BEHIND THE CURTAIN:
MECHANICAL TREATMENTS FOR BOWED MARBLE PANELS

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CHAPTER I: INTRODUCTION

Purpose of Study

Architecture of the recent past, particularly marble-clad buildings, demands the attention of preservationists immediately. Deterioration mechanisms, especially bowing of panels that lead to a decrease in flexural strength, are apparent in several post-WWII structures in America and, therefore, require intervention. In recent years, concerned architects, engineers, and conservators have examined such buildings, and have held conferences, published articles and books (see Bibliography), and some have tested the possible causes of this deterioration (TEAM present testing program). Nonetheless, further research is essential to understand problems associated with marble-clad buildings in conjunction with the steel frame and anchoring systems, in addition to proper conservation techniques in mediating deterioration. Often, the solution to failing marble cladding or metallic anchors is not only complete replacement of the anchoring system, but also of the marble panels, either in kind or with a substitute material. However, this severely alters the integrity of the structure by removal of original fabric. Do established conservation principles, such as minimum intervention, not apply to curtain-wall buildings?[1] Additionally, what happens when the material cannot be replaced, such as the presence of original carving, lack of available stone, or inability to match a substitute material with the original? Are through-face anchors and netting the only solutions? Ideally, regular maintenance and preventive methods of stone selection and fabrication would address these problems before they occur.

Unfortunately, the problems of marble panel deformation and failure are becoming quite evident and pose a serious public safety issue. This thesis reviews the existing literature on the use of marble in mid-late twentieth-century American architecture, as well as examining current theories and opinions concerning the causes of deterioration of marble panels and cladding, and contemporary testing and repair methods. The research will aid in the proposal and testing of possible mechanical treatments that can mitigate the bowing potential and increase the flexural strength of thin marble veneers. This thesis will by no means suggest that it is logically or economically feasible to treat, rather than replace, all severely deteriorated marble cladding, but that if there is a need for preservation, at least options for non-replacement intervention exist.

[1] This issue has been discussed in Susan D. Bronson, "Authenticity Considerations for Curtain-Wall Buildings: Seminar Summary," APT Bulletin 32, no. 1 (2001): 5-8.

Changing Technologies

Following the Industrial Revolution, there was rapid commercial growth in America's urban areas. Real estate values increased, and business owners sought to capitalize on the amount of land they owned by increasing the heights of the buildings, as well as the floor space. Additionally, the building was to convey a sense of permanence and stability that would be a source of advertisement.[2] With the advent of steel-framed structures in the late nineteenth century, a reduction in wall thickness was possible for cost, time, labor, and space efficiency. Although metal, glass, and terracotta were frequently used as cladding material, non-load-bearing stone panels were eventually utilized, especially beginning in the 1950s. Therefore, traditional load-bearing stone buildings were largely abandoned for lighter, cheaper, and faster constructed stone-clad steel-frame buildings. At first, the stone cladding was cut at three- or four- inch thicknesses, and did not experience as much bowing as thinner panels. However, advancing building technology and mechanization allowed stones to be cut faster, more accurately, and to thinner dimensions of two-, one-, and eventually half-inch thicknesses with the introduction of

[2] Michael D. Lewis, a contemporary architect, wrote that stone is a "permanent, durable material because we perceive it as solid, stout, and secure for shelter," as well as, "stone fulfills fundamental spiritual needs by relating to past uses and past places" in Michael D. Lewis, <u>Modern Stone Cladding: Design and Installation of Exterior Dimension Stone Systems</u> (Philadelphia: American Society for Testing and Materials, 1995), 5-7.

diamond-bladed tools and multi-bladed gang saws, thereby saving time and money.[3]

Figure 1.1 Multi-bladed gang saw. (Photo from Lewis, 19.)

Similar technological advances occurred regarding the accommodation of anchors. Saws suspended on beams above, cut edge kerfs, quirk miters, or anchor holes into the thin panels on the conveyor beds below, providing a quicker, easier, and thus less costly method of production.[4] Also, with the introduction of thin stone panels to the market, new anchors were adapted. In the 1930s interior cladding techniques, such as bronze, brass, or copper wires, were used for exterior

[3] Lewis, 18.
[4] Lewis, 20.

marble cladding. By the 1970s, anchors were usually stainless steel and attached in a way that visually guaranteed that the anchor had been properly attached, instead of the blind procedure used for interior cladding before. However, anchorage standards did not adapt as rapidly as stone veneer production.[5]

Figure 1.2 Quirk miter cutting. (Photo from Lewis, 20.)

Thus, the reason for this focus on the construction methods of post-WWII structures in America derives from the fact that much of the mechanization of quarrying, cutting, and finishing marble occurred in the

[5] S.A. Bortz, B. Erlin, and C.B. Monk, Jr., "Some Field Problems with Thin Veneer Building Stones," in New Stone Technology, Design, and Construction for Exterior Wall Systems, ed. Barry Donaldson (Philadelphia: American Society for Testing and Materials, 1988), 14.

1950s and into the present, therefore more buildings were constructed with this new technology.[6] However, the closing and depletion of quarries, as well as the increasing labor costs associated with quarry workers, masons, shipping, and construction labor caused the cost of marble panels to increase since it was no longer as readily available. Panels were cut increasingly thinner for affordability, and therein lies one of the main concerns relating to the deterioration of these marble panels. It was difficult to predict how the interrelated materials, anchors, and structures would deteriorate.[7] Evidence of deterioration emerged after construction, and was generally caused by insufficient accountability of stresses, interaction of connections with panels, insufficient size of joints to allow for movement, and problems relating to the properties of the marble itself.[8]

Basics of the Curtain Wall System

Generally, the components of a marble-clad structure include thin stone panels, anchorage system, steel framework, vapor retardant, and interior

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[6] Lewis, 18.

[7] Although several Roman buildings did face brick buildings with thin stone (as cited in M. Wilson and P. Harrison, Appraisal and Repair of Claddings and Fixings (London: Thomas Telford, 1993), 1.), the anchoring and structural framework is completely different in post-WWII buildings (steel structures and anchors), therefore indicating that some of the decay mechanisms may also be dissimilar.

[8] Marcy Li Wang, Isao Sakamoto, Bruce L. Bassler, Cladding: Council on Tall Buildings and Urban Habitat, Committee 12A (New York: McGraw-Hill, Inc., 1992), 8.

finish.[9] Wind, seismic, and gravity forces must be taken into account when designing curtain-wall structures, as well as the location and climate. Therefore, certain aspects of the curtain wall system will be discussed briefly:

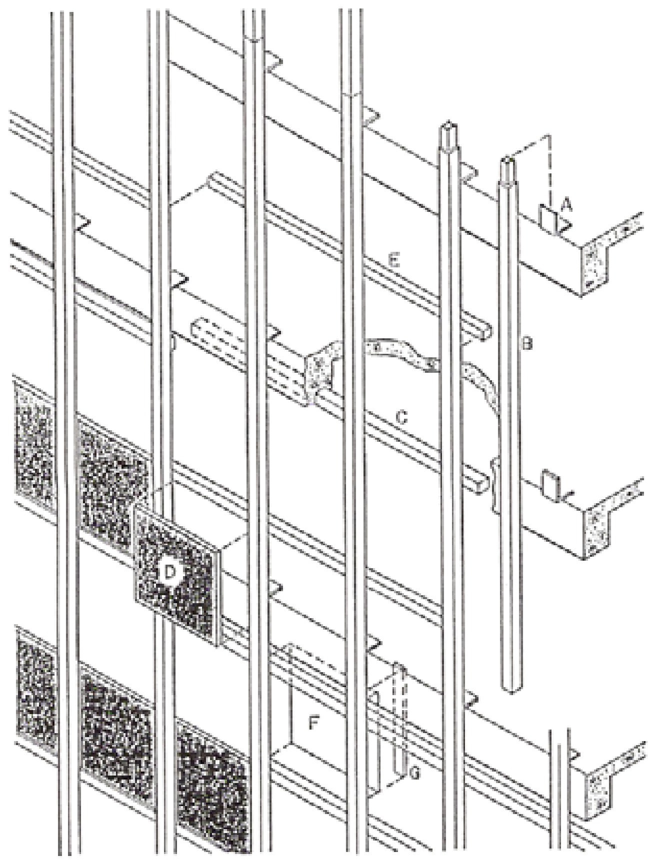

Fig. 1.4 Curtain-wall systems: A = anchor; B = mullion; C = cast-in-place rail; D = spandrel panel; E = horizontal rail; F = vision glass; G = interior trim.

Figure 1.3 Curtain-wall components. (Diagram from Wang, et al., 18.)

[9] Guideline for Condition Assessment of the Building Envelope (Reston, VA: American Society of Civil Engineers, 2000), 10.

