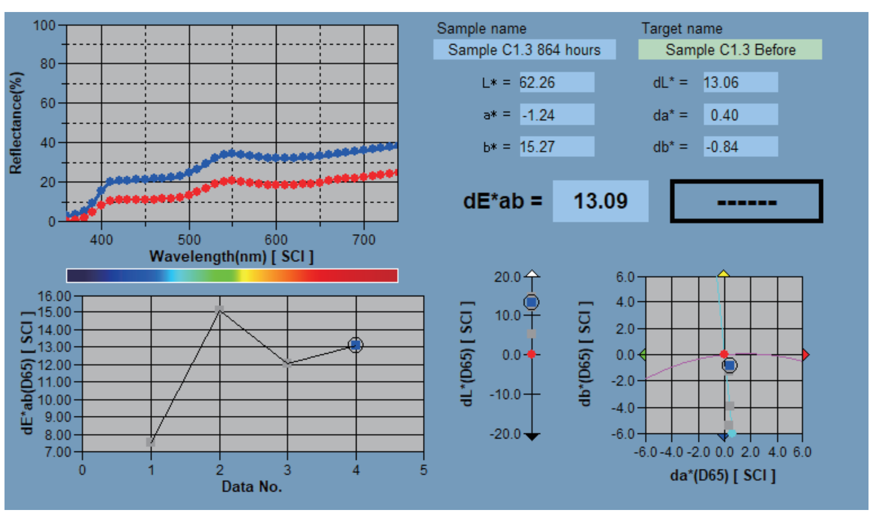
Appendix D – Spectrophotometry Results


Sample name
Sample C1.1 864 hours
Target name
Sample C1.1 Before
L* = 60.01
a* = -1.31
b* = 14.86
dL* = 18.55
da* = 0.59
db* = -1.11
dE*ab = 18.59

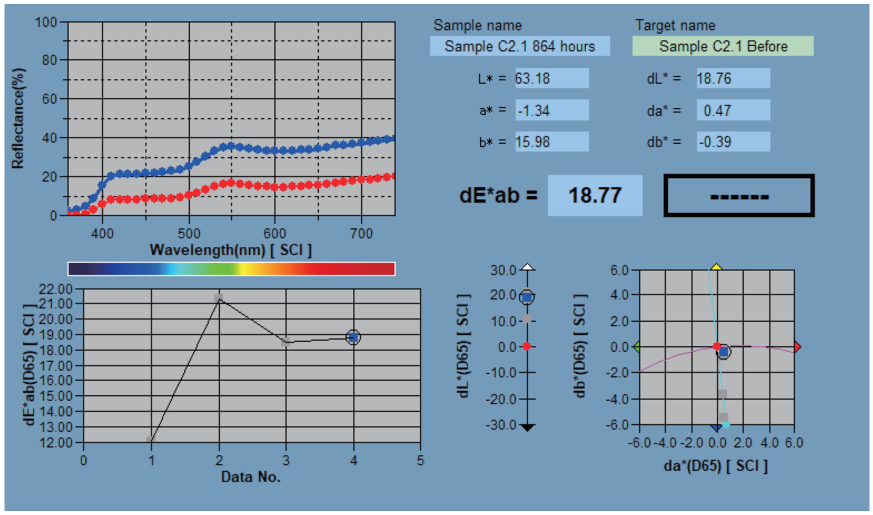
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

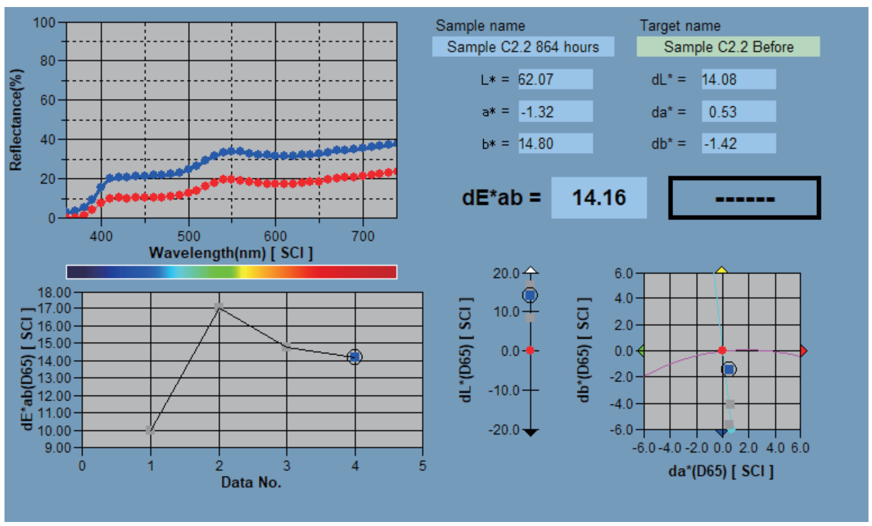

Sample name
Sample C1.2 648 hours
Target name
Sample C1.2 Before
L* = 61.10
a* = -1.44
b* = 14.12
dL* = 14.43
da* = 0.47
db* = -2.12
dE*ab = 14.60

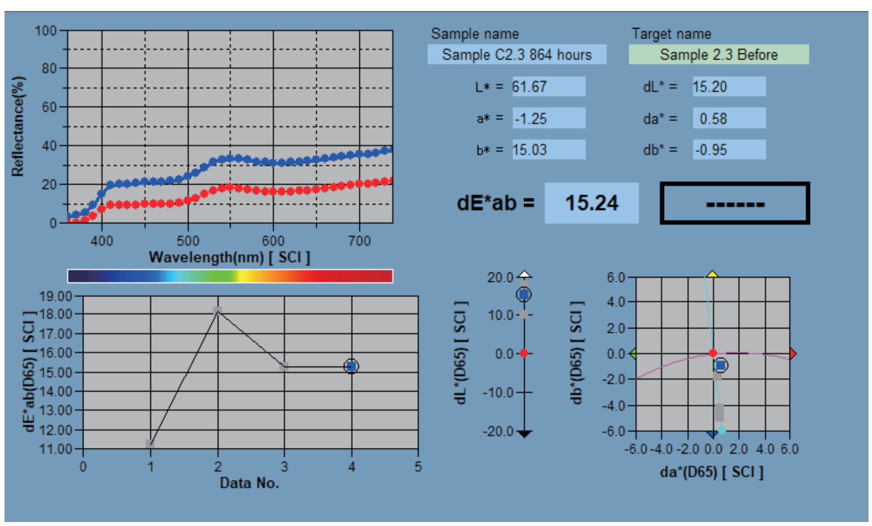
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

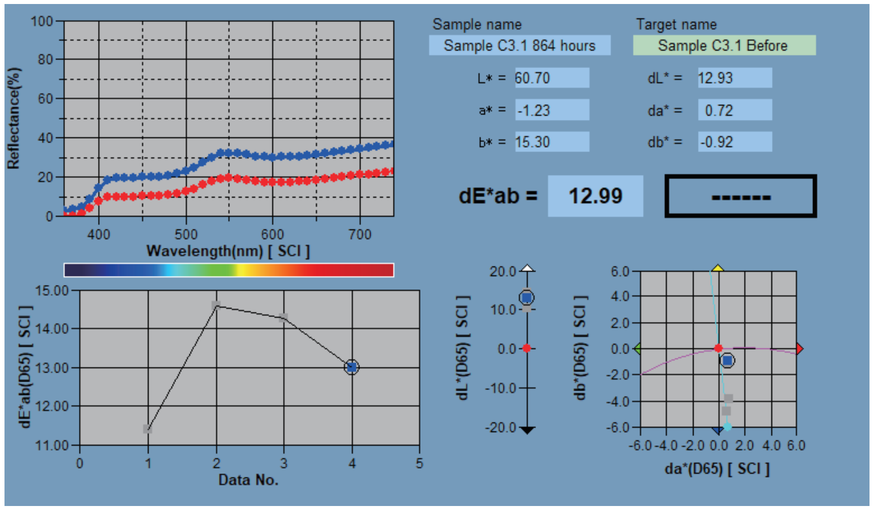

Sample name
Sample C1.3 864 hours
Target name
Sample C1.3 Before
L* = 62.26
a* = -1.24
b* = 15.27
dL* = 13.06
da* = 0.40
db* = -0.84
dE*ab = 13.09

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

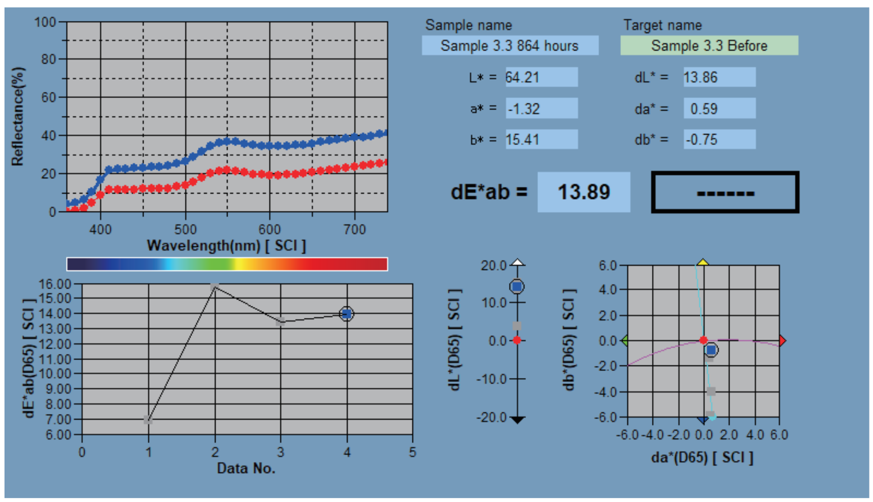

Reflectance(%)
Wavelength(nm) [SCI]
Sample name
Sample C2.1 864 hours
Target name
Sample C2.1 Before
L* = 63.18
a* = -1.34
b* = 15.98
dL* = 18.76
da* = 0.47
db* = -0.39
dE*ab = 18.77
----
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Reflectance(%)
Wavelength(nm) [SCI]
Sample name
Sample C2.2 864 hours
Target name
Sample C2.2 Before
L* = 62.07
a* = -1.32
b* = 14.80
dL* = 14.08
da* = 0.53
db* = -1.42
dE*ab = 14.16
----
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

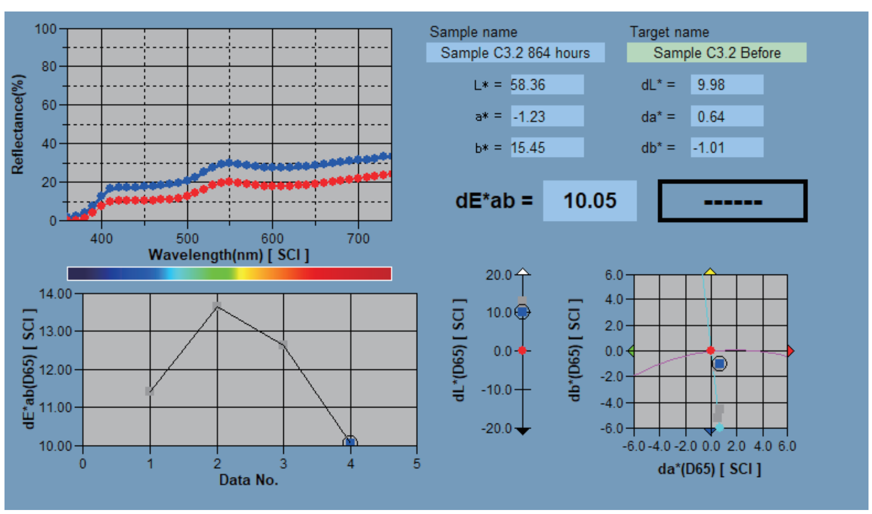

Reflectance(%)
Wavelength(nm) [SCI]
Sample name
Sample C2.3 864 hours
Target name
Sample 2.3 Before
L* = 61.67
a* = -1.25
b* = 15.03
dL* = 15.20
da* = 0.58
db* = -0.95
dE*ab = 15.24
----
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample C3.1 864 hours
Target name
Sample C3.1 Before
L* = 60.70
a* = -1.23
b* = 15.30
dL* = 12.93
da* = 0.72
db* = -0.92
dE*ab = 12.99

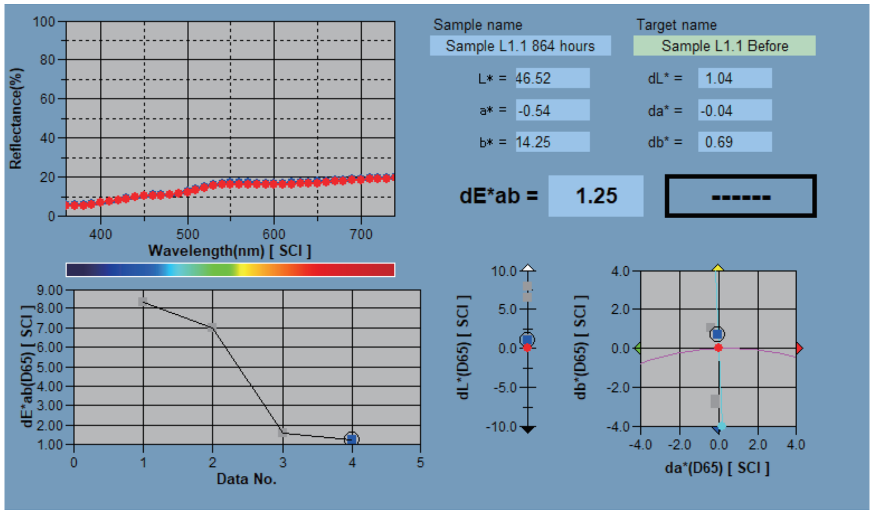
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample 3.3 864 hours
Target name
Sample 3.3 Before
L* = 64.21
a* = -1.32
b* = 15.41
dL* = 13.86
da* = 0.59
db* = -0.75
dE*ab = 13.89

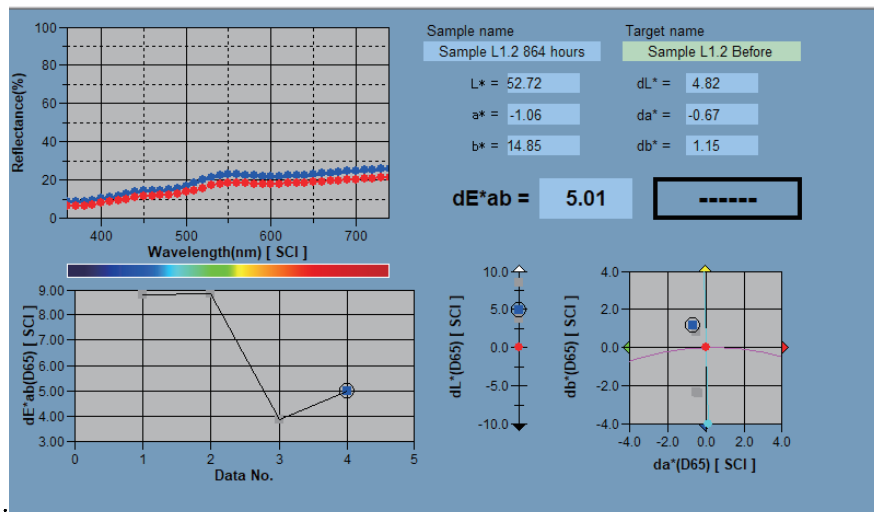
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample C3.2 864 hours
Target name
Sample C3.2 Before
L* = 58.36
a* = -1.23
b* = 15.45
dL* = 9.98
da* = 0.64
db* = -1.01
dE*ab = 10.05

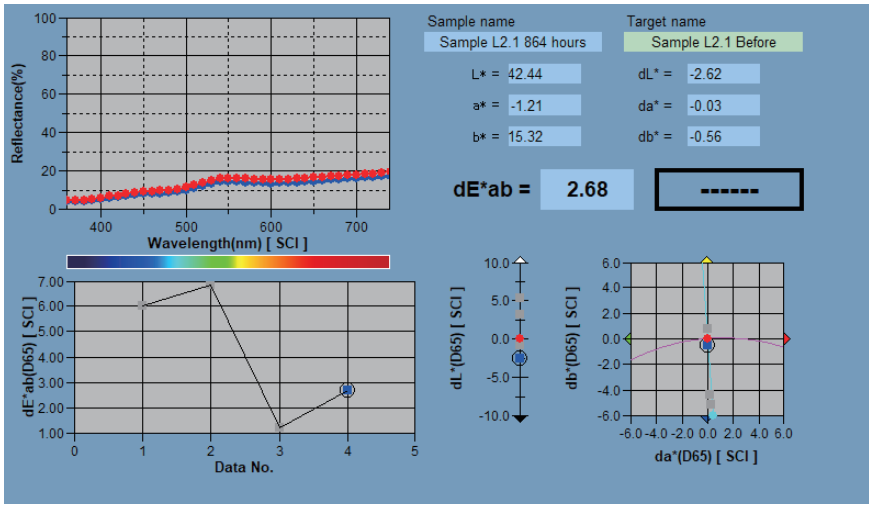
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L1.1 864 hours
Target name
Sample L1.1 Before
L* = 46.52
a* = -0.54
b* = 14.25
dL* = 1.04
da* = -0.04
db* = 0.69
dE*ab = 1.25

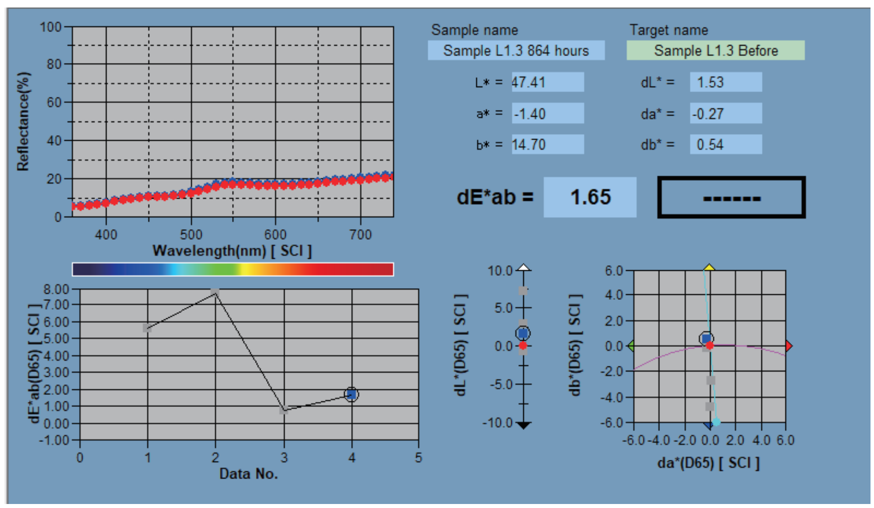
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L1.2 864 hours
Target name
Sample L1.2 Before
L* = 52.72
a* = -1.06
b* = 14.85
dL* = 4.82
da* = -0.67
db* = 1.15
dE*ab = 5.01