Marble Veneer

The cladding—marble, in this case—is the initial, and nearly always, the only barrier to the environment from the interior. The chosen panels must be lightweight, not only to alleviate loads on the frame, but also for relative ease of installation, and hence cost of construction and labor. Color is not usually a factor because various types of marble can exhibit signs of deformation. Preferably, the marble grain structure would be xenoblastic (amoeboid) as opposed to granoblastic (equigranular-polygonal), since the granoblastic marbles tend to bow more, as will be discussed later.[10] Despite the protective assets of a polished finish for the porosity and durability of the marble, atmospheric agents and acid rain may eventually destroy this finish on most calcitic and dolomitic marbles.[11] Additionally, since the marble panels are quite thin initially by design (¾" - 2"), the unequal movement of the grains causes the marble to bow when exposed to heat and moisture, more so than with thicker load-bearing masonry. The marble can also become thinner or possibly contracted due to disaggregation, differential erosion, or delamination, thereby indicating that minimum thickness standards should be abided for

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[10] L. Alnaes, et al., "Influence of Rock and Mineral Properties on the Durability of Marble Panels" (TEAM Conference Proceedings, 2004), 4.

[11] Alex S. Gere, "Stone Cladding Systems," in Exterior Claddings on High Rise Buildings, ed. Chicago Committee on High Rise Buildings (Chicago: The Fall 1989 Symposium Report, No. 12, 1990), 229.

maximum physical life. The marble should be relatively resistant to weathering, such as moisture penetration (rain and condensation), UV light, thermal fluctuations, freeze/thaw cycling, pollution, and acid rain. As will be discussed, the result of such exposure may be in the form of cracks, spalls, deformation, or detachment, all of which contribute to a more rapid rate of decay, and, eventually mechanical failure. Therefore, minimum standards regarding type, finish, dimensions, and thickness of stone panels should be examined in order to determine the safety of maintaining a potentially incipient loss.

Anchors

Anchoring systems are responsible for transferring gravity, as well as lateral or other vertical loads, to the support system, since marble cladding is non-load bearing. They are generally attached directly to the back or sides of the stone, and are available in many different formats, such as kerf anchors (**Figure 1.4 1a-c**) (those that fit into a groove cut into the stone), rod anchors (**Figure 1.4 2a-c**) (those that fit into drilled holes), tooled-rod anchors (the head of the bolt fits into the marble, and the threaded end is fastened to a clip angle on the frame), and rod-and-plug anchors (**Figure 1.4 3a-b**) (those that include a threaded rod inside a

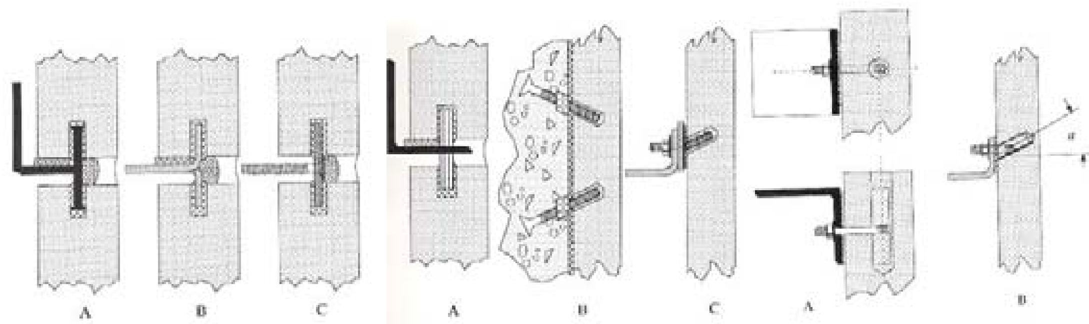

Figure 1.4 Anchor types: 1a-c) kerf anchors; 2a-c) rod anchors; 3a-b) rod-and-plug anchors. (Diagrams from Lewis, 89-93.)

smooth rod, then placed in a drilled hole).[12] Attachment systems are chosen according to the type and thickness of stone panels, since thinner stones are usually attached by continuous or individual clips, to accommodate inherent loading and anchoring stresses, as well as potential for differential movement.[13] The anchors should be metal that will not stain or corrode, such as stainless steel. Any anchoring system should be easy to install, cost effective, and compatible with the marble in terms of limiting potential deformation. For example, the Zibell anchoring system is specifically designed for 7/8 inch or 1¼ inch marble, and it is lightweight and relatively easy to install, thereby cost, time, and labor efficient.[14] Some guidelines do exist, such as those from ASTM and The Marble Institute of America, which recommend that there should be "…a minimum of four anchors per piece of stone up to 12 square feet of

[12] Lewis, 90-94.
[13] Wang, et al., 8.
[14] Fred Nashed, Time-Saver Details for Exterior Wall Design (New York: McGraw-Hill, 1996), 155 and 156.

surface area, and two for each additional eight square feet. Weight, size, shape, and type of stone may dictate deviations from the foregoing."[15] Therefore, the type of marble, thickness, weight, finish, design, and structure should all be taken into account when deciding which anchoring systems to use.

Joints

When designing joints between the panels, one must account for not only structural movement, but also the expansion and contraction of the panels. Any movement that is not accounted for has usually caused bowing. The type of sealant used for the joints should be resistant to moisture penetration and thermal breakdown, but also flexible, so that the marble panels will be able to move accordingly. Also, it is inevitable that water will penetrate the building at some point, whether through joints or from interior condensation. Thus, collection and diversion of water through flashings and weepholes need to be included in the design. Limiting the opportunities of deterioration within the marble panels during construction or intervention, in conjunction with routine maintenance, can greatly increase the chances of a longer lifespan for the material.

[15] Dimension Stone Design Manual IV (Farmington, MI: Marble Institute of America, 1991), 1.

Deterioration Mechanisms

The timeless and durable characteristics of marble were conferred upon these curtain-wall buildings, but one must remember that all materials deteriorate; it merely depends on the environment, and the specific material itself. Many factors affect the deterioration and deformation of marble cladding, including marble type, finish, thickness, joints, anchors, and, of course, the surrounding environment. For example, a number of deterioration mechanisms affect marble in general, such as salt crystallization in pores, gypsum crusts forming due to the presence of sulfur in the air from industrial and vehicular pollution, and natural and unnatural acidity levels in rainwater that can cause erosion, but there are a few conditions specifically related to marble cladding. Marble deformation can be caused by moisture infiltration, freeze/thaw cycling, metallic attachment corrosion, unplanned stresses, and hysteresis (see below).

Environment

The surrounding environment can cause the marble panels to weather. For example, marble panels are affected by thermal changes and freeze/thaw cycling, usually not only at the surface, but throughout the stone because they are so thin. Such exposure can cause hysteresis, which occurs when the marble panel is so thin that it cannot resist the

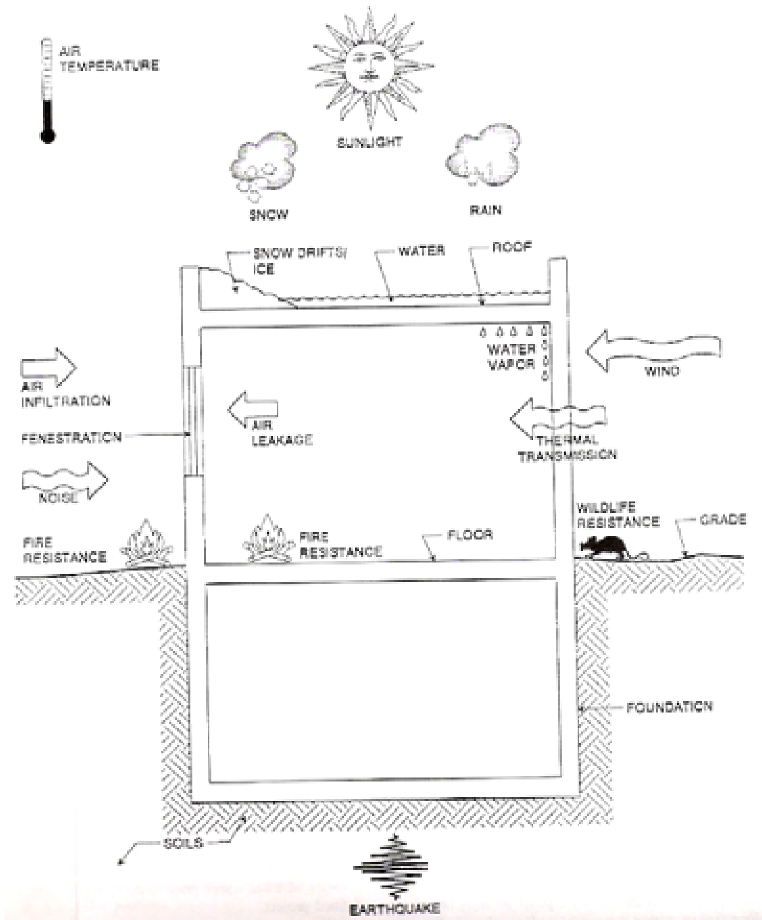

Figure 1.5 Building envelope environmental exposure. (Diagram from SEI and ASCE, 17.)

stresses caused by the anisotropic thermal expansion and contraction of its fine grains when exposed to heat and moisture. This causes microfractures within the grain boundaries, thereby increasing porosity and decreasing strength. Any time the porosity increases, more moisture can be absorbed and retained within the material, potentially resulting in salt crystallization, freeze-thaw cycling, and disaggregation caused by pollutants and acid rain within the marble itself, not just on the surface.

Marble panels can also heave caused by ice formation behind, if the weep hole drainage is not functioning properly, or if there is a break in the sealants or flashing, resulting in water flow into the interior. A way to prevent this is to accommodate the intrusion of water through a series of properly functioning interior gutters, downspouts, or weep holes. Usually, the marble panel is in direct contact with the metallic attachments, and if metallic corrosion occurs due to exposure to moisture, the metal will expand within the stone and result in cracks and spalls. Wind, seismic, and gravity forces can cause undue stresses on the marble panels, which can result in strength loss, movement, and possibly mechanical failure (since the marble veneer is supposed to be non-load-bearing). Over time, the microfractures can turn into larger cracks, the porosity can increase, thereby allowing more water, pollutants, and chemicals into the stone that can result in disaggregation, eventually minor losses (spalls), and bowing and deformation can occur, sometimes leading to complete failure.

Anchoring Systems

Additionally, the cladding and the anchoring systems affect each other. Moisture can come into contact with the steel-frame structure from the outside environment through rain via sealant failures or from the inside

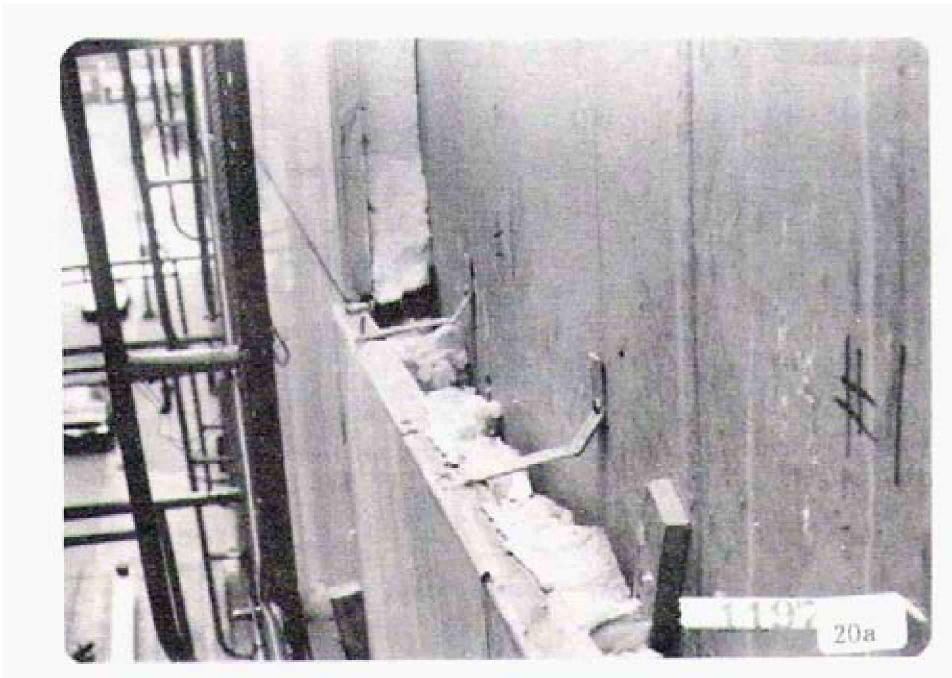

Figure 1.6 Bending anchor caused by lateral loading. (Photo from Bortz, et al., 27.)

environment through condensation if the vapor retardant is not properly functioning. In the case of improper diversion of water and/or moisture infiltration, if the moisture cannot escape, it will remain behind the curtain wall and can corrode the metallic elements, therefore resulting in material expansion that leads to cracking, spalling, and deformation of the marble, not to mention staining. Also, if anchors are missing, unintended loads can be exerted on the marble slabs, again resulting in deformation.[16] Anchors need to engage in resistance to lateral loads immediately, or else the stone will warp due to the unintended flexural

[16] Michael J. Scheffler, "Thin-Stone Veneer Building Facades: Evolution and Preservation," APT Bulletin 32, no. 1 (2001): 30.

stresses.[17] Anchors can fail due to lateral wind load, thereby imparting undue force on the marble cladding, which can result in bowing.

Joints

As discussed above, if joints are not designed large enough and if the appropriate sealant is not used, the result can be cracking, deformation and moisture infiltration. Thus, when repairing joints, often they are widened by abrading down the edges of the surrounding stones or a replacement sealant allowing for more movement is utilized.

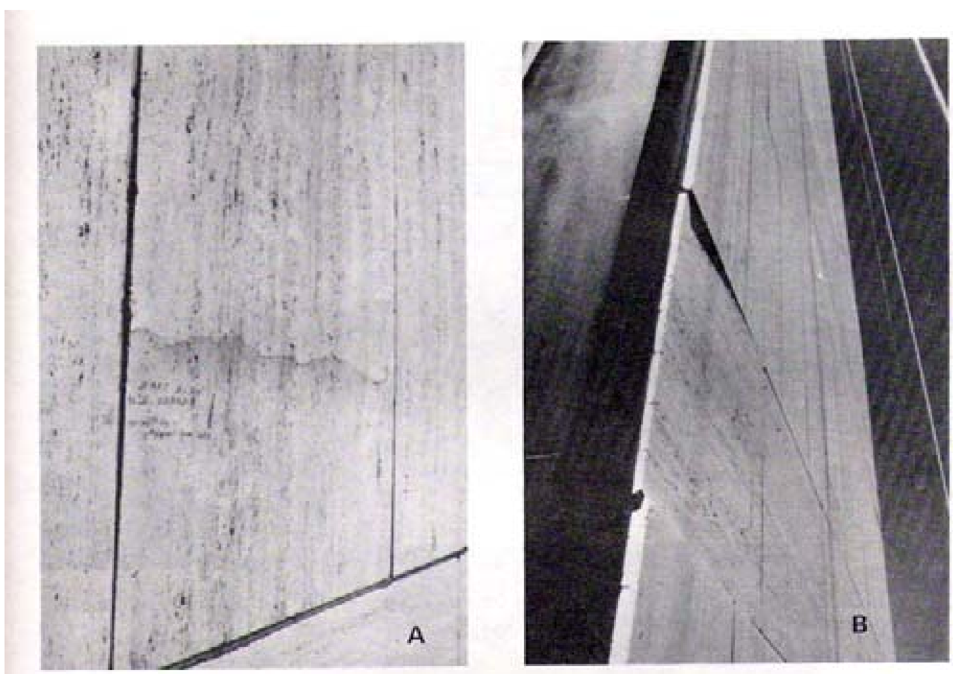

Figure 1.7 Deformational effects of restrained building movement. (Photo from Bortz, et al., 17.)

[17] Bortz, et al., 28.

Hysteresis

Although this topic will be covered in more detail in Chapter 2, it should be mentioned here as the most notable cause of marble deformation. Hysteresis occurs when the panel lacks the ability to resist stresses, since it is so thin, caused by the anisotropic thermal expansion of fine-grained marbles (exterior and interior faces expand at different rates), resulting in a permanent, generally convex, bowing. This becomes weaker over time because the water absorption capacity increases with subsequent heating cycles.[18] This loosens grain boundaries in marble, since calcite does not expand uniformly in all directions when heated, and the permeability/water absorption of marble slabs may be a contributing variable in this thermal deformation.[19] The strength of the microstructure depends on "the rift and cleavage of the crystals, the degree of cohesion, the interlocking of the crystals, and the nature of any cementing material present."[20] The deterioration of the marble begins with "thermal cracking…Weathering increases the pore spaces due to

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[18] William H. McDonald and Michael D. Lewis, "The Importance of Studying Exemplars when Designing Stone Facades," in Performance of Exterior Building Walls, ed. Paul G. Johnson (West Conshohocken, PA: ASTM International, 2003), 63.
[19] Clemens Widhalm, Elmar Tschegg, and Walter Eppensteiner, "Anisotropic Thermal Expansion Causes Deformation of Marble Claddings," Journal of Performance of Constructed Facilities, February 1996, 5.
[20] James E. Amrhein and Michael W. Merrigan, Marble and Stone Slab Veneer (Los Angeles: Masonry Institute of America, 1986),89.