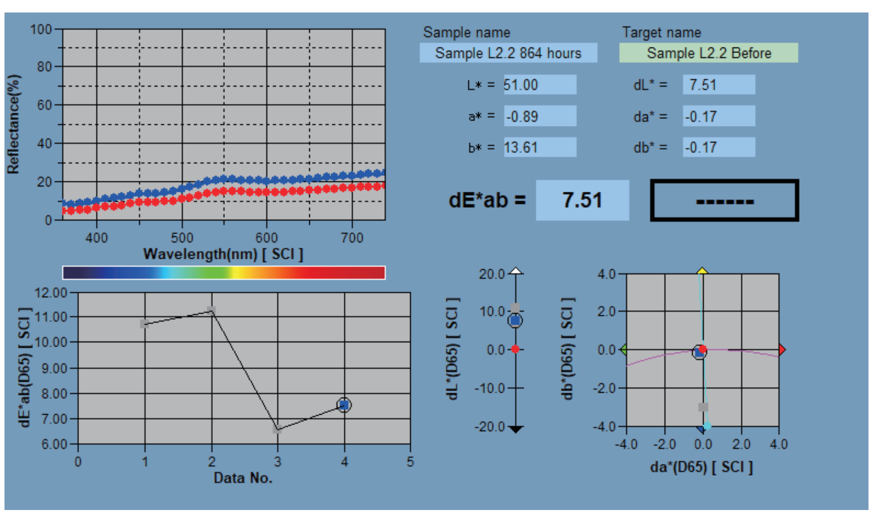
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L2.1 864 hours
Target name
Sample L2.1 Before
L* = 42.44
a* = -1.21
b* = 15.32
dL* = -2.62
da* = -0.03
db* = -0.56
dE*ab = 2.68

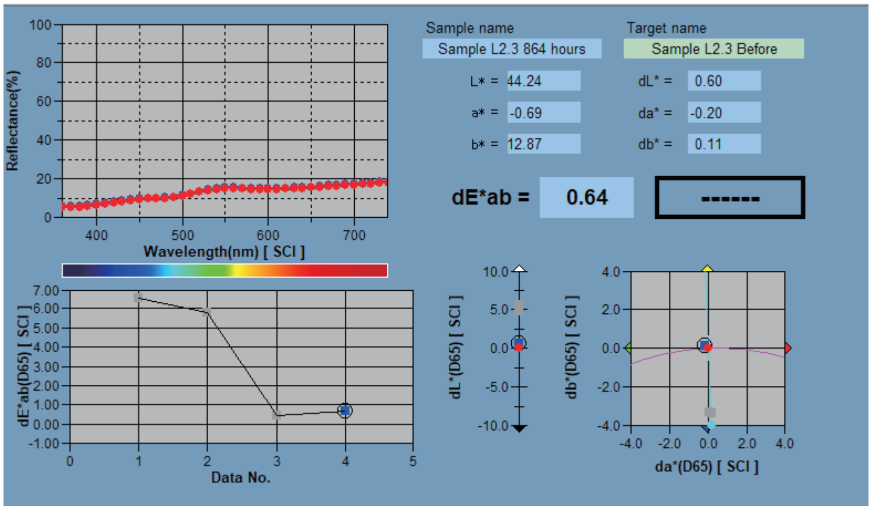
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L1.3 864 hours
Target name
Sample L1.3 Before
L* = 47.41
a* = -1.40
b* = 14.70
dL* = 1.53
da* = -0.27
db* = 0.54
dE*ab = 1.65

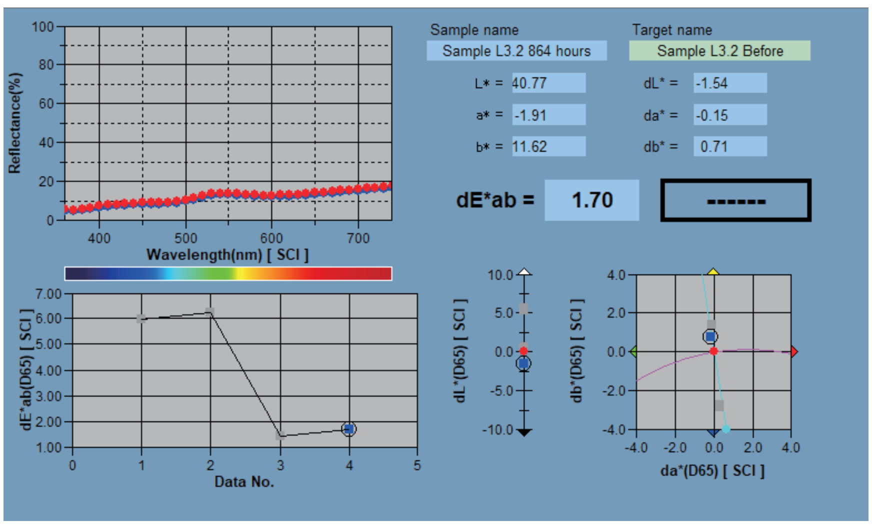
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L2.2 864 hours
Target name
Sample L2.2 Before
L* = 51.00
a* = -0.89
b* = 13.61
dL* = 7.51
da* = -0.17
db* = -0.17
dE*ab = 7.51

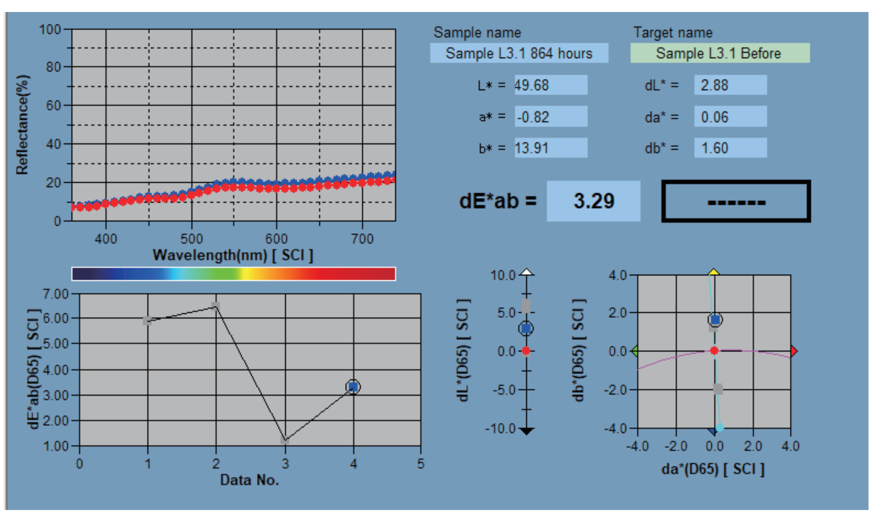
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L2.3 864 hours
Target name
Sample L2.3 Before
L* = 44.24
a* = -0.69
b* = 12.87
dL* = 0.60
da* = -0.20
db* = 0.11
dE*ab = 0.64

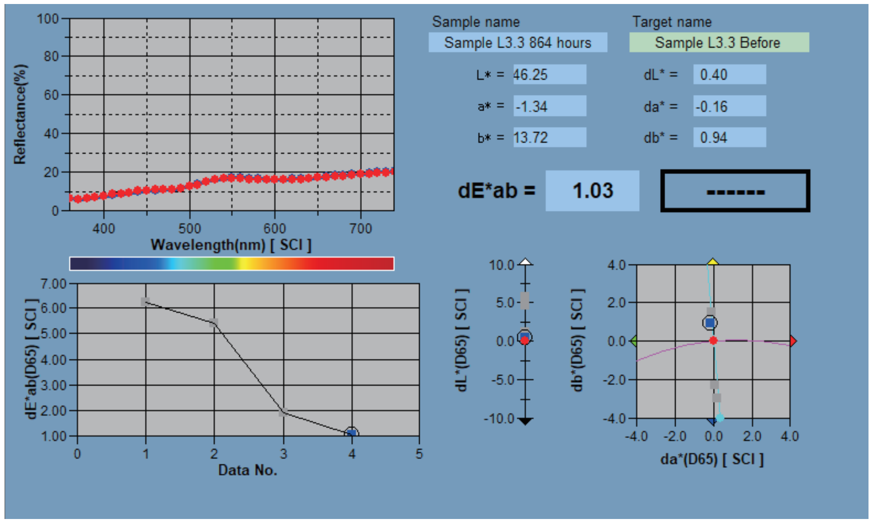
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L3.2 864 hours
Target name
Sample L3.2 Before
L* = 40.77
a* = -1.91
b* = 11.62
dL* = -1.54
da* = -0.15
db* = 0.71
dE*ab = 1.70

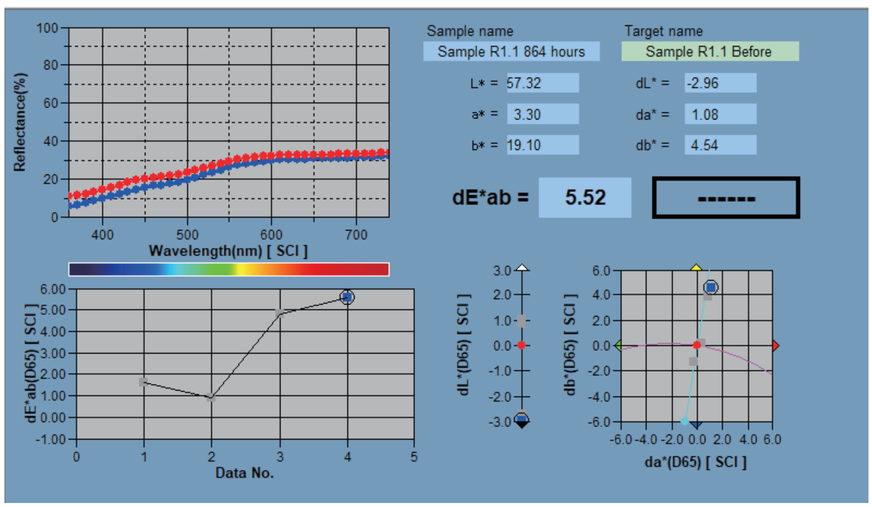
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L3.1 864 hours
Target name
Sample L3.1 Before
L* = 49.68
a* = -0.82
b* = 13.91
dL* = 2.88
da* = 0.06
db* = 1.60
dE*ab = 3.29

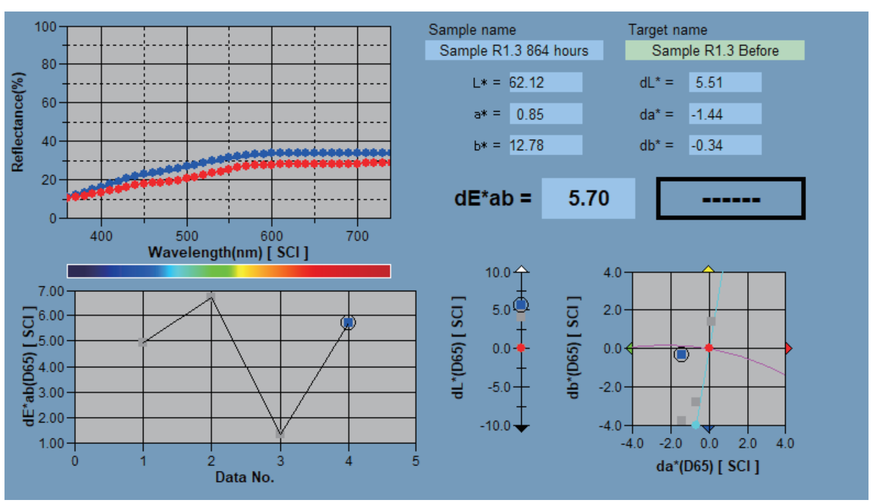
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L3.3 864 hours
Target name
Sample L3.3 Before
L* = 46.25
a* = -1.34
b* = 13.72
dL* = 0.40
da* = -0.16
db* = 0.94
dE*ab = 1.03

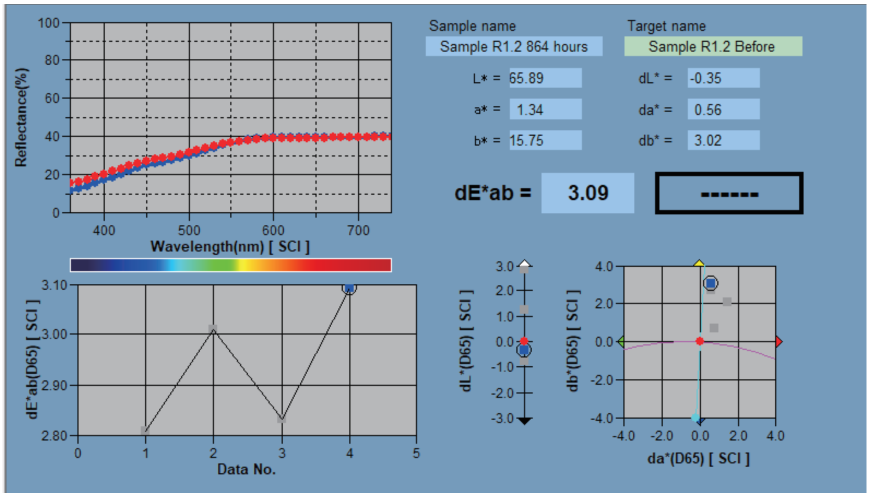
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R1.1 864 hours
Target name
Sample R1.1 Before
L* = 57.32
a* = 3.30
b* = 19.10
dL* = -2.96
da* = 1.08
db* = 4.54
dE*ab = 5.52

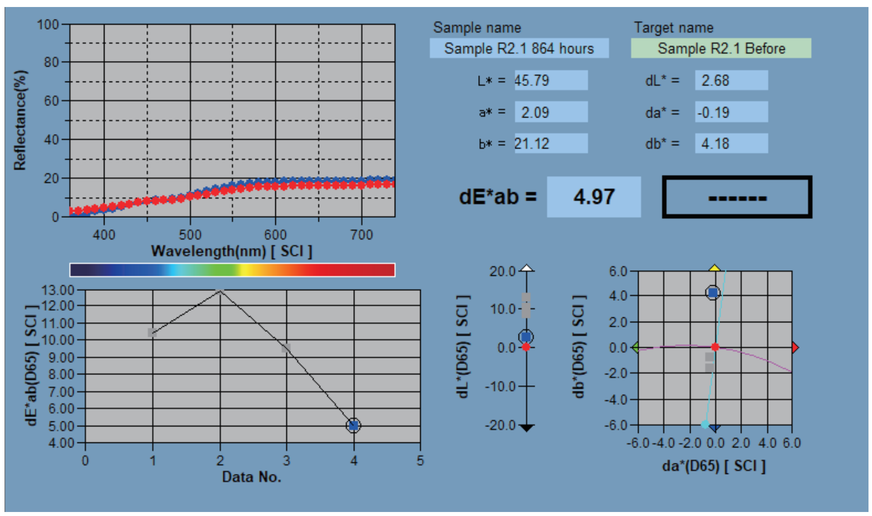
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R1.3 864 hours
Target name
Sample R1.3 Before
L* = 62.12
a* = 0.85
b* = 12.78
dL* = 5.51
da* = -1.44
db* = -0.34
dE*ab = 5.70

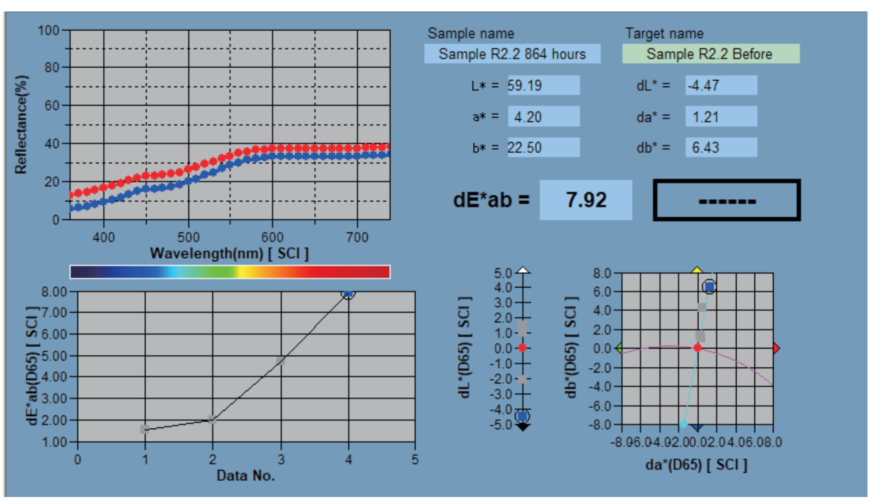
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R1.2 864 hours
Target name
Sample R1.2 Before
L* = 65.89
a* = 1.34
b* = 15.75
dL* = -0.35
da* = 0.56
db* = 3.02
dE*ab = 3.09

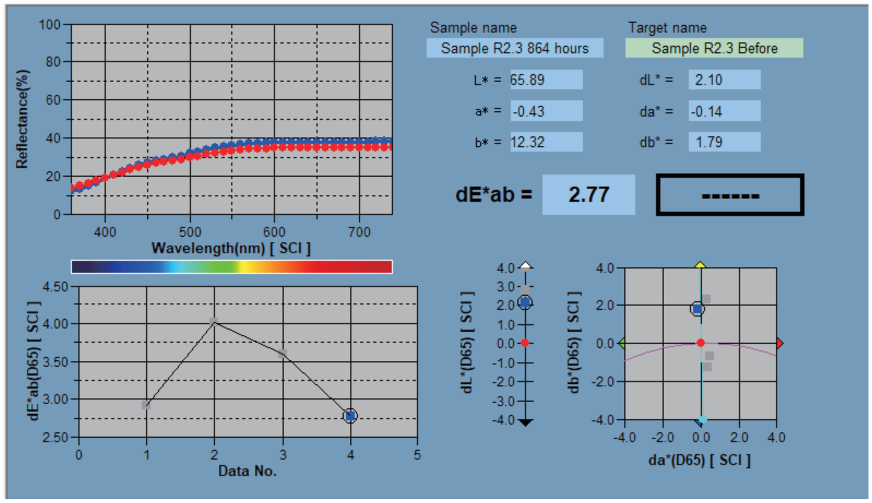
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R2.1 864 hours
Target name
Sample R2.1 Before
L* = 45.79
a* = 2.09
b* = 21.12
dL* = 2.68
da* = -0.19
db* = 4.18
dE*ab = 4.97