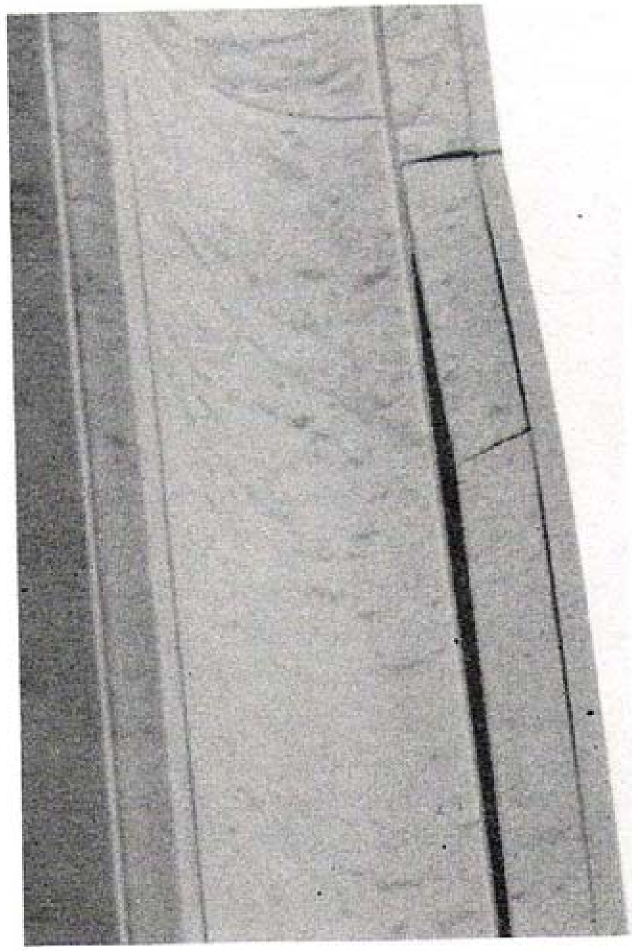

Figure 1.8 Marble bowing. (Photo from Wang, et al., 91.)

microcrack generation and subsequent solution/precipitation activities. The result is sugar-like disintegration…"[21] This bowing and subsequent weathering can be costly to repair, as in the case of the Amoco Building in Chicago, which was clad with 1¼ -inch Carrara marble panels in 1973,

[21] Thomas Weiss, Siegfried Siegesmund, and Patrick N.J. Rasolofosaon, "The Relationship between Deterioration, Fabric, Velocity and Porosity Constraint," in Proceedings of the 9th International Congress on Deterioration and Conservation of Stone, Venice, June 19-24, 2000, ed. Vasco Fassina (Amsterdam: Elsevier Science Publishing Company, 2000), 222.

and was later replaced in 1994 with 2-inch granite for $60-80 million.[22] This stone deformation could have been prevented if temperatures of the back side of the panel and the front side of the panel were stabilized.

Case Studies

Some sites have required complete replacement of both the anchoring systems and the cladding to ensure safety and to decrease the chances of similar deterioration reoccurrence. For example, at the Indiana National Bank in Indianapolis, completed in 1969, the Carrara marble column covers were bowing and warping already by the early 1970's. The decision was to face-drill the stones to re-anchor them, but the panels continued to deform. Thus, later in that same decade, the marble was replaced with metal panels.[23] This is quite similar to the second case study, the Amoco Building in Chicago, which has already been mentioned, although the replacement material was a thicker granite.

The third case study does not relate to marble cladding, but rather basalt, at the Whitney Museum of American Art in New York City. In 1996, it was discovered that the original steel anchors had corroded due to galvanic action between the steel bolts and the zinc-coated stainless

[22] Nashed, 160-161.
[23] McDonald and Lewis, 64.

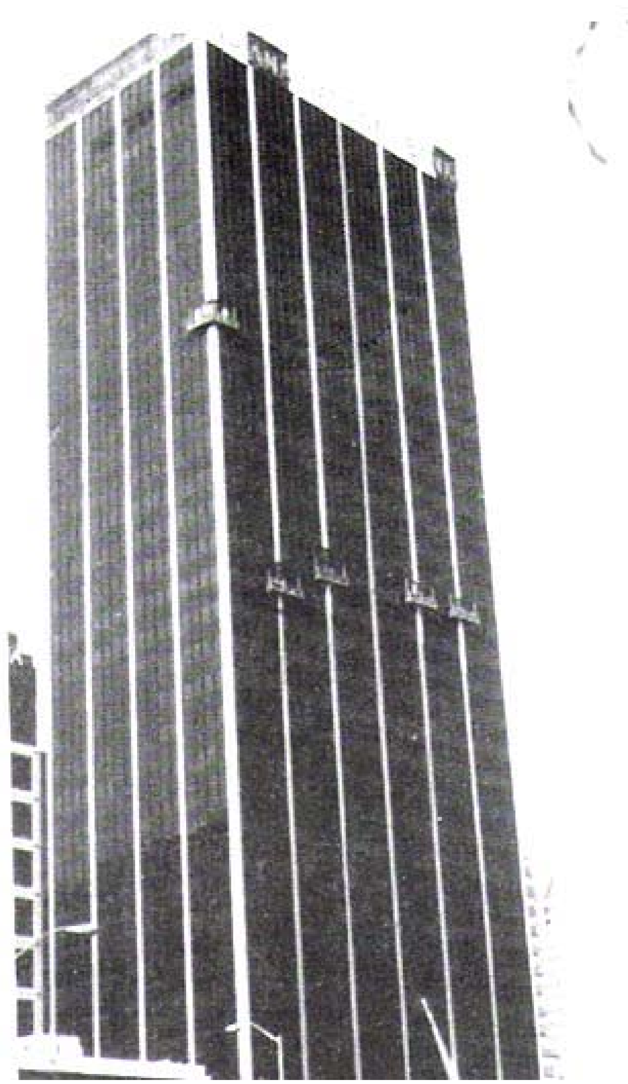

Figure 1.9 Indiana National Bank (1960). (Photo from McDonald and Lewis, 61.)

steel dowels, therefore loosening the stone cladding from the building.[24] Most of the basalt was repaired and retained, while the anchoring system was replaced; however, if it had been marble, potentially the deformation would have been quite severe and not salvageable.

[24] Eric Adams, "Collaborating with Conservators: Repairing the Whitney's Stone Curtain Wall," Architecture 86, no. 9 (1997): 142.

Although these techniques may be appropriate for some buildings, as with any treatment, they are not appropriate for all.

Contemporary Preservation and Testing Methods

In confronting the deterioration of marble-clad buildings, some architects, engineers, and conservators have developed new anchoring systems to reattach either the original marble or a replacement stone, so as to reinstate structural safety. Developed in the United Kingdom, the Cintec Designed Anchor System consists of inserting a steel rod wrapped in a fabric sock into a predrilled hole, and then pumping ultra-fine grout into the sock until the grout is forced through the sock to form a chemical bond between the anchor and the substrate, a technique that was used at the Essex County New Courts Building and Jail in Newark.[25] An additional treatment method to be considered is the option to increase the thickness of the marble slab, when feasible, with epoxy adhesive and aluminum honeycomb core, although this may cause difficulties for water vapor transmission.

In order to determine appropriate and compatible anchoring systems for future designs and treatments, testing of various anchoring systems should be conducted. Hence, TEAM (Testing and Assessment of

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[25] Eric Adams, "Cutting-Edge Masonry Repair," Architecture 87, no. 4 (1998): 119.

Marble and Limestone), a group of engineers, architects, and conservators in the Netherlands, has identified their purpose as to study why marble cladding bows and how the bowing affects the decrease in strength.[26] They have been conducting tests on various anchoring

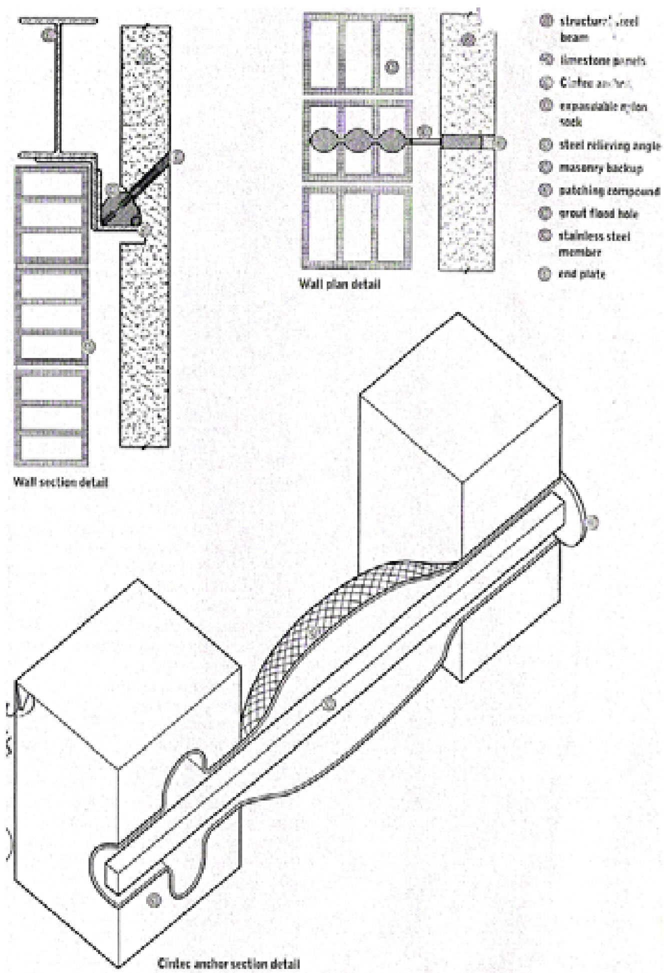

Figure 1.10 Cintec Anchoring System. (Diagram from Adams, "Cutting Edge Masonry," 118.)

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[26] T. J. S. Yates, et al., "Observations from the Inspection of Marble Cladding in Europe," in prep. Dimension Stone 2004, 1.

systems ("kerf, mortised, back face fixings FZP, dowels at vertical edges, and dowels at horizontal edges"[27]) on the same Carrara marble since 2003 in Fisherwerke, Waldachtal, Germany. The chief purpose of these tests is to analyze if there are any differences among the anchoring systems and how they affect bowing of the marble.[28] Also, TEAM is testing marbles to determine if impregnation with GypStop, an inorganic water-based product, and Anti Graffiti System, a water-based agent, aids in the decrease of bowing in thin marble panels.[29] The results will not be conclusive until the end of this year. While these tests, as well as the tests of treatments conducted in this thesis, may confirm alternative minimal intervention options, they are only available for those marbles that, although in danger of becoming so, are not already excessively deformed. When repairing thin-stone veneer systems safety, aesthetics, feasibility, cost, and serviceability should be considered.[30]

Proposed Treatments and Testing

In giving consideration to treatments or repairs of marble panels, one must implement tests on both the treated and untreated samples for

[27] K. Malaga, et al., "Field Exposure Sites and Accelerated Laboratory Test of Marble Panels," in prep. Dimension Stone 2004, 3.
[28] K. Malaga, et al., 3.
[29] K. Malaga, et al., 2-3.
[30] Scheffler, 33.

comparative purposes. Tests should be predicated upon what is known concerning deterioration mechanisms related to marble panels, as has been discussed. In order to determine the rates and how much water was absorbed or evaporated, as well as how it affected the sample, water absorption and evaporation should be tested. Since hysteresis caused by thermal changes is the chief reason for marble deformation, tests regarding thermal expansion and bowing potential should definitely be conducted. Likewise, any treatments should be tested for flexural and tensile strengths since thin panels are weak in this area, in addition to movement caused by the wind or material, anchoring, or structural movement. Those tests developed to determine compatibility of anchors with marble panel pre-construction could potentially be revised for material analysis regarding deteriorated samples. Tests would, ideally, be conducted regarding bowing potential, flexural strength, tensile strength, attachment strength, effects of thermal changes, and material compatibility. Few standards, however, exist specifically for this purpose regarding curtain-wall buildings, so some will need to be adapted.

For this thesis, however, due to time constraints, only the major properties were tested. Bowing potential and flexural strength tests were performed, as well as general characterization of the marble. The bowing potential and flexural strength tests are especially important, since according to one expert:

> A 1/8 inch (3 mm) reduction of a 1¼ inch (32 mm) veneer reduces bending strength by roughly 20 percent and may increase elastic deflection under wind loads by as much as 37 percent. This problem can be further affected by job-site weathering.[31]

Hysteresis is one of the major reasons for the bowing of marble panels, so any method of mitigating this type of deterioration before or after it occurs should be examined. That is why various mechanical treatments will be applied to the marble and tested, including carbon fiber straps and polypropylene honeycomb, both of which will be discussed more in depth in Chapter 2.

Marble cladding could potentially have an indefinite lifespan if designed with appropriate anchors, frame, and joints, taking into account rain, freeze/thaw cycling, wind, sun, temperature changes, pollution, and acid rain. All materials deteriorate, but the rate of decay can be controlled and extended through intervention. Technologies, codes, regulations, and standards need to be developed in accordance with the positive aspect of hindsight concerning the failures of past exemplars. Conservators need to learn from design mistakes, and determine how to

[31] Forrest Wilson, "The Perils of Using Thin Stone," Architecture, February 1989, 96, quoted in Fred Nashed, Time-Saver Details for Exterior Wall Design (New York: McGraw-Hill, 1996), 162.

prolong the lives of curtain-wall buildings, without compromising material and structural integrity where possible. Non-destructive or minimal intervention methods need to be examined as a viable option, rather than immediately choosing to replace anchors and panels. The deformation of marble panels via hysteresis is a concern, and ways to maintain temperatures on both sides of the panels should be determined as an afterthought to the design in order to preserve those marble panels that have not yet deformed. Treatments need to be proposed and tested prior to any conclusions concerning possible solutions to this problem.

CHAPTER II: METHODOLOGY

Rationale

Why stone veneer?

Thin marble panels on certain post-WWII American buildings have been bowing, deforming and failing, as discussed in Chapter 1. Stone tends to lose strength (flexural, tensile, shear, compressive, etc.) when it is exposed to thermal and moisture cycles, especially fine-grained white marbles.[32] In the past 10-15 years, more case studies of failing marble cladding have become apparent, and the body of literature regarding the reasons for this has slowly developed. However, short of total replacement, there is a lack of proposed treatments for this obvious problem, and little literature pertaining to the effectiveness of any potential treatments for retaining stone slabs and veneers. Although it is not economically feasible or even logical to consider treating all permanently bowed marble panels, it may be possible to increase the flexural strength and decrease the bowing potential by applying certain mechanical reinforcement treatments. Therefore, in an effort to address the absence of literature available regarding such treatments, this thesis will be a contributing factor to further research. Experimental treatments were designed and applied to

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[32] John P. Stecich, Ian R. Chin, and F. Dirk Heidbrink, "Testing for Thin Stone Veneers on Buildings," in Exterior Claddings On High Rise Buildings, eds. Chicago Committee on High Rise Buildings (Chicago: The Fall 1989 Symposium, Report No. 12, 1990), 125.

fresh Carrara marble samples. The samples underwent two chosen mechanical tests (bowing potential and flexural strength) and the results will be evaluated. Evaluations will be based according to criteria established for the treatments' ability to inhibit bowing potential and/or improve (flexural) strength with minimal intervention and maximum retreatability.

Why Carrara marble in particular?

Carrara marble, in particular, was chosen to test because 1) many monuments and several buildings, such as the Amoco Building, 1974 in Chicago, were clad with thin Carrara marble panels that failed and were later replaced with granite, 2) granoblastic Carrara marble, as opposed to other common veneer stone, such as granite, has a tendency to bow and deform much more readily than other types of stone and even other types of marble, and 3) due to time constraints, it is necessary to choose a marble that will bow and deform easily when exposed to moisture and thermal cycles. Although under extreme conditions, it will hopefully yield what would be realistic long-term results.

There are several causes for the deformation of thin marble panels, such as corroding metallic anchors, joints disallowing movement, exposure to moisture, and thermal changes, but, as stated above and in

Chapter 1, bowing of marble is often attributed to hysteresis. Hysteresis can be defined as "a permanent growth in the stone due to a differential temperature or moisture change through its thickness."[33] Hysteresis occurs when the panel lacks the ability to resist stresses, since it is so thin, caused by the anisotropic thermal expansion and contraction of fine-grained marbles (exterior and interior faces expand at different rates, since each is exposed to different levels of moisture and temperature changes). This results in a permanent, generally convex, bowing, becoming weaker over time because the water absorption capacity increases with subsequent

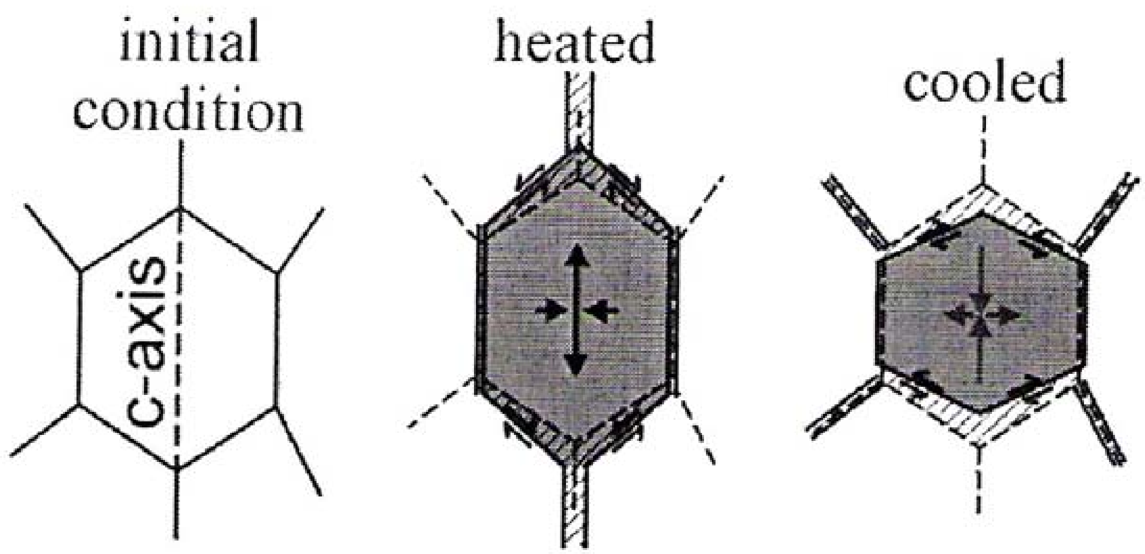

Figure 2.1 Anisotropic thermal behavior of a single calcite crystal. (Diagram from Grelk et al., 5.)