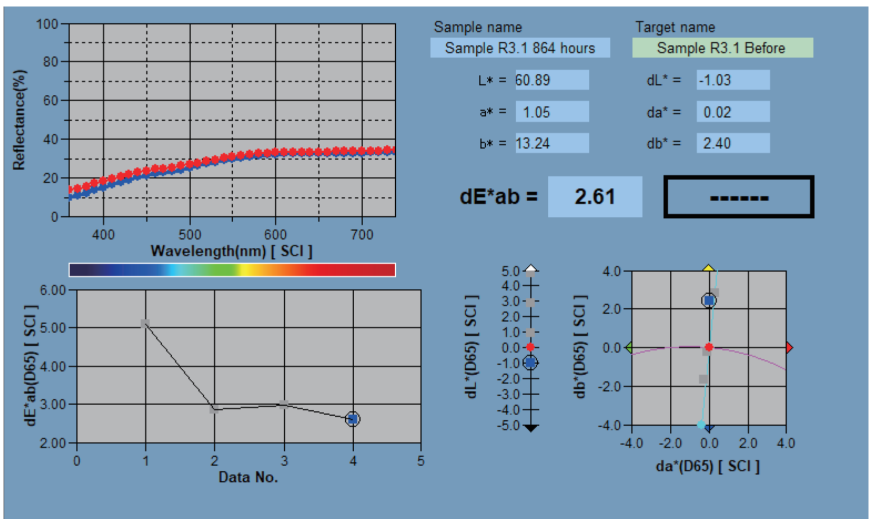
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R2.2 864 hours
Target name
Sample R2.2 Before
L* = 59.19
a* = 4.20
b* = 22.50
dL* = -4.47
da* = 1.21
db* = 6.43
dE*ab = 7.92

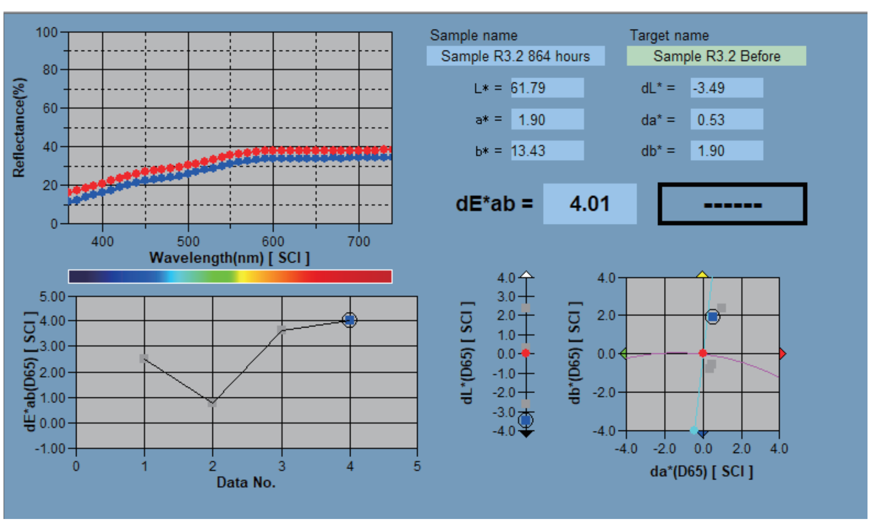
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R2.3 864 hours
Target name
Sample R2.3 Before
L* = 65.89
a* = -0.43
b* = 12.32
dL* = 2.10
da* = -0.14
db* = 1.79
dE*ab = 2.77

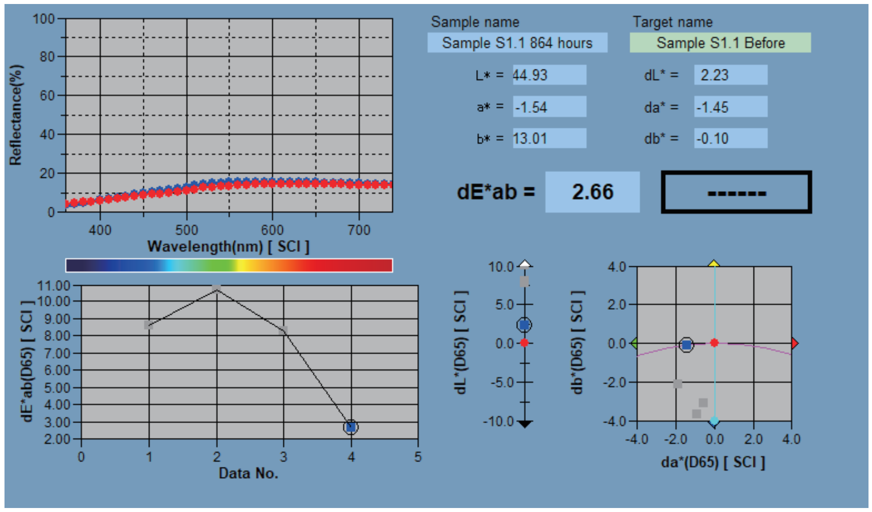
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R3.1 864 hours
Target name
Sample R3.1 Before
L* = 60.89
a* = 1.05
b* = 13.24
dL* = -1.03
da* = 0.02
db* = 2.40
dE*ab = 2.61

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

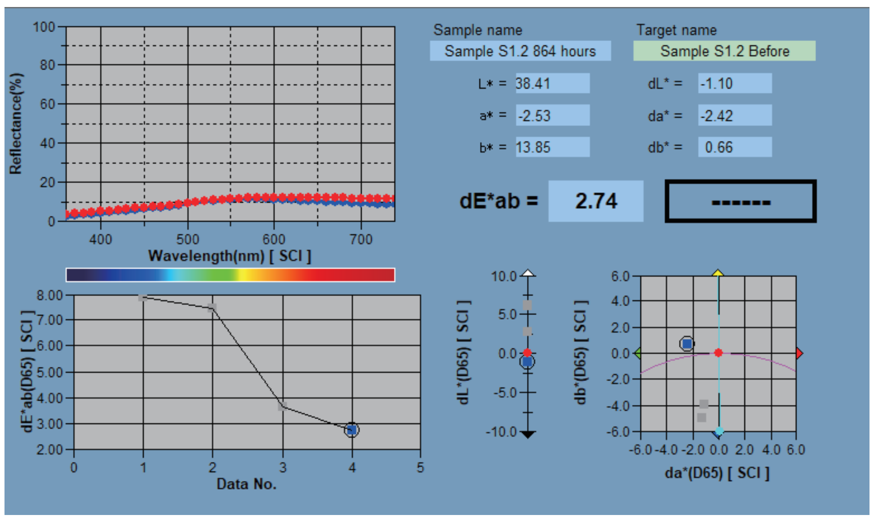

Sample name
Sample R3.2 864 hours
Target name
Sample R3.2 Before
L* = 61.79
a* = 1.90
b* = 13.43
dL* = -3.49
da* = 0.53
db* = 1.90
dE*ab = 4.01

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]



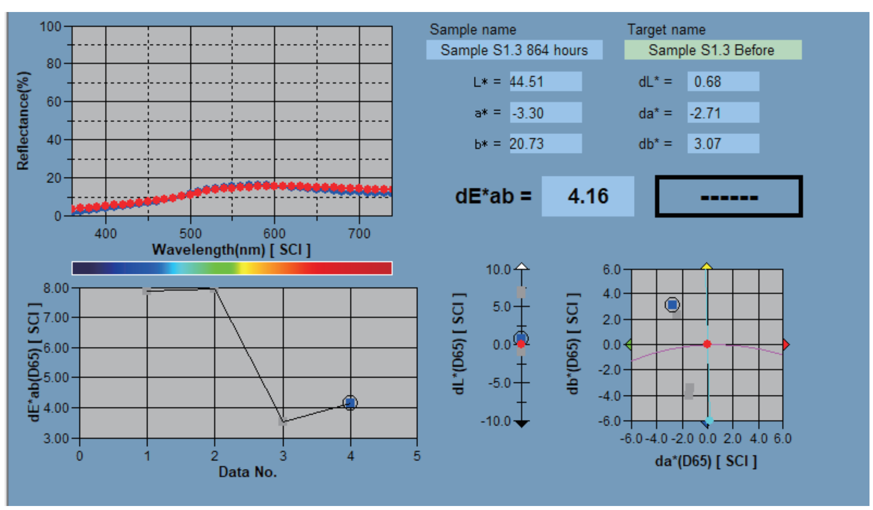
Sample name
Sample S1.1 864 hours
Target name
Sample S1.1 Before
L* = 44.93
a* = -1.54
b* = 13.01
dL* = 2.23
da* = -1.45
db* = -0.10
dE*ab = 2.66

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]



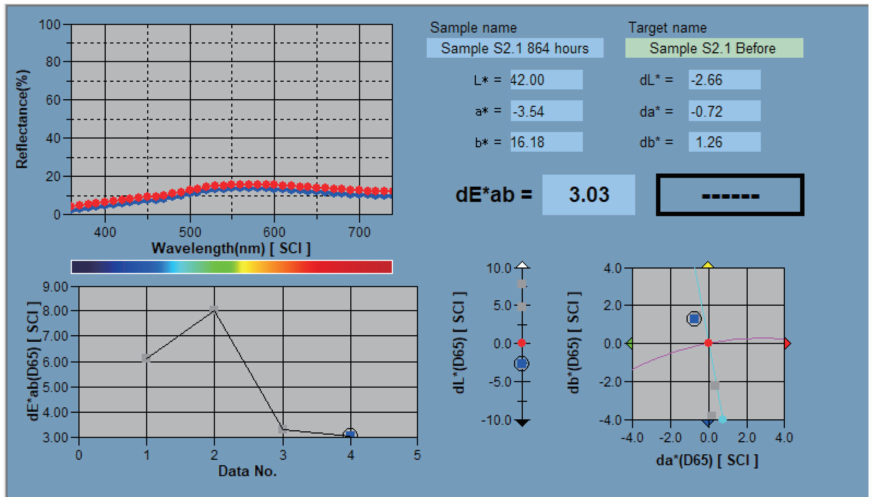
Sample name
Sample S1.2 864 hours
Target name
Sample S1.2 Before
L* = 38.41
a* = -2.53
b* = 13.85
dL* = -1.10
da* = -2.42
db* = 0.66
dE*ab = 2.74

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

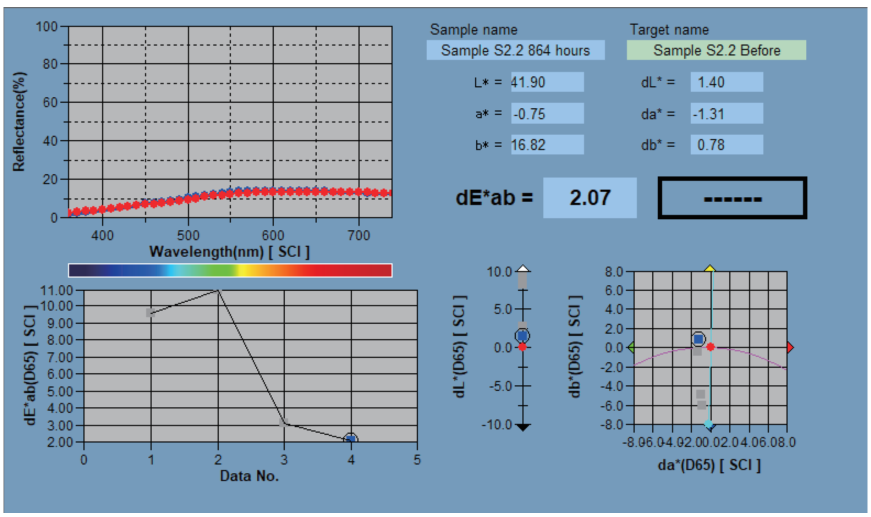


Sample name
Sample S1.3 864 hours
Target name
Sample S1.3 Before
L* = 44.51
a* = -3.30
b* = 20.73
dL* = 0.68
da* = -2.71
db* = 3.07
dE*ab = 4.16

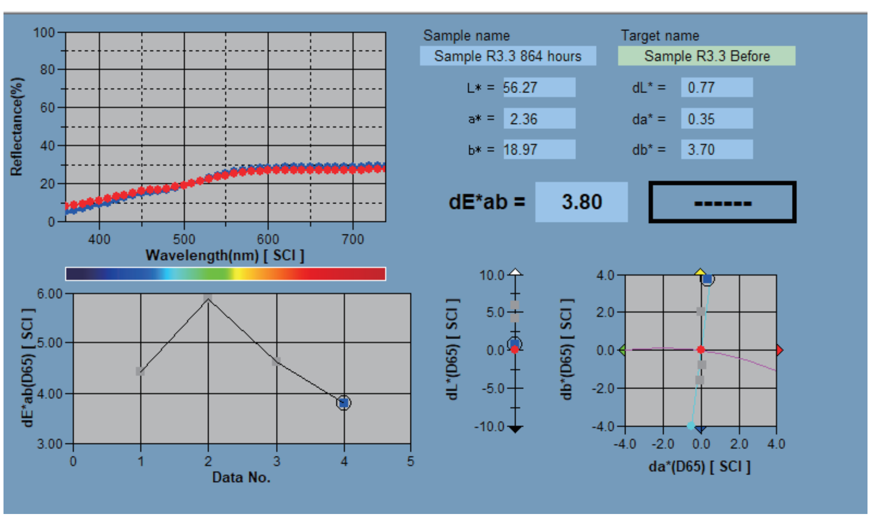
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample S2.1 864 hours
Target name
Sample S2.1 Before
L* = 42.00
a* = -3.54
b* = 16.18
dL* = -2.66
da* = -0.72
db* = 1.26
dE*ab = 3.03

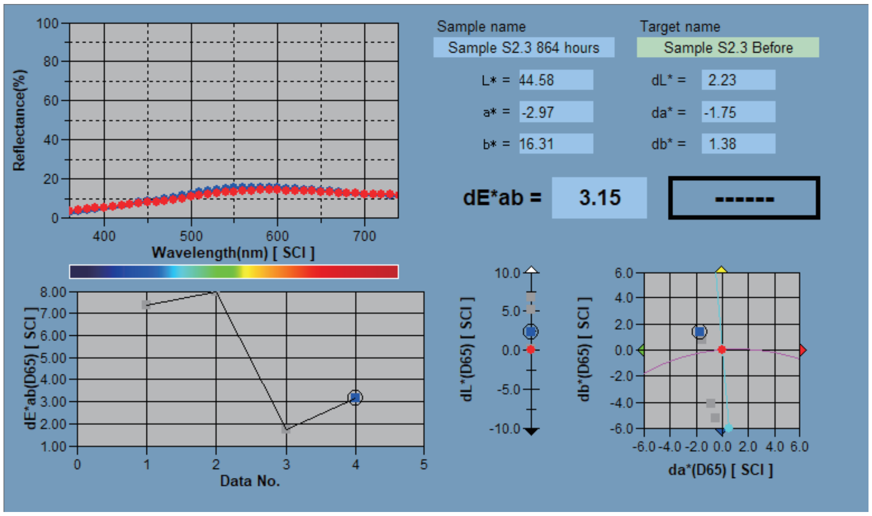
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample S2.2 864 hours
Target name
Sample S2.2 Before
L* = 41.90
a* = -0.75
b* = 16.82
dL* = 1.40
da* = -1.31
db* = 0.78
dE*ab = 2.07

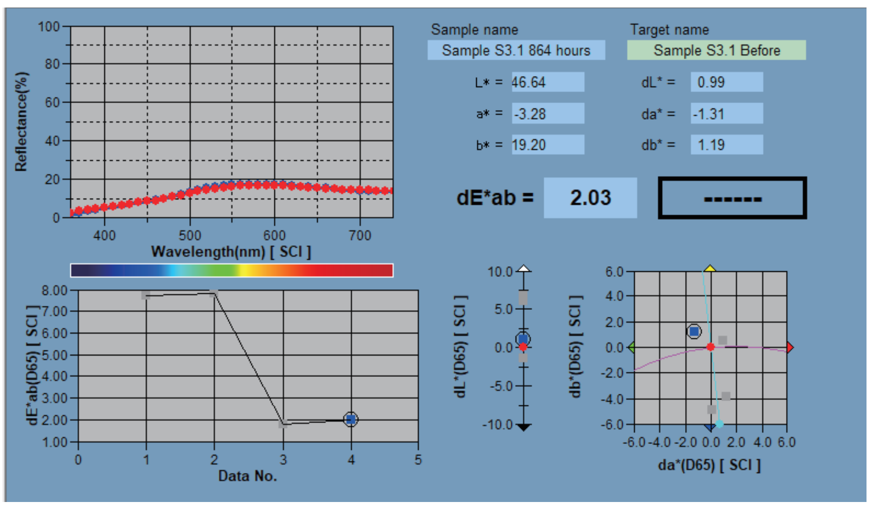
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R3.3 864 hours
Target name
Sample R3.3 Before
L* = 56.27
a* = 2.36
b* = 18.97
dL* = 0.77
da* = 0.35
db* = 3.70
dE*ab = 3.80

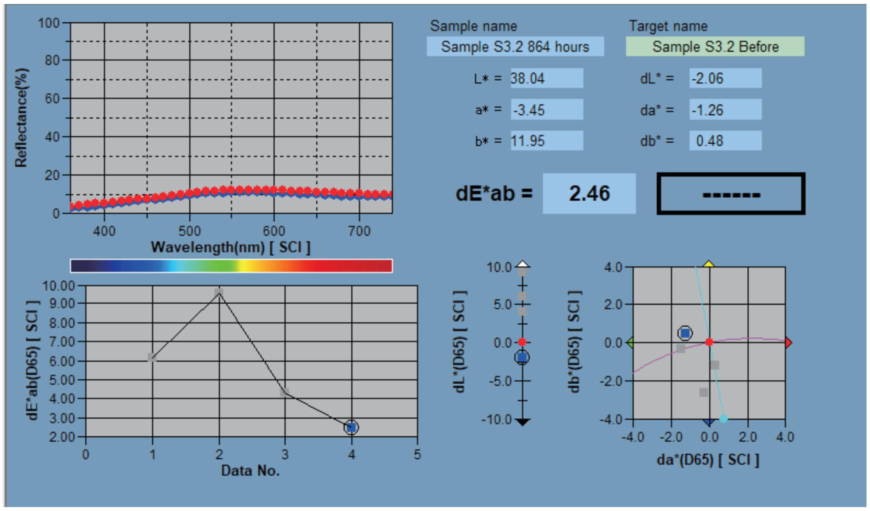
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