[33] Bortz et al., 16.

heating cycles and micro-cracking.[34] This loosens grain boundaries in marble, since calcite does not expand uniformly in all directions when heated and the permeability/water absorption of marble slabs may be a contributing variable in this thermal deformation.[35] This is because "when the calcite crystals relax to their original locations during temperature drop, dislocations along crystal edges keep crystals from returning to their original positions, resulting in a slight volume increase and slight increase in porosity due to dislocations along crystal boundaries."[36]

Although hysteresis was discussed briefly in Chapter 1, it is important to mention it again here since this was one contributing factor in the type of marble chosen for testing. The causes of bowing in Carrara marble (and other types of marble) have been tested by several scientists, including TEAM, and many agree that what affects the potential for bowing is grain boundaries and micro-structure. This means that marbles with grains that do not interlock well and have straight boundaries will bow more, such as with granoblastic marbles (i.e. fine-grained Carrara marble).[37] Attention will be given to examine the granoblastic ("a

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[34] McDonald and Lewis, 63.
[35] Widhalm et al., 5.
[36] Bernard Erlin, "Contribution to a Better Understanding of the Mechanism Causing Dishing Failures of the Carrara Marble When Used for Outside Building Facades," in Dimension Stone Cladding: Design, Construction, Evaluation, and Repair, ed. Kurt R. Hoigard (West Conshohocken, PA: ASTM, 2000), 78.
[37] Alnaes, et al., 6.

granular mosaic texture in which the grains are tightly compacted, the minerals are dominantly of equidimensional kinds and present irregular mutual boundaries"[38]) nature of the marble. "Granoblastic marble has both a higher initial grain boundary porosity and gets a more pronounced intergranular decohesion during exposure."[39] Since the more marble panels bow, the greater the decrease in strength, especially flexural strength, it is essential to examine the effects of exposing marble that is prone to bowing when exposed to temperature and moisture cycles (hysteresis) when considering treatments. "The marble becomes permanently elongated, its porosity increased and its ultimate strength is diminished."[40]

Although it may be impossible to halt the effects of hysteresis, without stabilizing the environment, at the very least it may be possible to increase the flexural strength and slow bowing potential with mechanical treatments such as those proposed in this thesis. In combination with chemical treatments it may be possible to equalize the different moisture and thermal exposures to the two sides of the marble panel to decrease hysteresis, but this thesis only addressed the potential of increasing flexural strength and decreasing bowing potential via mechanical treatments.

[38] Amrhein and Merrigan, 2.
[39] Alnaes, et al., 2.
[40] Gere, 230.

Additionally, general characteristics of the marble, such as grain size, grain size distribution, porosity and texture, were examined. The marble samples tested were white Carrara marble 15" x 4" x ¾", (described in more detail in Chapter 3). The panels were obtained from Cava International, located at 2001 Washington Avenue in Philadelphia, Pennsylvania (**see Appendix 1**).

Figure 2.2 AnchorFix 3 epoxy gel used to adhere mechanical treatments to the marble panels.

Proposed Treatments

All of the treatments were applied to the marble samples with an epoxy gel adhesive, Sikadur AnchorFix 3. AnchorFix 3 is a "2-component, 100% solids, moisture-tolerant, high-modulus, high-strength, structural epoxy."[41] Component A contains epoxy resins and talc, while Component B contains amines, nonyl phenol, and talc.[42] One of its uses is re-anchoring of veneer masonry, so it is particularly important and relevant to these experiments. Additionally, the 24-hour cure time is practical and efficient and it is easy to apply with a caulking gun.

Carbon Fiber Straps

Although limited literature exists regarding the use of carbon fiber straps in treating stone in general, carbon fiber straps have been used frequently in the surface repair of concrete beams. For example, the Center for Transportation Research at the University of Texas in Austin tested carbon fiber composites to determine if they would increase the flexural strength of concrete bridges.[43] The team tested two configurations, one with straps applied longitudinally (one direction), and those applied both

[41] Product information obtained from the Sika website, www.sika.com.
[42] Ibid.
[43] Sergio F. Brena, Sharon L. Wood, and Michael E. Kreger, "Using Carbon Fiber Composites to Increase the Flexural Capacity of Reinforced Concrete Bridges," in Project Summary Report 1776-S: Development of Methods to Strengthen Existing Structures with Composites (online article, 2001), 1.

longitudinally and transversally (two directions). They found that the treatment failed for all configurations due to debonding of the carbon fiber composite that started at the location of flexural cracks within the shear span (although those with transverse straps did, in fact, delay debonding of the carbon fiber straps from the concrete), and also that flexural capacity did, in fact, increase.[44] Other researchers discovered similar results, stating that "the CFRP system can significantly increase the serviceability, ductility, and ultimate shear strength of a concrete beam."[45] Marble, of course, has quite different properties than concrete, but since the flexural, tensile and shear strengths were increased with concrete, possibly similar results will occur with the marble.

For the purposes of this thesis the carbon fiber straps will only be applied in one direction in the middle of the sample on one side of the marble panel, due to the small size of the samples.[46] Since AnchorFix 3 was used to attach the straps, resultant damage at the adhesive-stone interface could be examined. The type of carbon fiber straps used were Sika CarboDur CFRP Plates (15" x 2" x 1/32"), produced by the pultrusion

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[44] Brena, Wood, and Kreger, 3.
[45] Zhichao Zhang, Cheng-Tzu Thomas Hsu, and Jon Moren, "Shear Strengthening of Reinforced Concrete Deep Beams using Carbon Fiber-Reinforced Polymer Laminates," Journal of Composites for Construction 8, no. 5 (2004), 414.
[46] Kevin Collins at Sika also recommended to only use one carbon-fiber strap in one direction, as opposed to criss-crossing them, since he believed that would be sufficient reinforcement for the size of the samples.

process and manufactured to increase flexural strength.[47] The intent for applying carbon fiber straps was to determine if this particular treatment does in fact increase the flexural strength of the marble and also to determine if it deters bowing. Straps are flexible longitudinally along their axis. One must always keep in mind that the sample must be retreatable (the reason for failure within the bond). Failure mode must also be predictable and acceptable.

Figure 2.3 Carbon fiber straps.

[47] Product information from the Sika website, www.sika.com.

Polypropylene Honeycomb Backing

Similar to the carbon fiber straps, there is little evidence of using polypropylene honeycomb to repair marble, or even stone, cladding. In the latter years of the 1980s, 1/16-inch stone veneer was sometimes applied to an aluminum honeycomb core, but not much has been written about its condition, maintenance or treatments.[48] However, honeycomb panels (aluminum, paper, plastic) are frequently used in the conservation of mosaics and wall paintings and, more relevantly, in the construction of composite panels[49]. Starting in the 1950s, honeycomb cores were used in constructing laminated composite panels. In general, the honeycomb cores are lightweight, but strong, resistant to moisture and temperature changes, and offer stability and flexibility.[50] All of these properties are important for treating a thin marble panel, especially the latter characteristic, since the honeycomb core can move with and adjust to the changes of the stone facing, and therefore not fail as easily. The honeycomb core does not have insulating properties, which could aid in equalizing the temperature and moisture changes between the interior and exterior faces of the stone, thereby resulting in less bowing

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[48] Ian R. Chin, "Common Causes of Failure of Stone Claddings on Buildings," in Dimension Stone Cladding: Design, Construction, Evaluation, and Repair, ed. Kurt R. Hoigard (West Conshohocken, PA: ASTM, 2000), 152.
[49] Nashed, 149.
[50] William Dudley Hunt, Jr., The Contemporary Curtain Wall: Its Design, Fabrication, and Erection (New York: F.W. Dodge Corporation, 1958), 322.

deformation, but could have negative impacts on the overall building system.

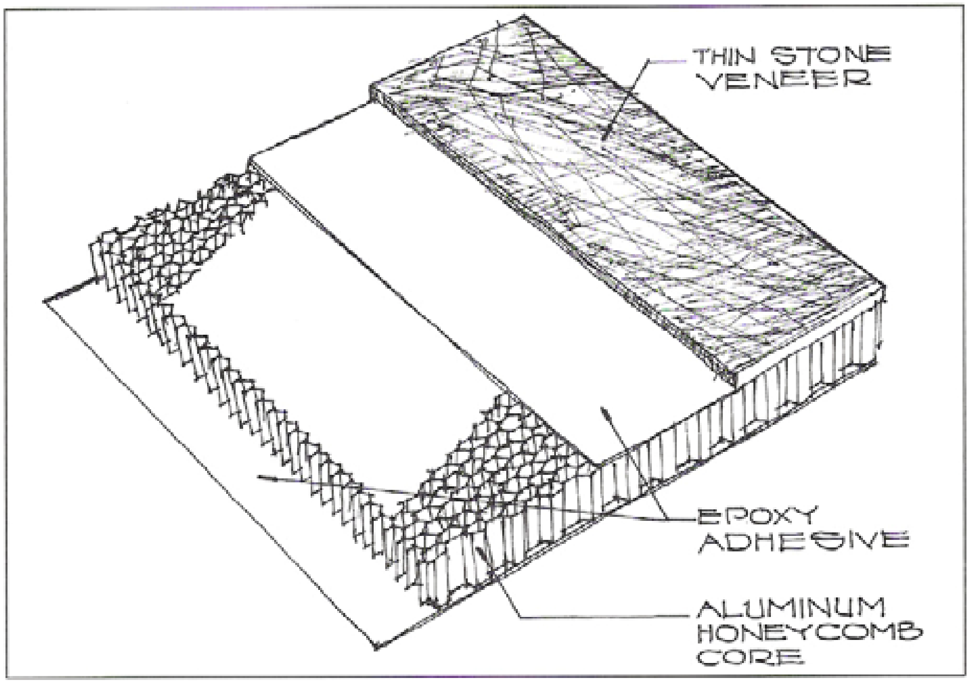


Figure 2.4 Composite panel. (Diagram from Nashed, 149.)

This type of treatment can potentially fail within itself or in the bond, both options being favorable since it is sacrificial to the marble panel, although that is one reason why these composite panels have failed frequently in the past.[51] In the case of applying honeycomb backing to thin stone veneers, they are more cost-effective than other techniques because they are lightweight and easy to manufacture, but the "long-term durability" is unknown since they have only been used for the last 15

[51] Hunt, 325.

or so years.[52] Although often epoxy adhesives are used in application, some scientists do not recommend this adhesive because some marbles and epoxies are thermally incompatible, expanding and contracting at different rates, resulting in "debonding of connections, cracking of stone panels at connections, debonding of joints between sections of stone, and cracking of stone panel away from connections."[53] However, if a suitable attachment method is chosen, it can be an appropriate and desirable method of attachment. Adhesives must be durable, strong, withstand creep, and be flexible, resistant to moisture, resistant to high temperatures, have good bond strength, and be easily applied.[54]

The polypropylene honeycomb used for treatment in this thesis is from Nida-Core (15" x 4" x ¾"). This material is noted for its "inherent toughness, extreme chemical resistance, and elongation."[55] The idea is that the greater the thickness of the core, the more resistance shall exist to bending. However, although not known at the time of the treatment, one should note that this particular product has a flexural modulus rating of 4 out of 10, so that maybe a honeycomb material with a higher flexural

[52] Nashed, 151.
[53] Chin, 155-156.
[54] Hunt, 334-335.
[55] "Nida-Core Structural Honeycomb Materials: Rigid-Elastic Technology Handbook" (Port St. Lucie, Florida: Nida-Core Corporation, 2005), 45.

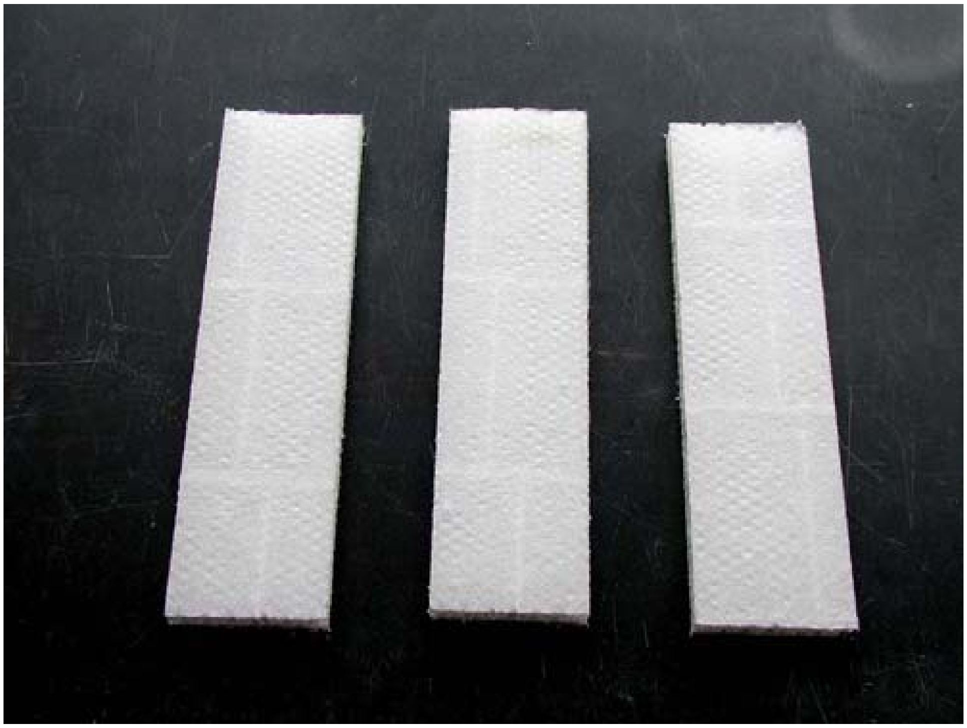


Figure 2.5 Polypropylene honeycomb.

strength capacity should be chosen next time.[56] Additionally, this polypropylene honeycomb is rated 10 out of 10 for moisture resistance, which is ideal for the purposes of the bowing potential test, although a lower resistance to water vapor transmission rating may be required, since this is 5 out of 10, as well as one that has higher thermal insulation, since this is also 5 out of 10.[57] The effects of these properties regarding the flexural strength tests will be discussed in Chapter 3.

[56] Ibid., 46.
[57] Ibid., 46.

Testing Program

Bowing Potential[58]

One purpose of this thesis was to examine how and why marble bows above and in combination with remedial treatments. Therefore, the main focus was to determine the amount of bowing for the white Carrara marble samples with two different treatments and one control, and to compare which treatments inhibit the bowing potential of the thin marble panel. Although this experiment directly measures the amount of moisture- and thermal-induced bowing, the inherent tendency of granoblastic marble to bow must be considered an additional factor.

Two treatments were applied: 1) carbon fiber straps applied in one direction with continuous adhesion and 2) polypropylene honeycomb backing attached to one side also with continuous adhesion. Each treatment was applied with an epoxy gel adhesive. Also to allow retreatability, Acryloid B-72 dissolved in toluene (1:1 w/w) was applied to the side of the marble that was treated to allow the bond to break at the stone-epoxy interface, to avoid permanently damaging the marble.[59] Each treatment was applied to four samples in order to average the final

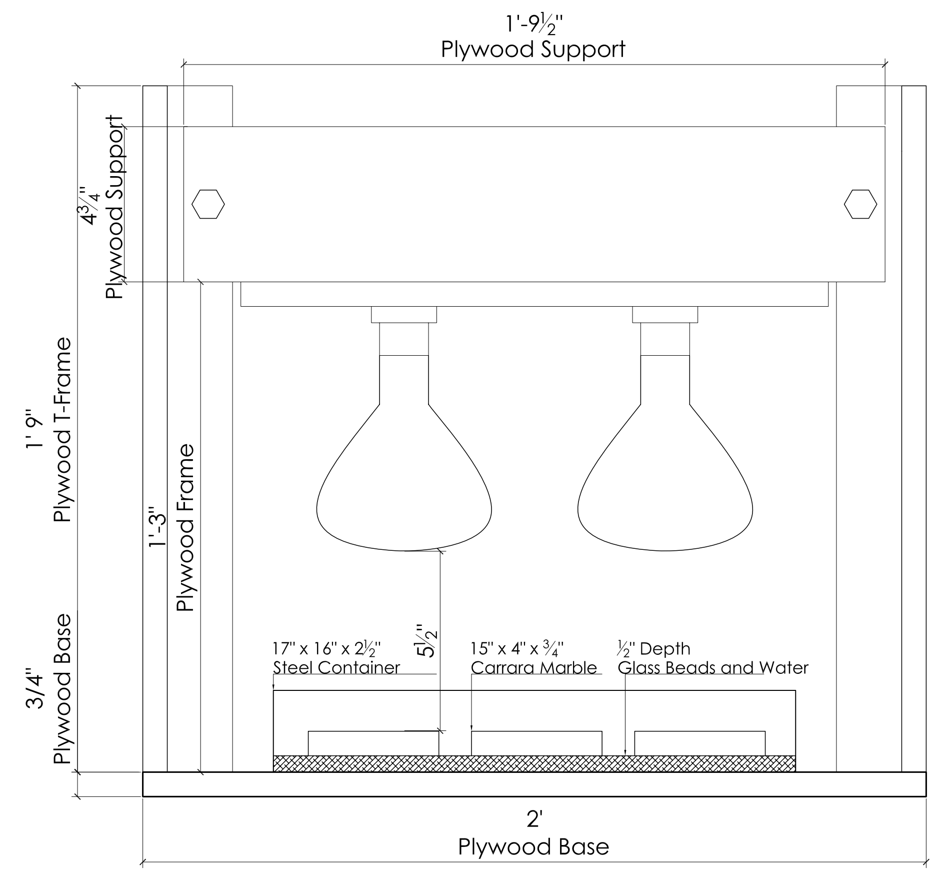
[58] Modified from test standard Nordtest Method NT Build 499, Cladding Panels: Test for Bowing, 2002.
[59] Jerry Podany, et al., "Paraloid B-72 as a Structural Adhesive and as a Barrier Within Structural Adhesive Bonds: Evaluations of Strength and Reversibility," in Journal of the American Institute for Conservation, 40, no. 1 (2001): 21.