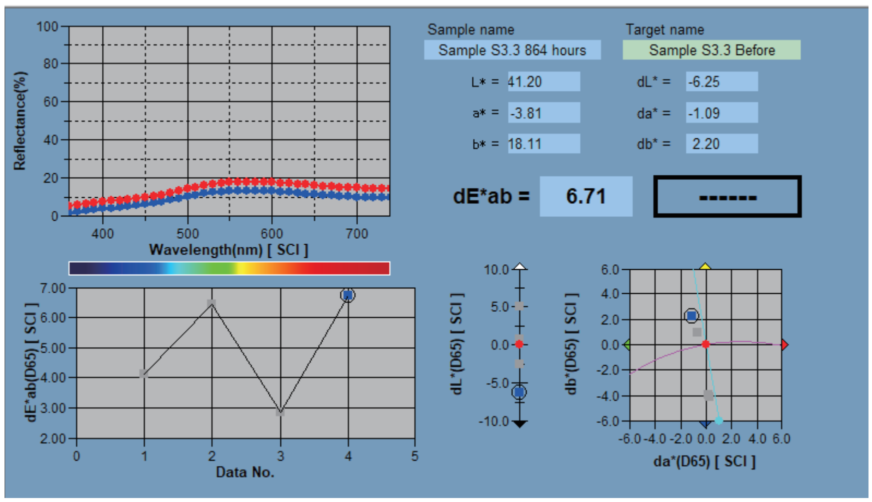

Sample name
Sample S2.3 864 hours
Target name
Sample S2.3 Before
L* = 44.58
a* = -2.97
b* = 16.31
dL* = 2.23
da* = -1.75
db* = 1.38
dE*ab = 3.15

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample S3.1 864 hours
Target name
Sample S3.1 Before
L* = 46.64
a* = -3.28
b* = 19.20
dL* = 0.99
da* = -1.31
db* = 1.19
dE*ab = 2.03

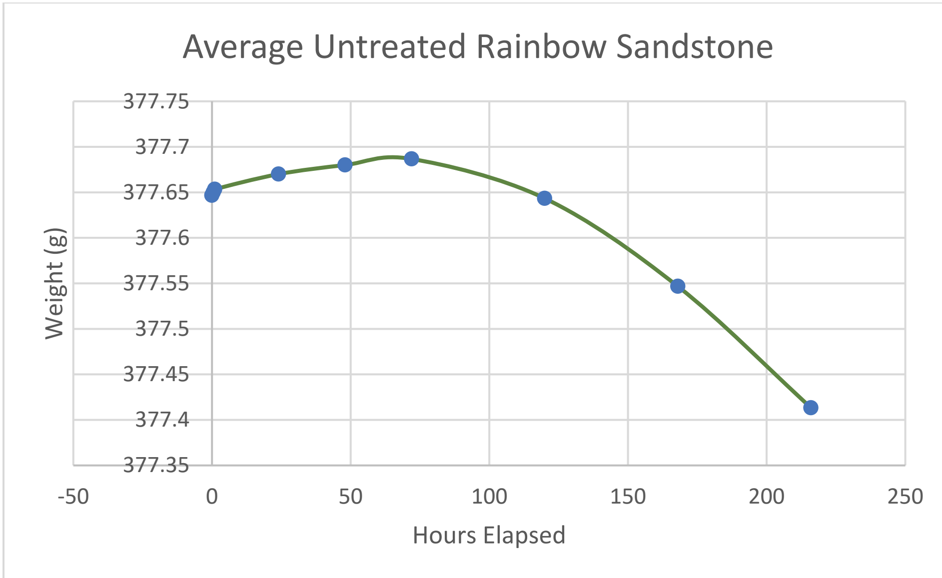
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

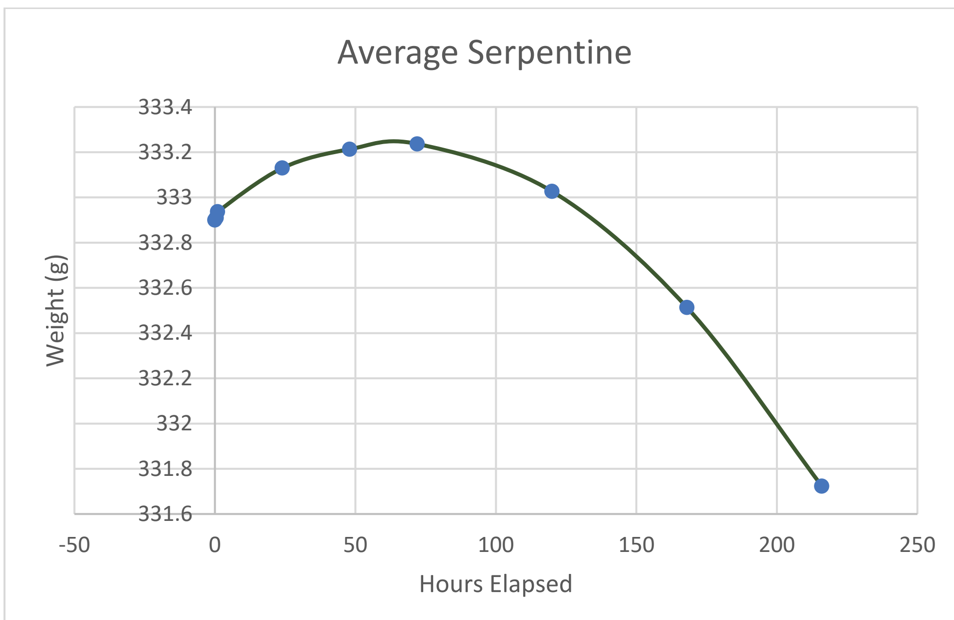

Sample name
Sample S3.2 864 hours
Target name
Sample S3.2 Before
L* = 38.04
a* = -3.45
b* = 11.95
dL* = -2.06
da* = -1.26
db* = 0.48
dE*ab = 2.46
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

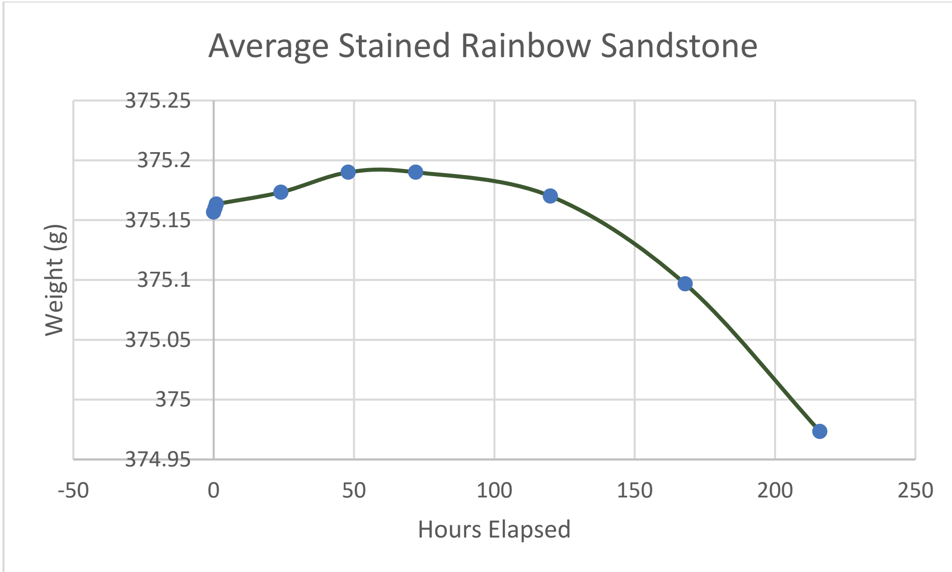

Sample name
Sample S3.3 864 hours
Target name
Sample S3.3 Before
L* = 41.20
a* = -3.81
b* = 18.11
dL* = -6.25
da* = -1.09
db* = 2.20
dE*ab = 6.71
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

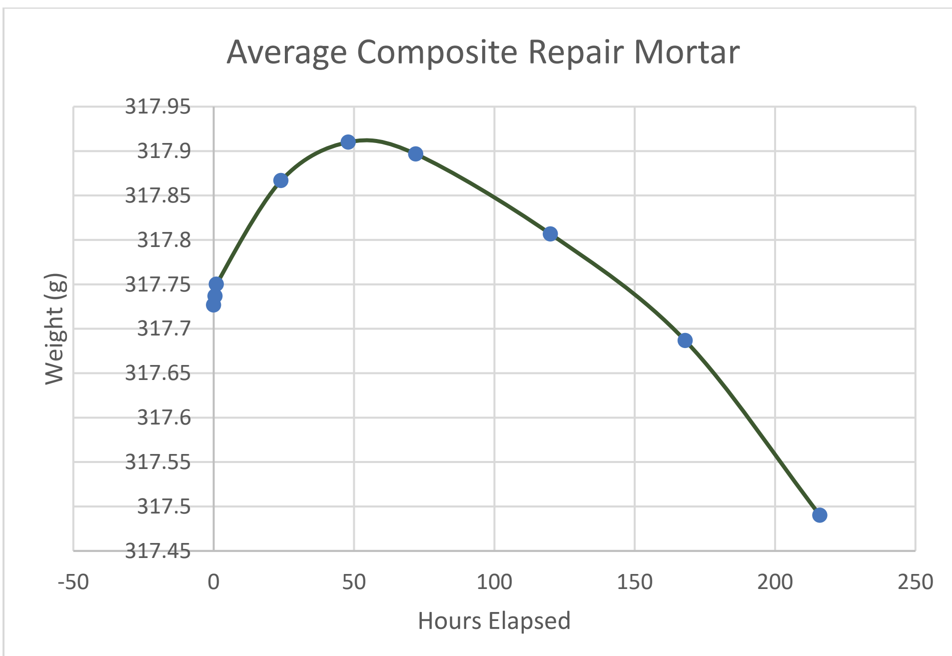
Appendix E – Water Vapor Transmission Results

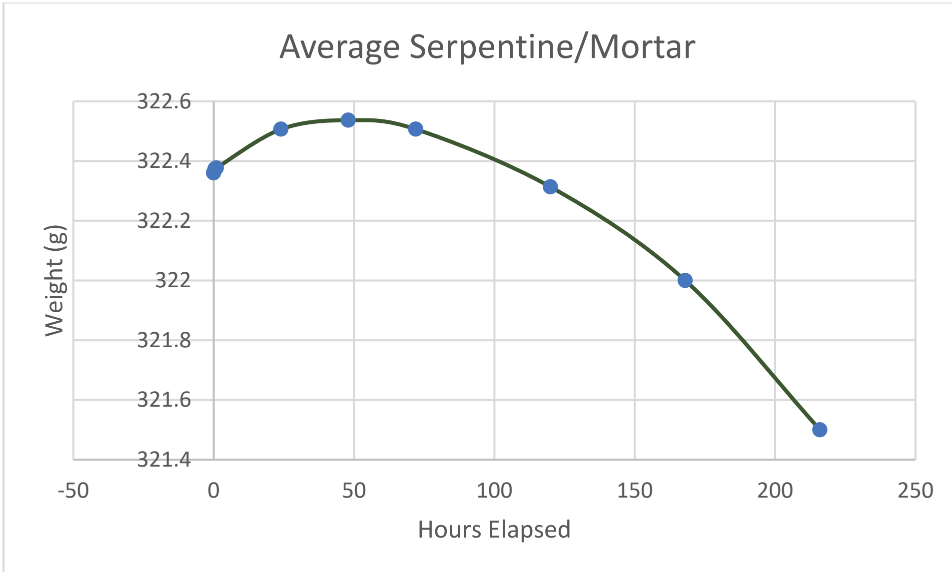
	Weight (grams) at Time Elapsed									Test Area (m2)	Weight Change/Hours (g/t)	Rate of Water Vapor Transmission (g/(h/m2)	Average Temperature (C)	Saturated Vapor Pressure	R1 - R2	Permeance (perms)
Sample No.	0	0.5	1	24	48	72	120	168	216							
SS1	335.9	335.92	335.94	336.14	336.26	336.29	336.09	335.60	334.92							
SS2	334.72	334.72	334.75	334.94	335	335.04	334.8	334.33	333.4							
SS3	328.08	328.09	328.12	328.31	328.38	328.38	328.19	327.61	326.85							
Average Serpentine	332.9	332.91	332.9367	333.13	333.2133	333.2367	333.0267	332.5133	331.7233	0.00383	1.05E-02	2.74	21.34	19.05	0.22	0.64
UR1	382.39	382.39	382.39	382.41	382.42	382.42	382.38	382.26	382.09							
UR2	378.85	378.85	378.86	378.87	378.88	378.89	378.84	378.77	378.64							
UR3	371.7	371.71	371.71	371.73	371.74	371.75	371.71	371.61	371.51							
Average Untreated Rainbow Sandstone	377.646667	377.65	377.6533	377.67	377.68	377.6867	377.6433	377.5467	377.4133	0.00383	1.90E-03	0.50	21.34	19.05	0.22	0.12
SR1	369.83	369.83	369.84	369.84	369.86	369.86	369.83	369.77	369.67							
SR2	383.14	383.15	383.14	383.16	383.17	383.17	383.16	383.08	382.96							
SR3	372.5	372.5	372.51	372.52	372.54	372.54	372.52	372.44	372.29							
Average Stained Rainbow Sandstone	375.156667	375.16	375.1633	375.1733	375.19	375.19	375.17	375.0967	374.9733	0.00383	1.50E-03	0.39	21.34	19.05	0.22	0.09
LM1	317.23	371.24	317.25	317.37	317.4	317.39	317.28	317.18	316.94							
LM2	320.45	320.45	320.47	320.58	320.62	320.6	320.52	320.38	320.24							
LM3	315.5	315.52	315.53	315.65	315.71	315.7	315.62	315.50	315.29							
Average Composite Repair Mortar	317.726667	335.7367	317.75	317.8667	317.91	317.8967	317.8067	317.6867	317.49	0.00383	2.82E-03	0.74	21.34	19.05	0.22	0.17
SL1	328.61	328.62	328.63	328.76	328.78	328.74	328.5	328.15	327.55							
SL2	315.15	315.17	315.17	315.3	315.34	315.31	315.11	314.83	314.43							
SL3	323.32	323.33	323.33	323.46	323.49	323.47	323.33	323.02	322.52							
Average Serpentine/Mortar	322.36	322.3733	322.3767	322.5067	322.5367	322.5067	322.3133	322	321.5	0.00383	6.99E-03	1.82	21.34	19.05	0.22	0.43


Average Untreated Rainbow Sandstone
377.75
377.7
377.65
377.6
377.55
377.5
377.45
377.4
377.35
Weight (g)
-50
0
50
100
150
200
250
Hours Elapsed


Average Serpentine
333.4
333.2
333
332.8
332.6
332.4
332.2
332
331.8
331.6
Weight (g)
-50
0
50
100
150
200
250
Hours Elapsed

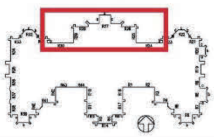
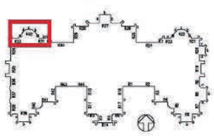
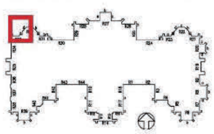

Average Stained Rainbow Sandstone
Weight (g)
375.25
375.2
375.15
375.1
375.05
375
374.95
-50
0
50
100
150
200
250
Hours Elapsed


Average Composite Repair Mortar
Weight (g)
317.95
317.9
317.85
317.8
317.75
317.7
317.65
317.6
317.55
317.5
317.45
-50
0
50
100
150
200
250
Hours Elapsed

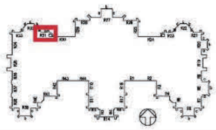
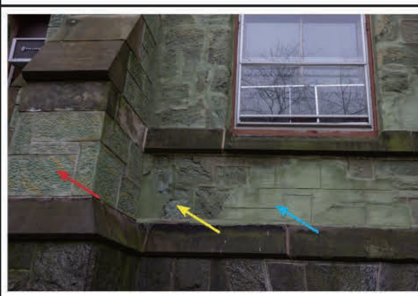
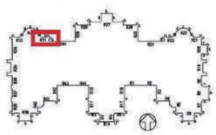
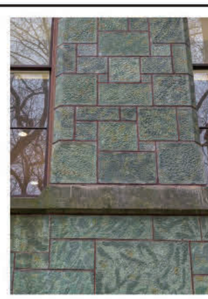
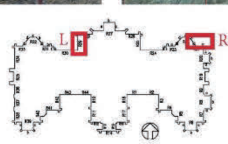

Average Serpentine/Mortar
322.6
322.4
322.2
322
321.8
321.6
321.4
Weight (g)
-50
0
50
100
150
200
250
Hours Elapsed

Appendix F – College Hall

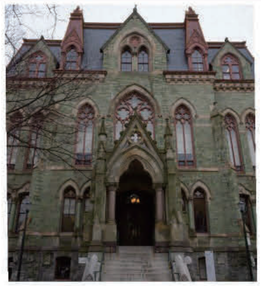
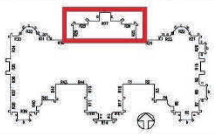
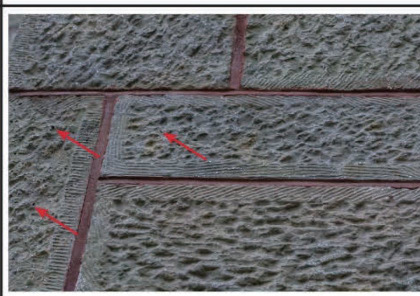
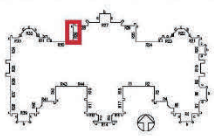
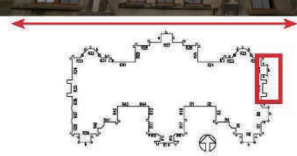
College Hall Conditions Survey

No.	Picture & Location	Notes
01	 	**Repair Type:** Primarily Cast-Stone **Year Installed:** 1994 - 1996 **Observation:** The principal facade of College Hall, facing north, displays a cohesive exterior. In this photograph, almost every stone on the central bay and eastward was replaced with cast-stone. The color of the cast-stone matches well with the remaining original serpentine on western portion.
02	 	**Repair Type:** Stucco, Early Cast-Stone **Year Installed:** Various **Observation:** A closer look at the unrepaired western end shows a quilt like pattern of old and new temporary stucco patching, original serpentine at different stages of deterioration, and early cast-stone replacements.
03	 	**Repair Type:** Early Cast-Stone Replacement **Year Installed:** C. 1950 **Observation:** Early cast-stone replacements used crushed serpentine as a colorant, and the serpentine has yellowed over time. The yellowing is caused by the breakdown of certain minerals into limonite.[1] Later cast-stone replacements used more stable, inorganic mineral oxide pigments that are colorfast and alkaliproof. 1 Meierding, Thomas C. Weathering of Serpentine Stone Buildings in the Philadelphia, Pennsylvania, Region: A Geographic Approach Related to Acidic Deposition. Stone Decay in the Architectural Environment / Vol. 390. Boulder, Colo. : Geological Society of America, 2005.

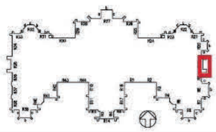
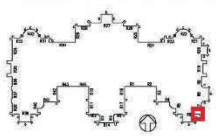
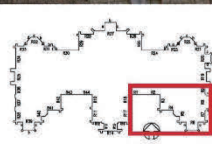
Photographs: Taken by author, February 2019.
Site Plan: Courtesy of Keast & Hood

No.	Picture & Location	Notes
04	 	**Repair Type:** Partially Stuccoed Serpentine **Year Installed:** Likely Post-2000 **Observation:** This detail photograph shows the extent of serpentine degradation that is representative of most remaining exposed serpentine surface. Note the depth of some of these fissures (arrow), these spots allow water to penetrate deeply into the stone and cause accelerated damage. Much of these serpentine were patched with stucco as a temporary mitigation while the project awaits Phase VI.
05	 	**Repair Type:** Cast-stone, Stucco **Year Installed:** 1994 to post-2000 **Observation:** This photograph shows the contrast between cast-stone replacement (red arrow), original serpentine (yellow arrow), and the temporary stucco patching (blue arrow). The cast-stone demonstrate a fairly close match to the original serpentine, while the stucco, intended as a temporary mitigation, was poorly color simulated.
06	  	**Repair Type:** Cast-stone **Year Installed:** 1994 - 1996 **Observation:** Some aesthetic inconsistancy in cast-stone replacements can be observed. The blending of colors of the units on the left look well integrated and natural, while the units on the left appear deliberate and unnatural.

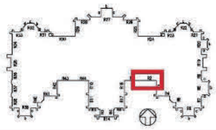
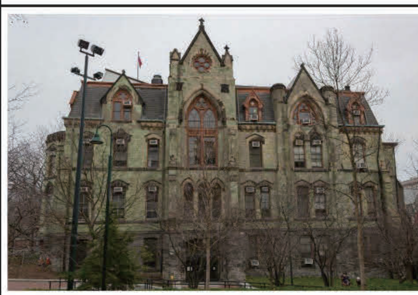
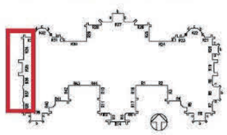
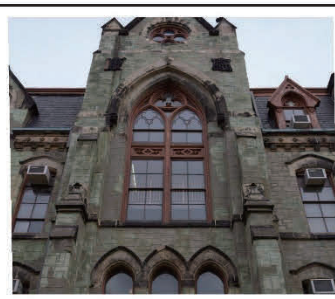
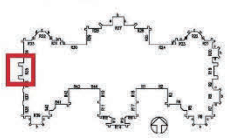
Photographs: Taken by author, February 2019.
Site Plan: Courtesy of Keast & Hood

No.	Picture & Location	Notes
07	 	**Repair Type:** Cast-stone **Year Installed:** 1994 - 1995 **Observation:** Krier's method of using a family of different sized cast-stone successfully created ashlar pattern that is repeated but not does not appear repetitive.
08	 	**Repair Type:** Cast-stone **Year Installed:** 1994 - 1995 **Observation:** Some voids on the surface in the size of large sand grains are observed. These could be made by air bubbles during casting or large aggregates popping out of the surface.
09	 	**Repair Type:** Early Cement Stucco **Year Installed:** Mid 20th Century **Observation:** The section of the elevation indicated by red arrow is in a paler yellow-green color than the masonry on either side. This was from an earlier cement stucco repair campaign around mid 20th century.

Photographs: Taken by author, February 2019.
Site Plan: Courtesy of Keast & Hood

No.	Picture & Location	Notes
10	 	**Repair Type:** Early Cement Stucco **Year Installed:** Mid 20th Century **Observation:** A close-up of the early pebbled cement stucco shows signs of deterioration: yellowing, spalls, partial loss, and erosion.
11	 	**Repair Type:** Composite Repair Mortar Patching **Year Installed:** c. 1989 **Observation:** Early attempts were made to patch the serpentine with composite repair mortar. The stone substrate continued to deteriorate, causing the patching mortar to detach and fall off. Some remains are attached to the surrounding mortar while the serpentine substrate has eroded (arrow).
12	 	**Repair Type:** Various **Year Installed:** Various **Observation:** The south elevation was not completely replaced with cast-stone. This view shows different past repairs varying in colors and textures, most are in good condtion, some display signs of erosion and spalling.

Photographs: Taken by author, February 2019.
Site Plan: Courtesy of Keast & Hood

No.	Picture & Location	Notes
13	 	**Repair Type:** Various **Year Installed:** c. 1987 **Observation:** This section of the wall was tested as prototype in the early phase of the project. The team tried to preserve as much serpentine as possible. Various mixtures of stucco patching material was tested here.
14	 	**Repair Type:** Early Stucco, Early Cast-stone, Modern Stucco **Year Installed:** Various **Observation:** This photograph was taken from approximately 100 feet away. The discoloration of different type of repairs on this elevation are clearly visible. More recent deteriorations were patched with bright green stucco. Most if not all will be replaced with cast-stone during Phase VI.
15	 	**Repair Type:** Early Stucco, Early Cast-stone, Modern Stucco **Year Installed:** Various **Observation:** This close-up of the central bay shows deteriorated early repairs patched with bright green stucco, scored to create the illusion of mortar joints.

Photographs: Taken by author, February 2019
Site Plan: Courtesy of Keast & Hood

Case Study 1: College Hall List of Interviewees

Marianna Thomas

Principal, Marianna Thomas Architects

Marianna Thomas was the chief architect of the renovation campaign from 1986 to 2001, including the cast-stone replacement. Her firm provided design services, organized materials testing, and managed the subcontractors and consultants on the project.

Thomas Ewing

Sr. Director, SAS Facilities Planning & Operations, University of Pennsylvania

Thomas Ewing was working at the Facilities and Real Estate Services of the University of Pennsylvania, who was the client of the project, at the time of the cast-stone replacement campaign. Although not directly involved, he is familiar with the project.

Brian Wentz, PE, CDT

Director of Historic Preservation, Keast & Hood Structural Engineers

Brian Wentz provides structural engineer consultation for Phase IV and conducts bi-annual exterior inspection of College Hall. He is familiar with the cast-stone replacement campaign, although not directly involved at the time.

Constantine (Dean) Doukakis, PE

Senior Principal, Keast & Hood Structural Engineers

Dean Doukakis provides structural engineer consultation for Phase IV and conducts bi-annual exterior inspection of College Hall. He is familiar with the cast-stone replacement campaign, although not directly involved at the time.

Vern Knapp

Founder/Owner, Knapp Masonry

Vern Knapp worked as a mason for Masonry Preservation Group, who performed all masonry work including the cast-stone installation.

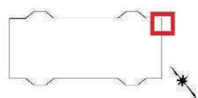
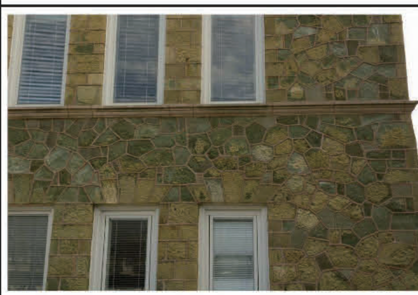
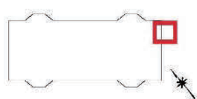
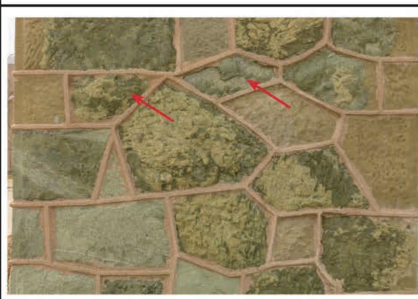
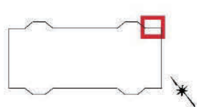
Jennifer Knapp

Founder/Owner, Knapp Masonry

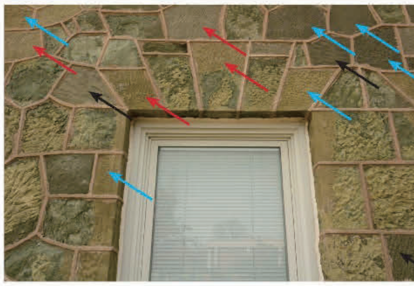
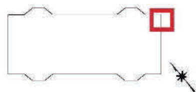
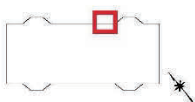
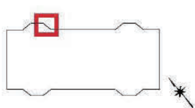
Jennifer Knapp worked in College Hall during the time of the renovation campaign. She worked there for 37 years and is a representative of the building's occupant.

Appendix G – Recitation Hall

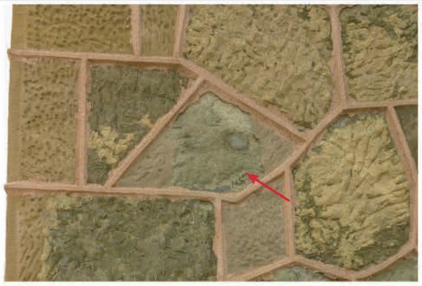
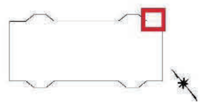
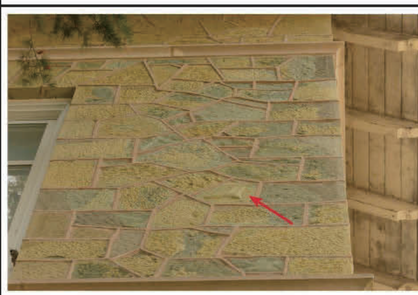
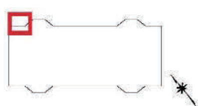
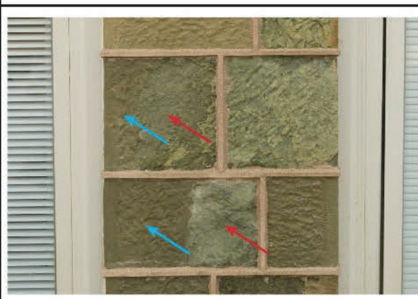
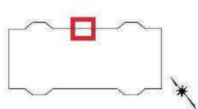
Recitation Hall Conditions Survey

No.	Picture & Location	Notes
01	 	**Subject:** Exterior Detail **Observation:** The serpentine stones vary in color and texture. The yellow surface is a crust formed by oxidized mineral. The crust preserved the original tooling in most cases. The green colored stones have lost this protective crust.
02	 	**Subject:** Comparasion between patching and original stone **Observation:** This photograph was taken approximately 20 feet away. From this distance the patched stones are indistinguishable from original.
03	 	**Subject:** Serpentine deterioration **Observation:** Original serpentine continues to deterioration, showing signs of flaking and spalling.

Photographs: Taken by author, March 2019.
Site Plan: Courtesy of West Chester University Facilities Design and Construction Department

No.	Picture & Location	Notes
04	 	**Subject:** Tooling **Observation:** A variety of tooling techniques can be observed here. Red arrows point to patches with a slashing pattern, blue arrows point to a pitted finish, and black arrows point the a surface made by removing pockets of the mortar.
05	 	**Subject:** Composite Repair Mortar **Observation:** The eroded Entrance carving was reproduced with composite repair mortar.
06	 	**Subject:** Partially patched stones **Observation:** Some stones were partially patched. The boundary between the composite repair mortar and serpentine become more pronounced as the stone continues to deteriorate.

Photographs: Taken by author, March 2019.
Site Plan: Courtesy of West Chester University Facilities Design and Construction Department

No.	Picture & Location	Notes
01	 	**Subject:** Composite repair mortar **Observation:** The center of this patching has detached from the substrate.
02	 	**Subject:** Relief carving **Observation:** Several relief carvings, including the boot pictured here, were found during the conditions assessment. These features were carefully preserved during the construction.
03	 	**Subject:** Color matching **Observation:** Some color matches are close the the original serpentine. Others show a degree of variation. Composite repair mortar is indicated by blue arrows, original serpentine by red arrows.

Photographs: Taken by author, March 2019.
Site Plan: Courtesy of West Chester University Facilities Design and Construction Department

Case Study 2: Recitation Hall List of Interviewees

Lorraine Schnabel

Principal, Schnabel Conservation L.L.C.

Schnabel conducted conditions survey of the facing stones of Recitation Hall in 2008. Her report included conditions assessment based on stone by stone sounding survey and petrographic study, as well as treatment recommendations for stone and mortar.

Rodney Lukens

Project Manager (retired 2018), West Chester University Facilities Design and Construction Department

Lukens represented the owner, West Chester University, and oversaw the restoration campaign from 2009 to its completion in 2011.

Van Burriss

Independent Manufacturer's Representative for Conproco Corporation

Burriss provided field support and troubleshooting for the composite repair mortar supplied by Conproco. He was onsite periodically for quality assurance inspection. He also acted as an intermediary between the project team and Conproco's Color Lab, which provides custom color simulations.

Gregory Hess

President & CEO, Caretti Restoration & Preservation Services, L.L.C.

Hess received weekly report from Caretti project manager and conducted several site visits to Recitation Hall. He was not actively involved with the physical restoration.

Cody Wilson

Foreman, Caretti Restoration & Preservation Services, L.L.C.

Wilson was the site foreman and performed hands-on composite repair mortar patching for Ruby Jones Hall, which was an identical process as Recitation Hall. He was not directly involved with Recitation Hall project.

Ralph Hart

Estimator/Project Manager, Caretti Restoration & Preservation Services, L.L.C.

Hart was the project manager for Ruby Jones Hall restoration. He was not directly involved with Recitation Hall project.

Appendix H – St. Francis of Assisi Church

Case Study 3: St. Francis of Assisi, List of Interviewees

Rex A. Cyphers, P.E.

Principal, COO, WDP & Associates

WDP designed the façade repair and replacement program for St. Francis of Assisi. The project team performed structural analysis, coordinated testing, and developed a reliable method to systematically replace the stone while keeping the occupants safe.

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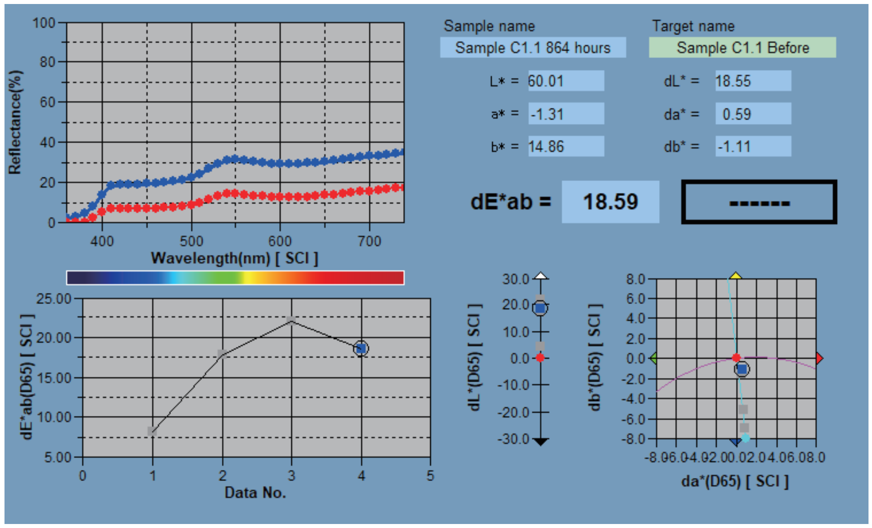
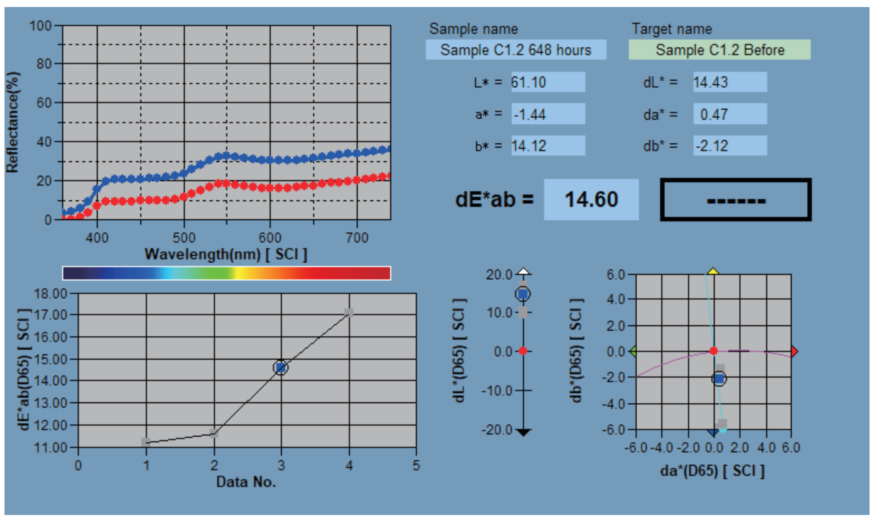
Figure 51. North elevation pre-construction. (Courtesy of Caretti Restoration & Preservation Services, L.L.C., 2010)

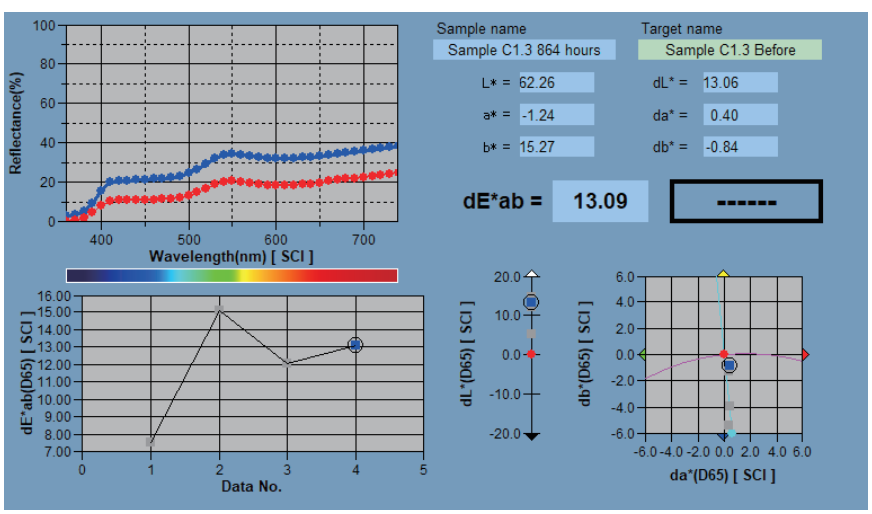
Figure 52. North elevation, eight years after restoration campaign. (Different lighting and weather conditions may alter the appearance of color between the two photographs.) (Photograph by author, 2019)


Sample name
Sample C1.1 864 hours
Target name
Sample C1.1 Before
L* = 60.01
a* = -1.31
b* = 14.86
dL* = 18.55
da* = 0.59
db* = -1.11
dE*ab = 18.59

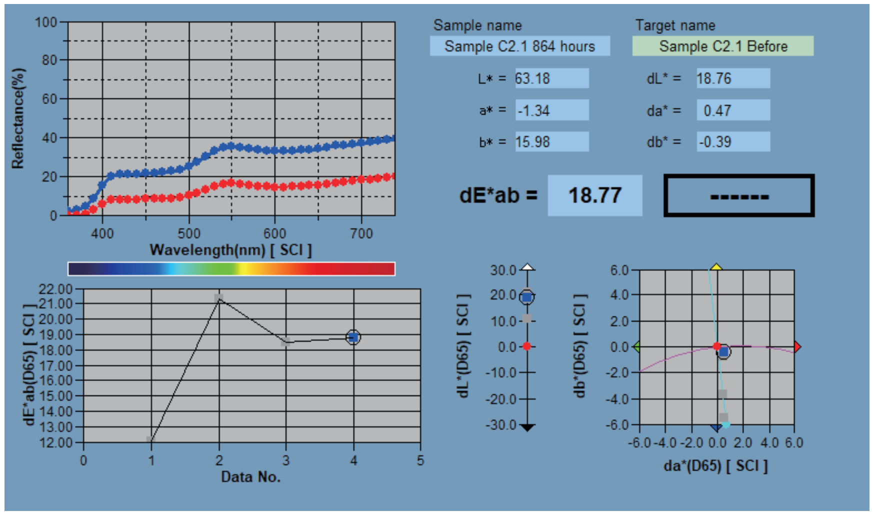
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample C1.2 648 hours
Target name
Sample C1.2 Before
L* = 61.10
a* = -1.44
b* = 14.12
dL* = 14.43
da* = 0.47
db* = -2.12
dE*ab = 14.60

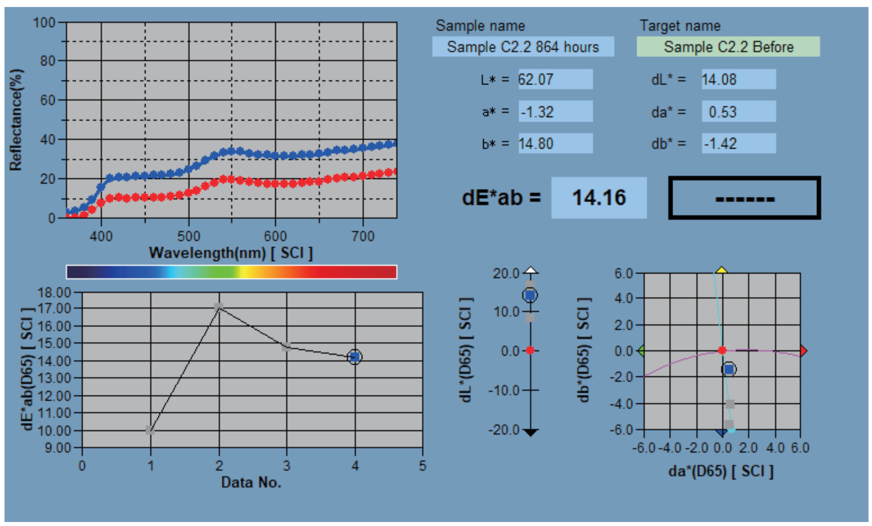
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample C1.3 864 hours
Target name
Sample C1.3 Before
L* = 62.26
a* = -1.24
b* = 15.27
dL* = 13.06
da* = 0.40
db* = -0.84
dE*ab = 13.09

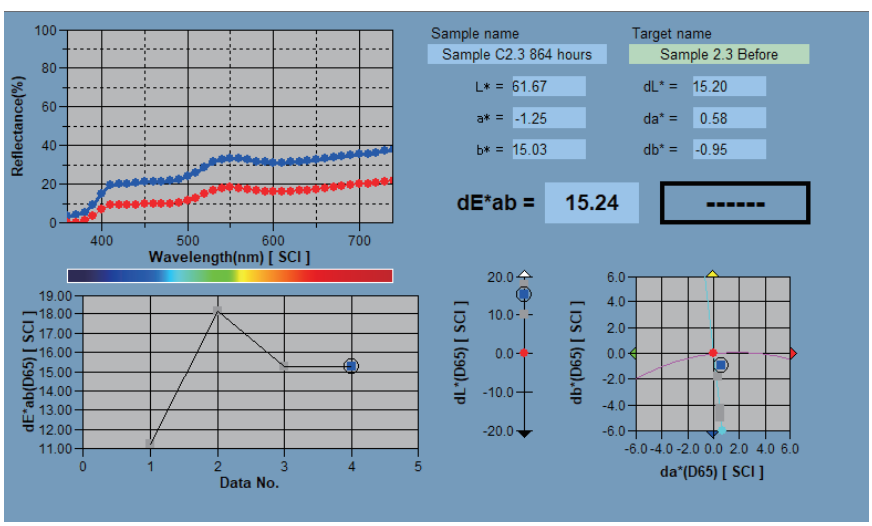
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample C2.1 864 hours
Target name
Sample C2.1 Before
L* = 63.18
a* = -1.34
b* = 15.98
dL* = 18.76
da* = 0.47
db* = -0.39
dE*ab = 18.77

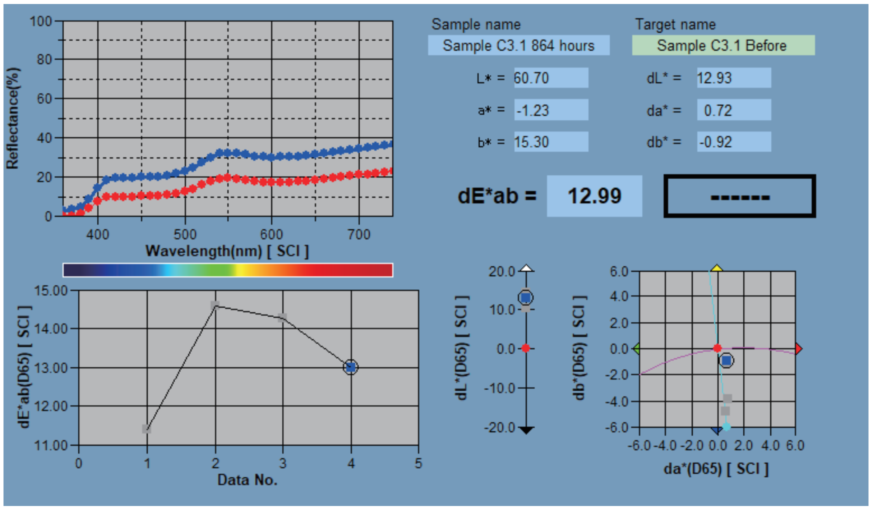
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample C2.2 864 hours
Target name
Sample C2.2 Before
L* = 62.07
a* = -1.32
b* = 14.80
dL* = 14.08
da* = 0.53
db* = -1.42
dE*ab = 14.16

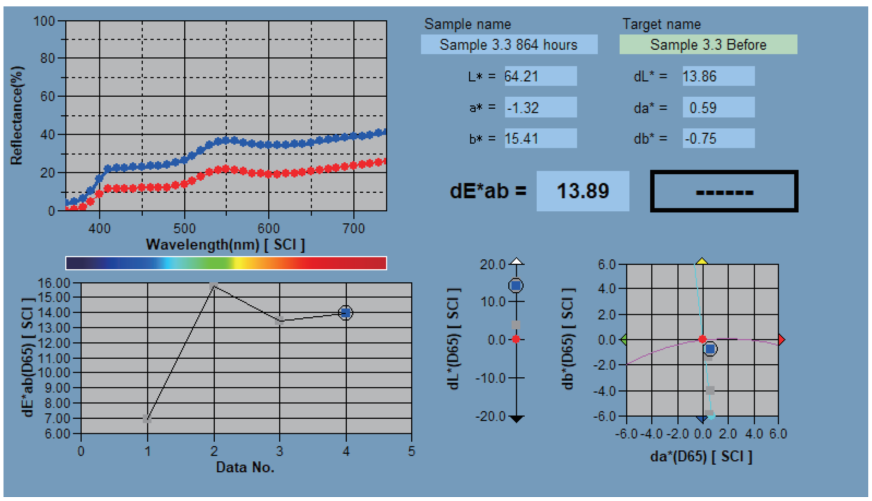
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample C2.3 864 hours
Target name
Sample 2.3 Before
L* = 61.67
a* = -1.25
b* = 15.03
dL* = 15.20
da* = 0.58
db* = -0.95
dE*ab = 15.24

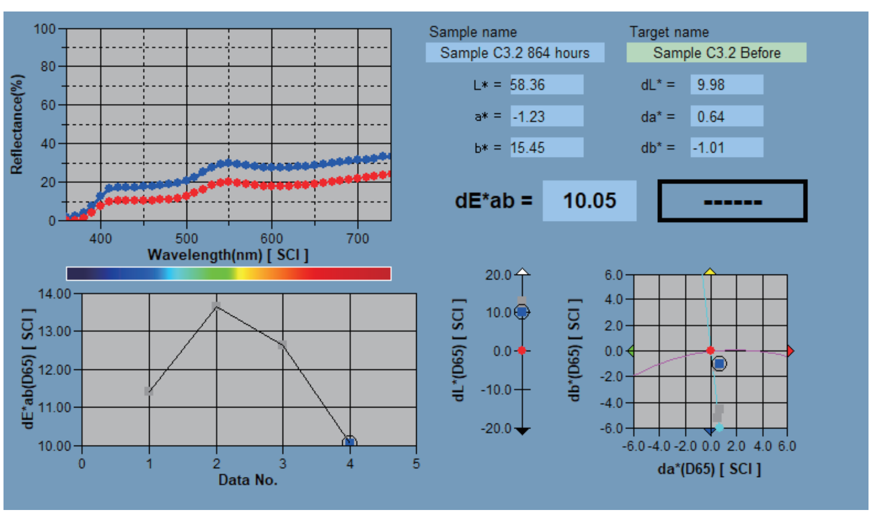
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample C3.1 864 hours
Target name
Sample C3.1 Before
L* = 60.70
a* = -1.23
b* = 15.30
dL* = 12.93
da* = 0.72
db* = -0.92
dE*ab = 12.99

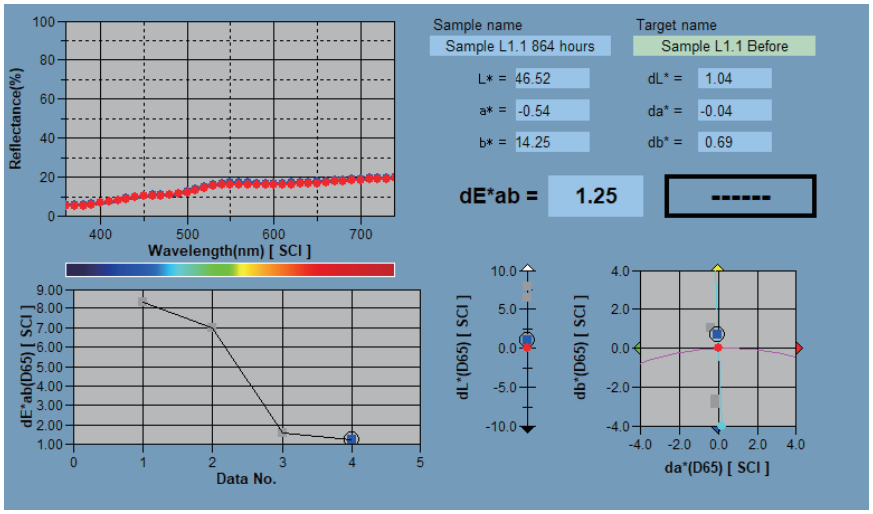
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample 3.3 864 hours
Target name
Sample 3.3 Before
L* = 64.21
a* = -1.32
b* = 15.41
dL* = 13.86
da* = 0.59
db* = -0.75
dE*ab = 13.89

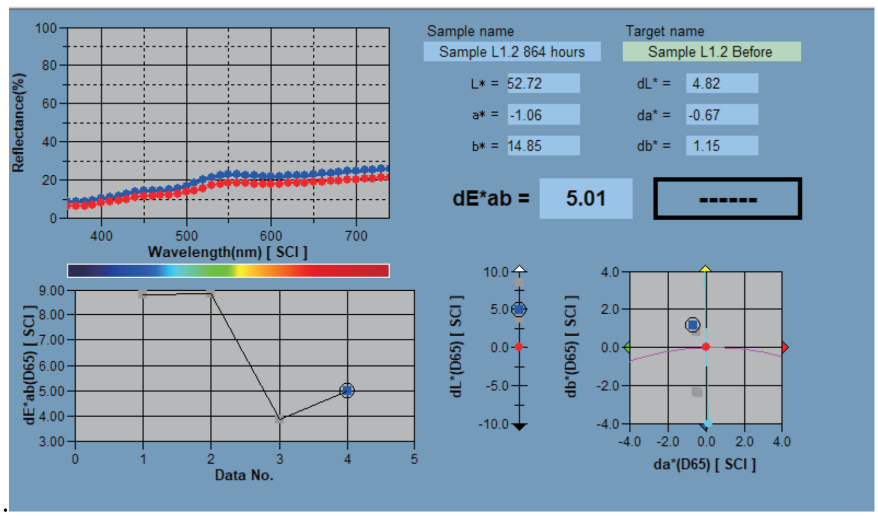
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample C3.2 864 hours
Target name
Sample C3.2 Before
L* = 58.36
a* = -1.23
b* = 15.45
dL* = 9.98
da* = 0.64
db* = -1.01
dE*ab = 10.05

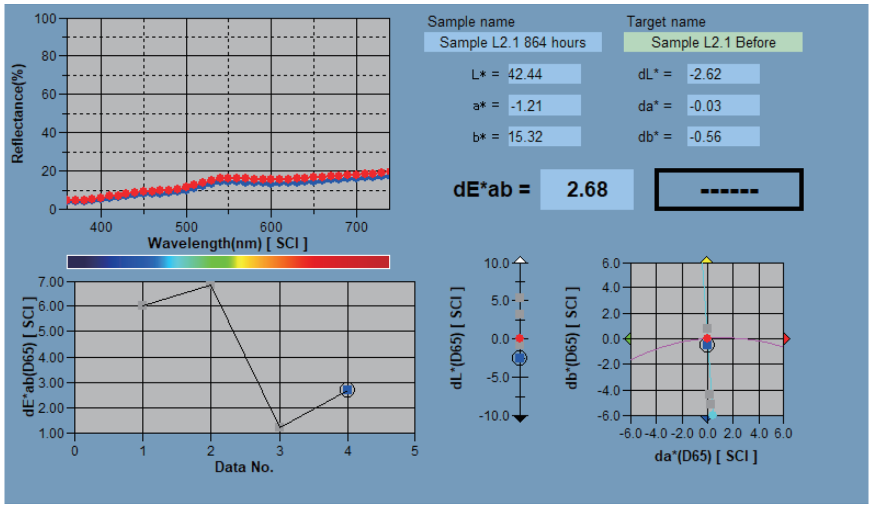
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L1.1 864 hours
Target name
Sample L1.1 Before
L* = 46.52
a* = -0.54
b* = 14.25
dL* = 1.04
da* = -0.04
db* = 0.69
dE*ab = 1.25

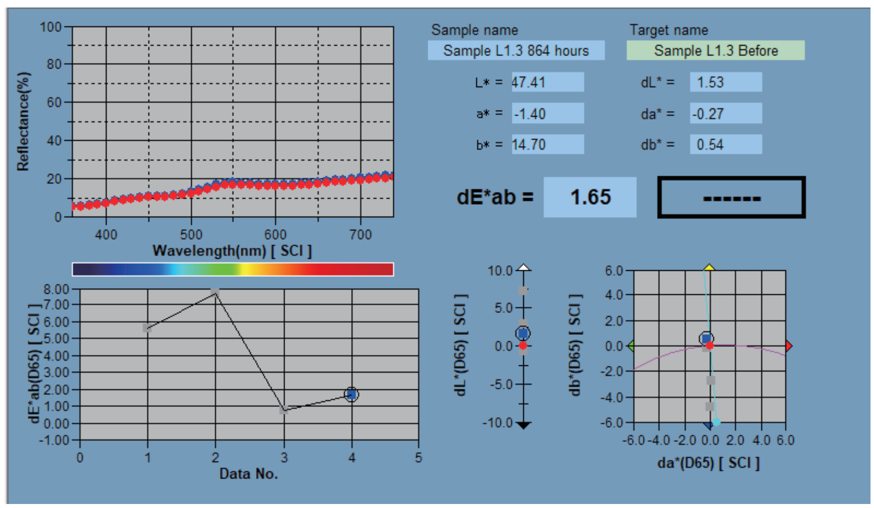
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L1.2 864 hours
Target name
Sample L1.2 Before
L* = 52.72
a* = -1.06
b* = 14.85
dL* = 4.82
da* = -0.67
db* = 1.15
dE*ab = 5.01

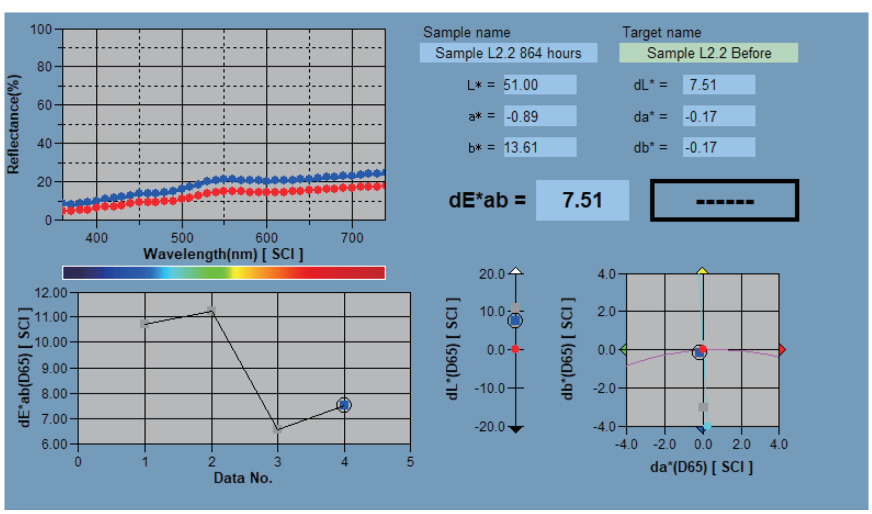
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L2.1 864 hours
Target name
Sample L2.1 Before
L* = 42.44
a* = -1.21
b* = 15.32
dL* = -2.62
da* = -0.03
db* = -0.56
dE*ab = 2.68

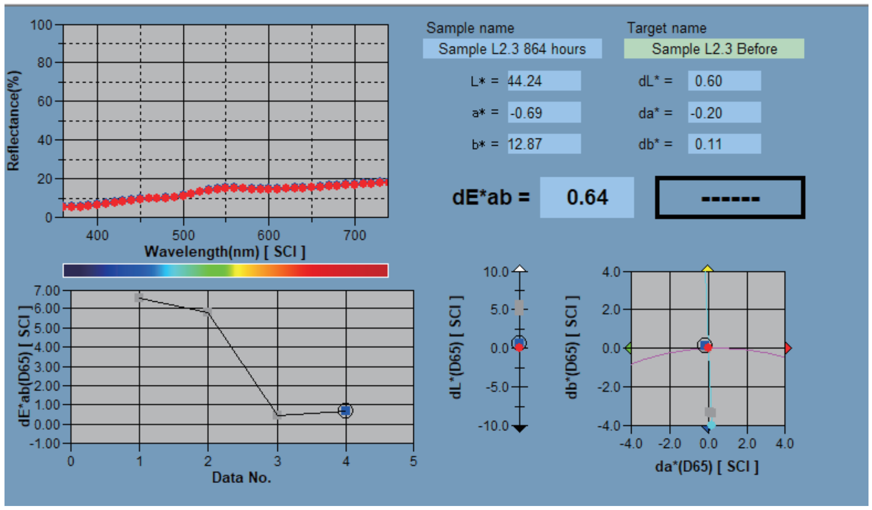
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L1.3 864 hours
Target name
Sample L1.3 Before
L* = 47.41
a* = -1.40
b* = 14.70
dL* = 1.53
da* = -0.27
db* = 0.54
dE*ab = 1.65

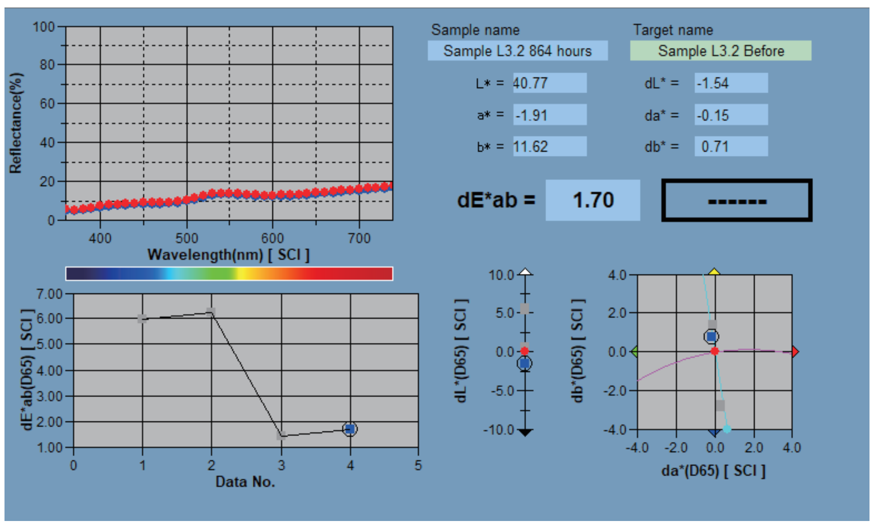
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L2.2 864 hours
Target name
Sample L2.2 Before
L* = 51.00
a* = -0.89
b* = 13.61
dL* = 7.51
da* = -0.17
db* = -0.17
dE*ab = 7.51

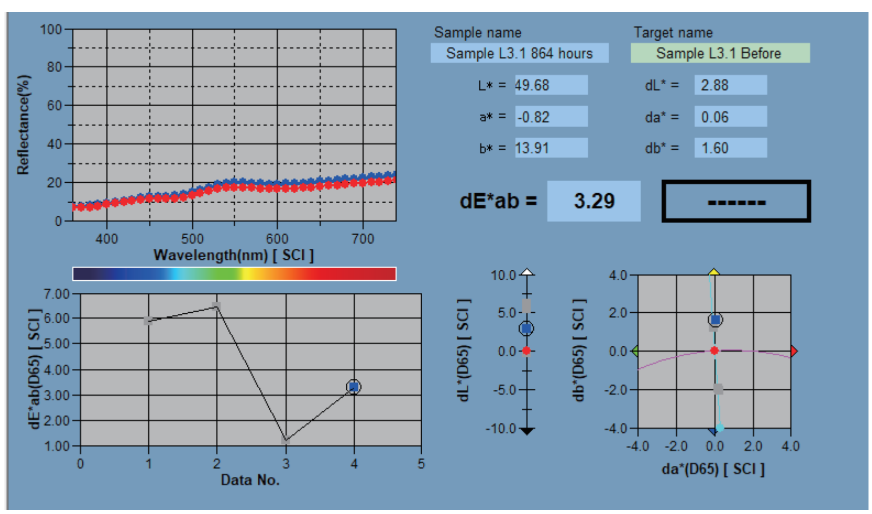
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L2.3 864 hours
Target name
Sample L2.3 Before
L* = 44.24
a* = -0.69
b* = 12.87
dL* = 0.60
da* = -0.20
db* = 0.11
dE*ab = 0.64

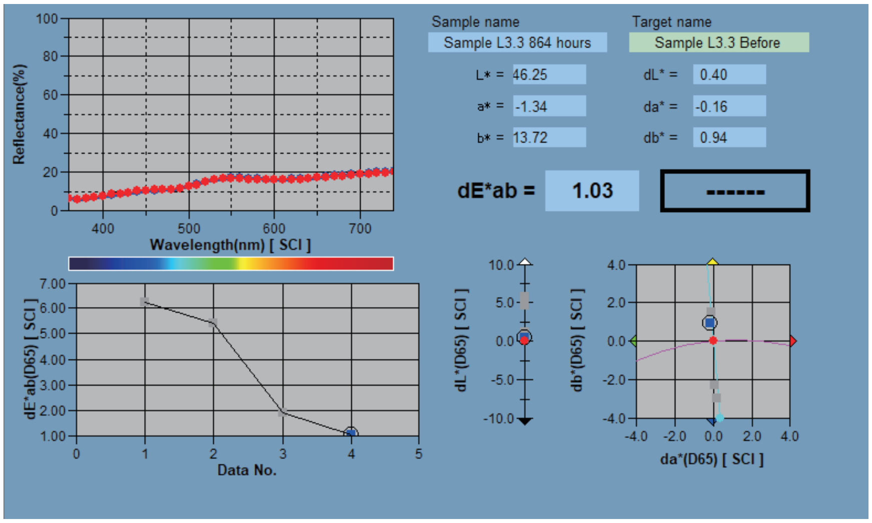
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L3.2 864 hours
Target name
Sample L3.2 Before
L* = 40.77
a* = -1.91
b* = 11.62
dL* = -1.54
da* = -0.15
db* = 0.71
dE*ab = 1.70

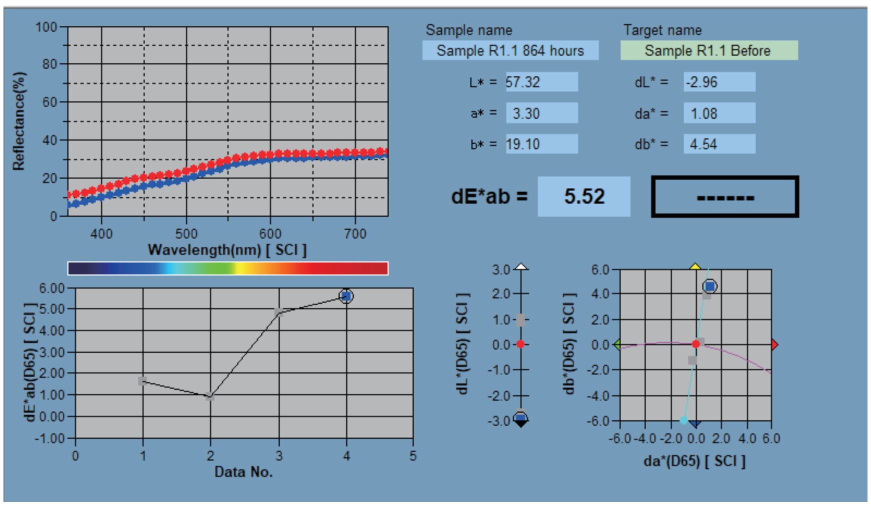
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L3.1 864 hours
Target name
Sample L3.1 Before
L* = 49.68
a* = -0.82
b* = 13.91
dL* = 2.88
da* = 0.06
db* = 1.60
dE*ab = 3.29

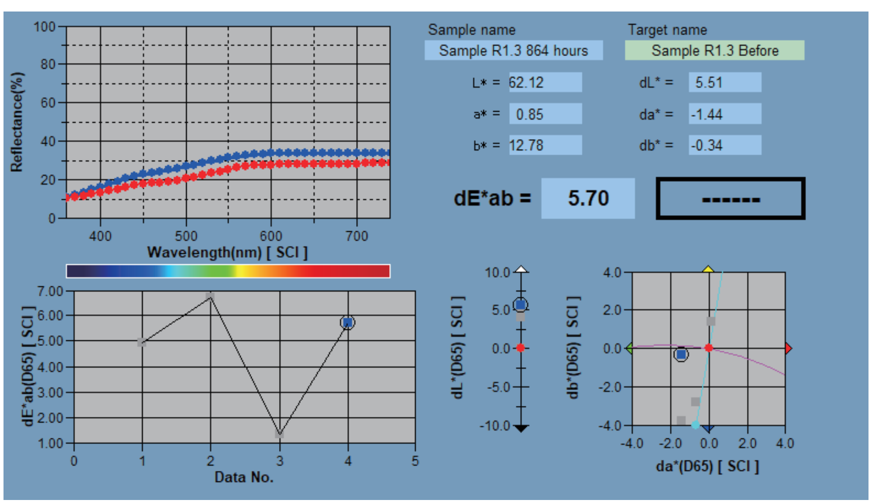
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample L3.3 864 hours
Target name
Sample L3.3 Before
L* = 46.25
a* = -1.34
b* = 13.72
dL* = 0.40
da* = -0.16
db* = 0.94
dE*ab = 1.03

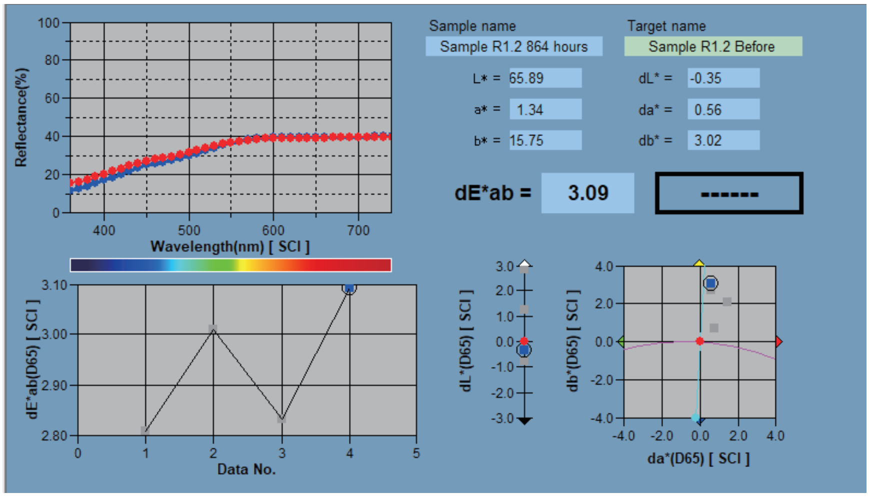
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R1.1 864 hours
Target name
Sample R1.1 Before
L* = 57.32
a* = 3.30
b* = 19.10
dL* = -2.96
da* = 1.08
db* = 4.54
dE*ab = 5.52

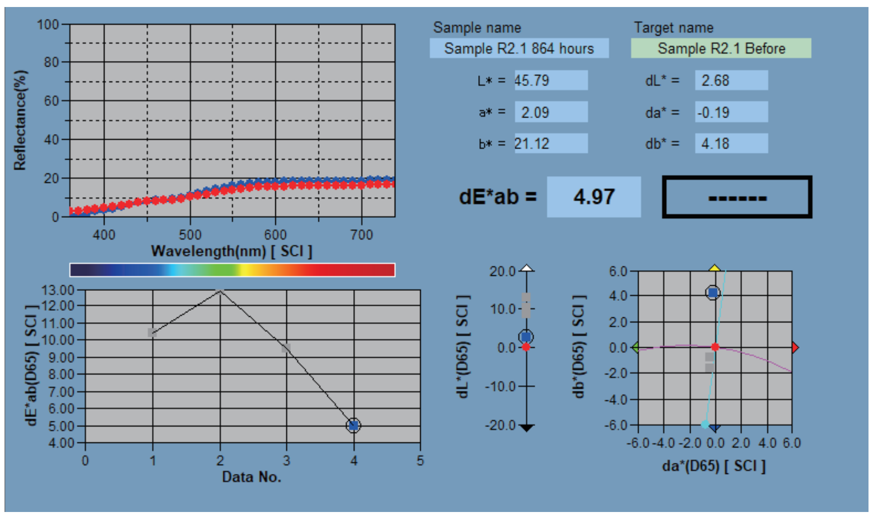
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R1.3 864 hours
Target name
Sample R1.3 Before
L* = 62.12
a* = 0.85
b* = 12.78
dL* = 5.51
da* = -1.44
db* = -0.34
dE*ab = 5.70

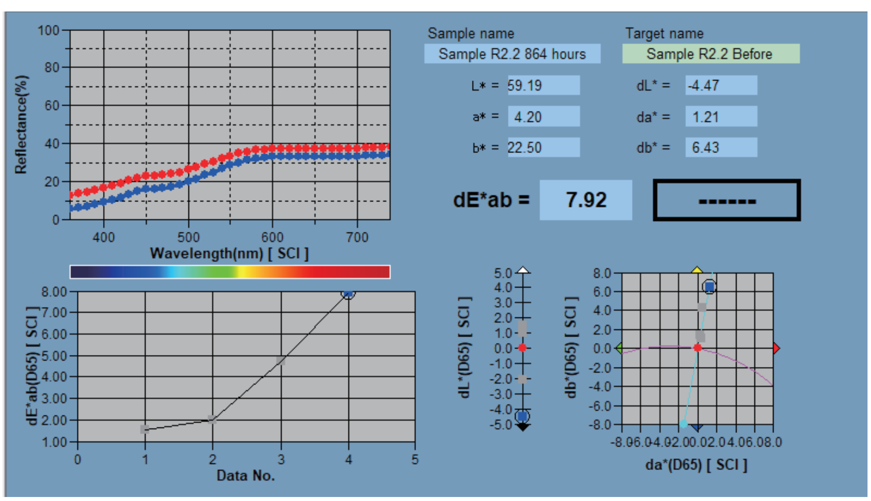
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R1.2 864 hours
Target name
Sample R1.2 Before
L* = 65.89
a* = 1.34
b* = 15.75
dL* = -0.35
da* = 0.56
db* = 3.02
dE*ab = 3.09

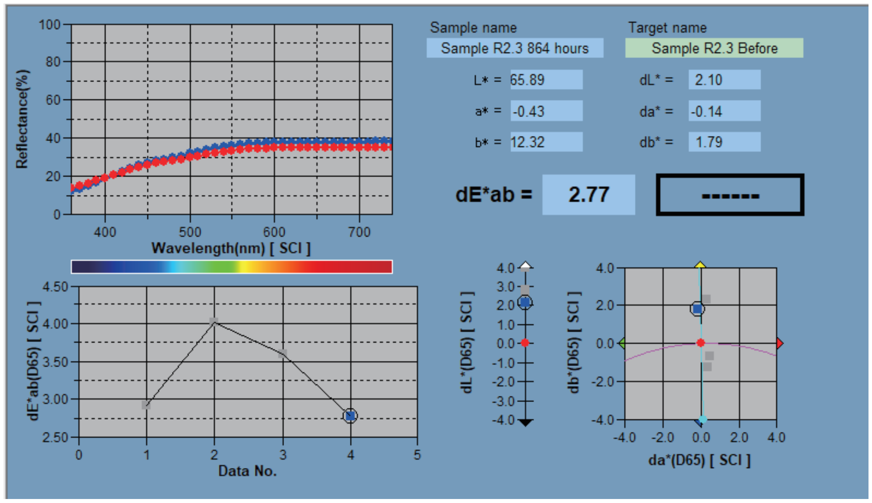
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

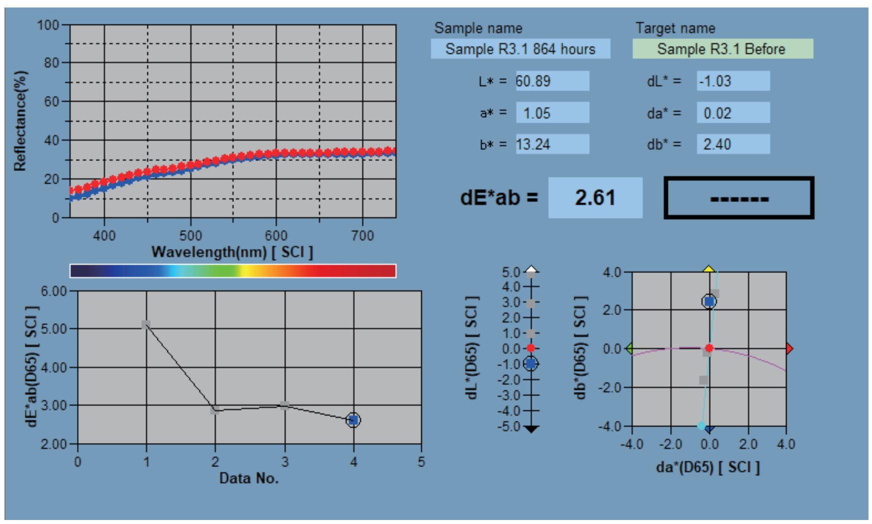

Sample name
Sample R2.1 864 hours
Target name
Sample R2.1 Before
L* = 45.79
a* = 2.09
b* = 21.12
dL* = 2.68
da* = -0.19
db* = 4.18
dE*ab = 4.97

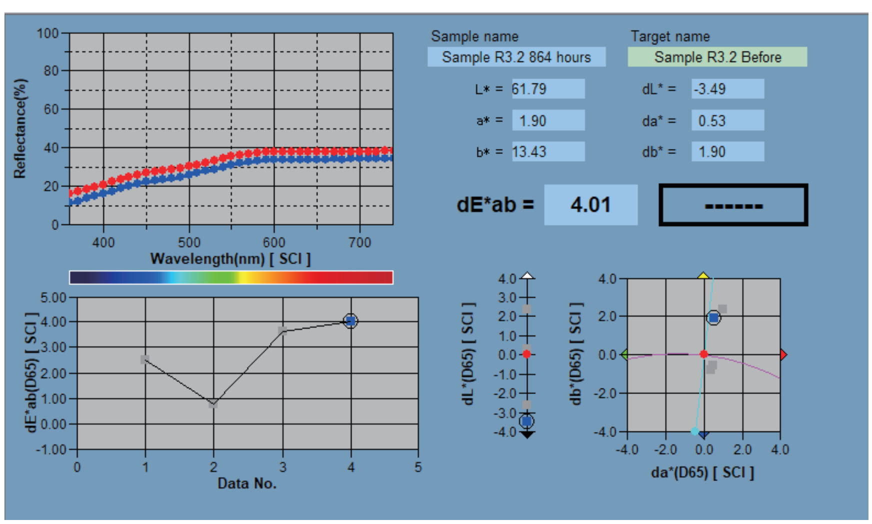
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

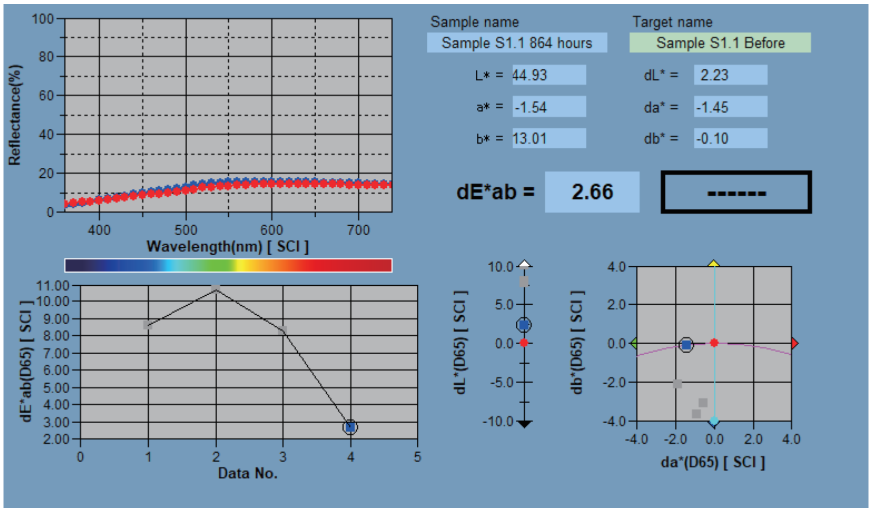

Sample name
Sample R2.2 864 hours
Target name
Sample R2.2 Before
L* = 59.19
a* = 4.20
b* = 22.50
dL* = -4.47
da* = 1.21
db* = 6.43
dE*ab = 7.92

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

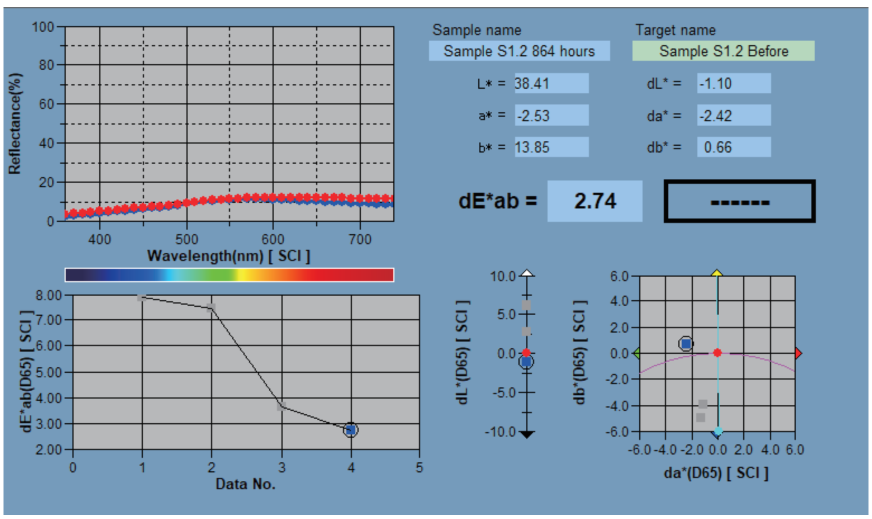

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
Sample name
Sample R2.3 864 hours
Target name
Sample R2.3 Before
L* = 65.89
a* = -0.43
b* = 12.32
dL* = 2.10
da* = -0.14
db* = 1.79
dE*ab = 2.77
------
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
Sample name
Sample R3.1 864 hours
Target name
Sample R3.1 Before
L* = 60.89
a* = 1.05
b* = 13.24
dL* = -1.03
da* = 0.02
db* = 2.40
dE*ab = 2.61
------
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

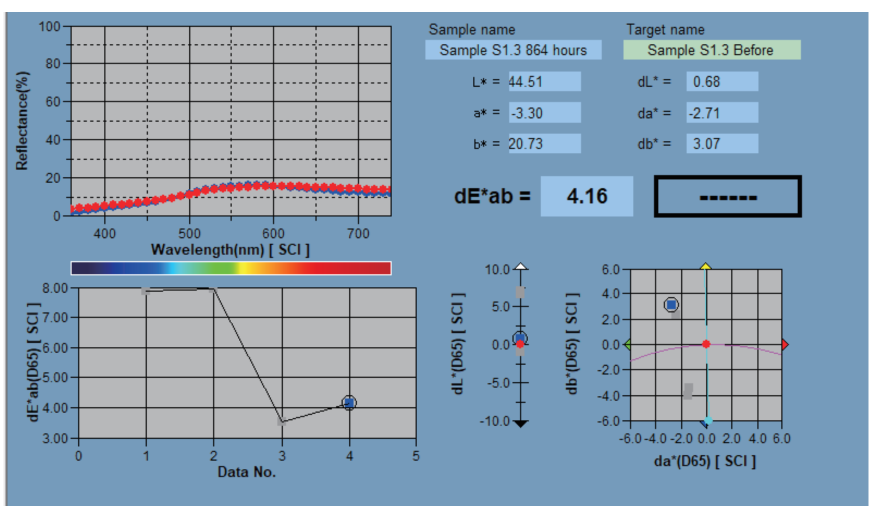

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
Sample name
Sample R3.2 864 hours
Target name
Sample R3.2 Before
L* = 61.79
a* = 1.90
b* = 13.43
dL* = -3.49
da* = 0.53
db* = 1.90
dE*ab = 4.01
------
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample S1.1 864 hours
Target name
Sample S1.1 Before
L* = 44.93
a* = -1.54
b* = 13.01
dL* = 2.23
da* = -1.45
db* = -0.10
dE*ab = 2.66

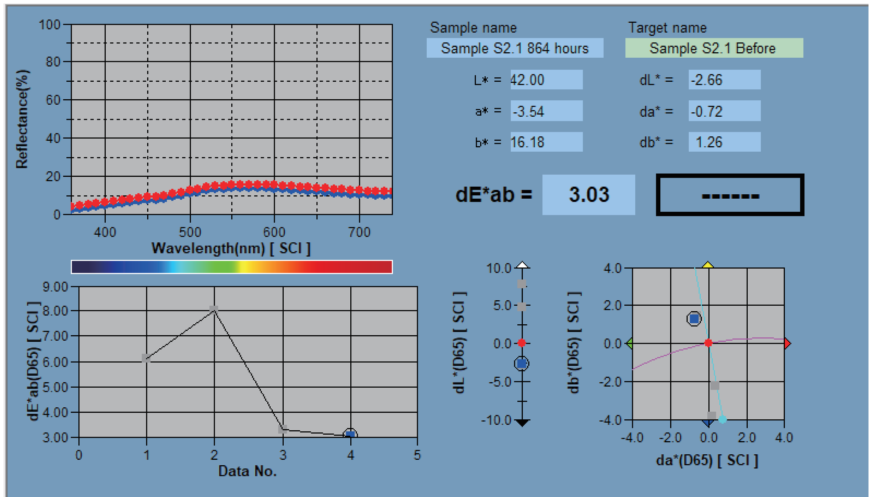
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample S1.2 864 hours
Target name
Sample S1.2 Before
L* = 38.41
a* = -2.53
b* = 13.85
dL* = -1.10
da* = -2.42
db* = 0.66
dE*ab = 2.74

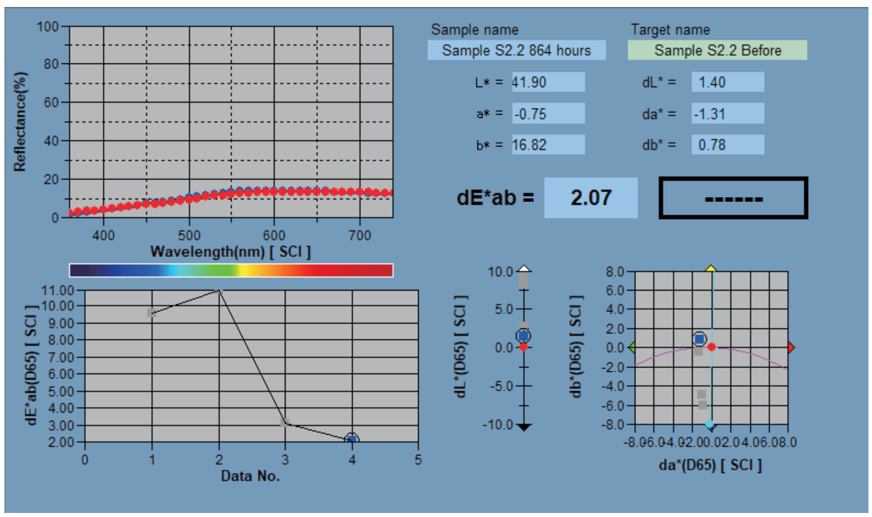
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample S1.3 864 hours
Target name
Sample S1.3 Before
L* = 44.51
a* = -3.30
b* = 20.73
dL* = 0.68
da* = -2.71
db* = 3.07
dE*ab = 4.16

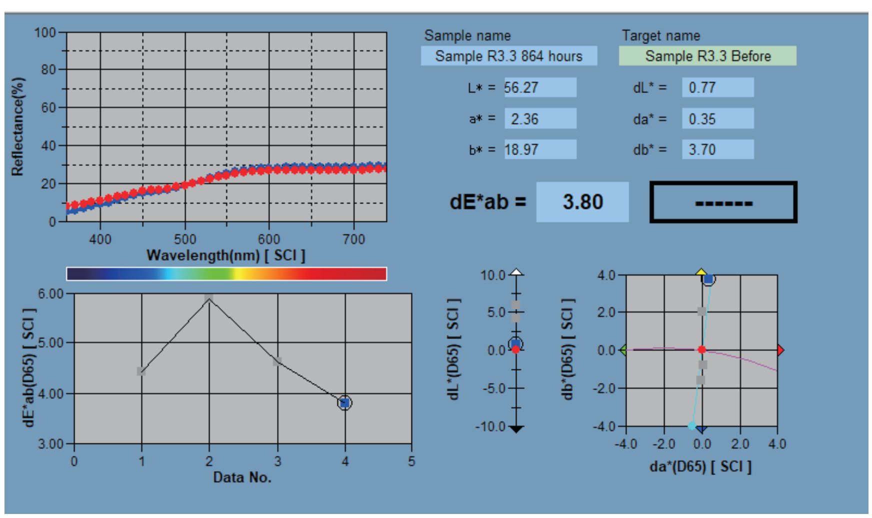
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample S2.1 864 hours
Target name
Sample S2.1 Before
L* = 42.00
a* = -3.54
b* = 16.18
dL* = -2.66
da* = -0.72
db* = 1.26
dE*ab = 3.03

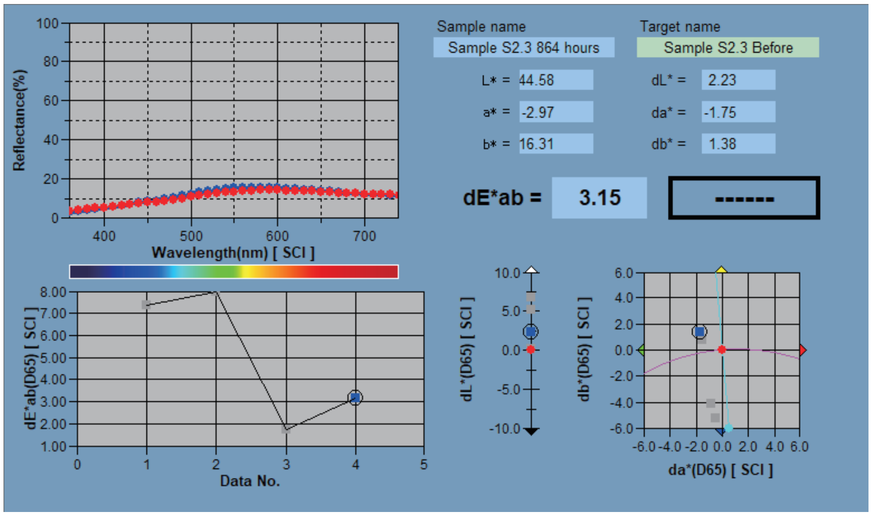
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample S2.2 864 hours
Target name
Sample S2.2 Before
L* = 41.90
a* = -0.75
b* = 16.82
dL* = 1.40
da* = -1.31
db* = 0.78
dE*ab = 2.07

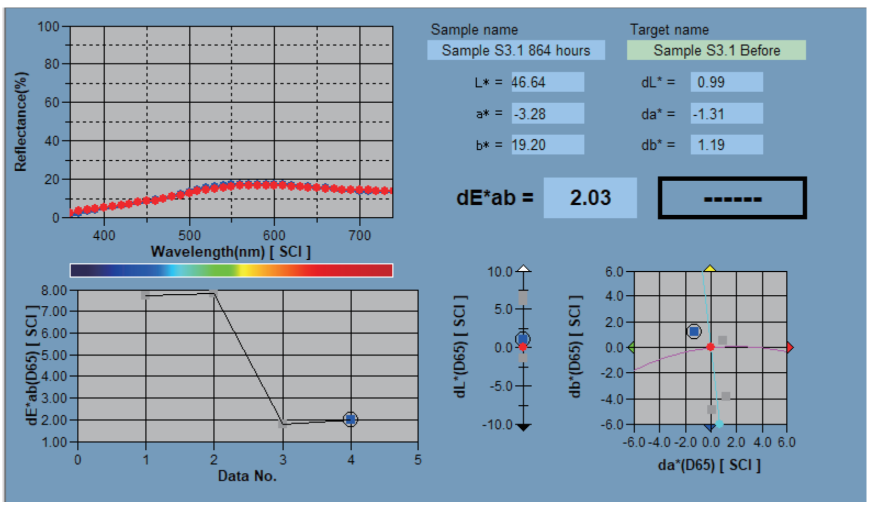
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample R3.3 864 hours
Target name
Sample R3.3 Before
L* = 56.27
a* = 2.36
b* = 18.97
dL* = 0.77
da* = 0.35
db* = 3.70
dE*ab = 3.80

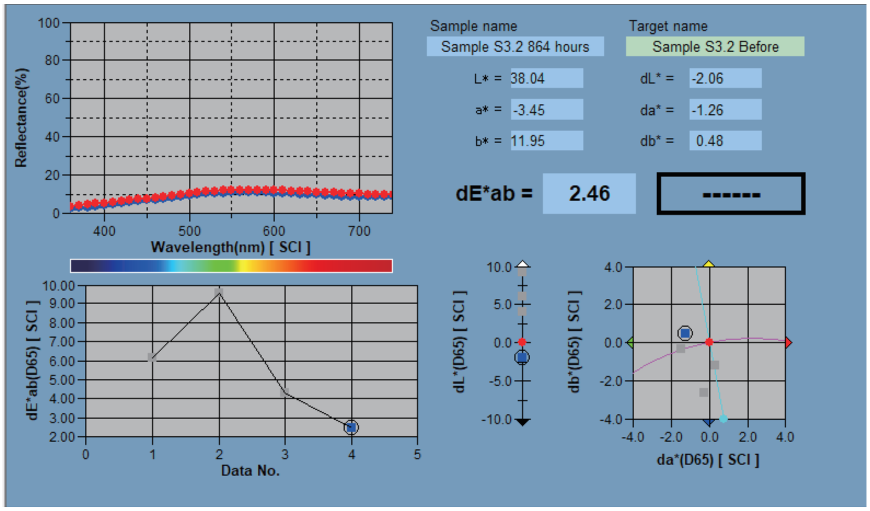
Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]


Sample name
Sample S2.3 864 hours
Target name
Sample S2.3 Before
L* = 44.58
a* = -2.97
b* = 16.31
dL* = 2.23
da* = -1.75
db* = 1.38
dE*ab = 3.15

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]

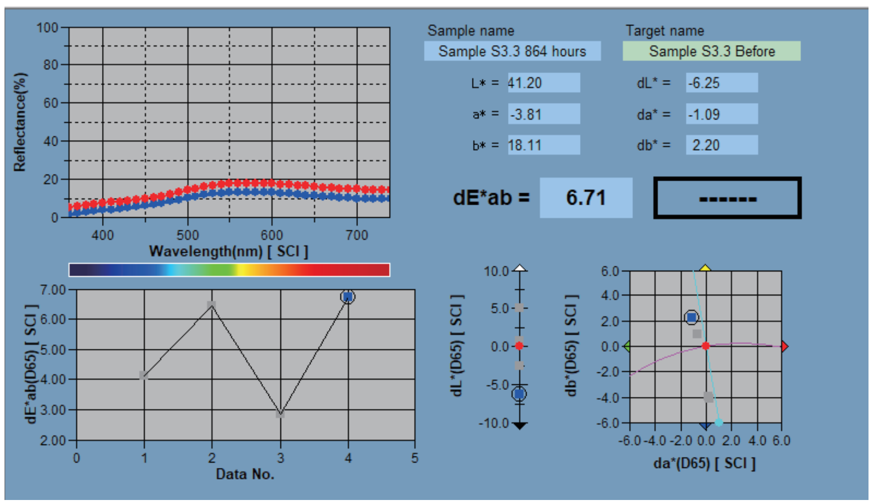

Sample name
Sample S3.1 864 hours
Target name
Sample S3.1 Before
L* = 46.64
a* = -3.28
b* = 19.20
dL* = 0.99
da* = -1.31
db* = 1.19
dE*ab = 2.03

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]



Sample name
Sample S3.2 864 hours
Target name
Sample S3.2 Before
L* = 38.04
a* = -3.45
b* = 11.95
dL* = -2.06
da* = -1.26
db* = 0.48
dE*ab = 2.46

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]



Sample name
Sample S3.3 864 hours
Target name
Sample S3.3 Before
L* = 41.20
a* = -3.81
b* = 18.11
dL* = -6.25
da* = -1.09
db* = 2.20
dE*ab = 6.71

Reflectance(%)
Wavelength(nm) [SCI]
dE*ab(D65) [SCI]
Data No.
dL*(D65) [SCI]
db*(D65) [SCI]
da*(D65) [SCI]