results of those samples that had been cycled for forty days for higher accuracy (the fourth sample of each was only cycled for twenty days, treated, and then tested for flexural strength with no further cycling). The six treated samples that were cycled for forty days were first cycled untreated for twenty days, treated with either the carbon fiber straps or the polypropylene honeycomb, and then cycled for another twenty days prior to the flexural strength tests.

All of the treated and untreated samples were placed in steel pans (17" x 16" x 2 ½") on glass marbles with water up to ½" below the surface of the samples (moisture exposure component) to ensure even exposure to moisture and ease in movement during expansion/contraction. According to TEAM tests "it is assumed that temperature variations in combination with humidity are the external factors required for bowing to occur…exposed solely to heat resulted in no bowing."[60] The samples were exposed to 40 heating cycles, the infrared lamps heating the sample from 68'F – 180'F, one cycle per 24 hours (thermal exposure component). Since bowing is largely attributable to hysteresis, as discussed above, the thermal and moisture cycling will address this fact since both sides are exposed to different thermal and moisture conditioning. The bowing was measured with a thickness gauge to the

[60] Malaga, et al., 4.

nearest thousandth of an inch at the sample space on the marble each time, and subsequent measurements were subtracted from the original thickness measurement as the reference point. After the test was completed, the change in height due to bowing was calculated and each treatment and control was compared to determine the effect, if any, of the repair system on the bowing potential of the marble.



Bowing Potential Test Assembly Section

Scale: 3" = 1'-0"

Figure 2.6 Schematic of bowing potential test assembly. (Design based on TEAM's Nordtest BUILD 499 Bowing Potential test standard.)

Flexural Strength[61]

As a direct result of bowing and deformation, the flexural strength of thin marble panels decreases over time. The problem is compounded when the marble is restricted by design or subjected to the forces of gravity, wind and, sometimes, earthquakes. If the marble cladding is subjected to too many of these forces, along with hysteresis caused by differential exposure to thermal and moisture changes, failure will occur and the stone will detach from the structure or the building. Therefore, the main purpose of this test was to determine the flexural strength of variously treated thin marble panels, and to determine if and how the treatments increase the flexural strength for the given Carrara marble samples. If the flexural strength is increased by the treatments, this will provide viable options for times when a panel has or will have the potential to bow, thereby causing a decrease in flexural strength, and will effectively inhibit failure by increasing its flexural strength.

All of the samples that were used in the bowing potential test discussed above, after cycling were tested for flexural strength. This includes: three fresh samples (**U1-U3**); one untreated sample cycled for twenty days (**C4**); three untreated samples cycled for forty days (**C1-C3**);

[61] Modified from ASTM Designation: C 880-98, "Standard Test Method for Flexural Strength of Dimension Stone," 2004.

one sample cycled for twenty days and then treated with carbon fiber (**CFV4**); three samples cycled for twenty days, treated with carbon fiber straps, and cycled for another twenty days (**CFV1-CFV3**); one cycled for twenty days and then treated with polypropylene honeycomb (**PH4**); and three cycled for twenty days, treated with polypropylene honeycomb, and then cycled for another forty days (**PH1-PH3**). The final results for each sample group were averaged for higher accuracy. Each of the samples was placed on the testing apparatus consisting of a lower knife upon which each sample sits, an upper knife that is in contact with the top of each sample, a steel ball that applies load evenly between the upper knife and the load cell, and a load cell that will consistently add weight onto each sample. The type of loading is quarter-point loading, whereby there are four contact points on the top of each sample. The span of the lower knife was 8 inches (the standard recommends the span to be between 7.5 and 11 inches for the sample size tested) and the upper knife span was 3 inches, which was decided in conjunction with Dr. Alex Radin. The sample was placed on the lower knife, the upper knife was lowered onto the top of the sample, the sample was centered, and the load was applied until the sample failed, either in the bond or within the sample itself. Once the sample failed, the results were compared to determine strength increase and failure mode. Here, again, the treatment provides options for minimum intervention and retreatability when needed.

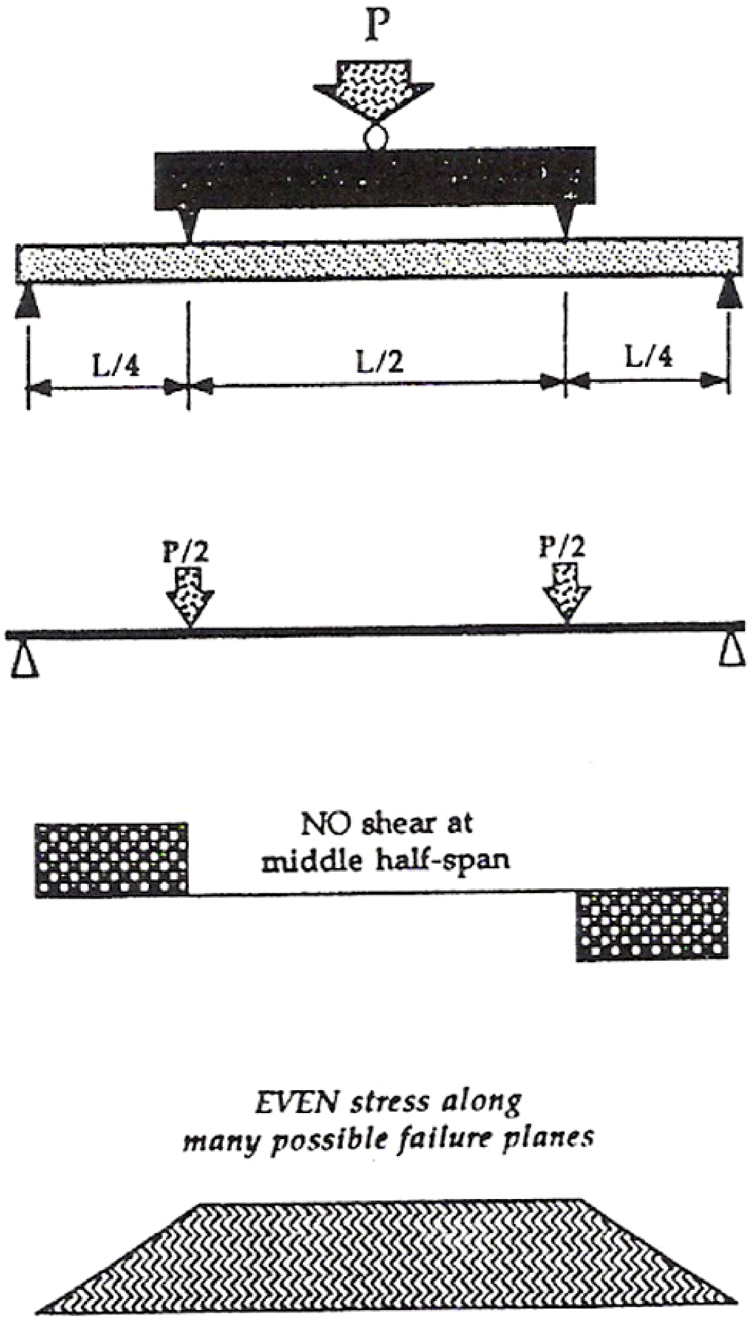


Figure 2.7 Flexural strength test drawing. (Diagram from Lewis, 68.)

General Marble Characterization

The microstructure of the marble samples was examined in order to determine general characteristics of the stone. Although marble usually is thought to have high density, high strength, and low porosity, a microscopic examination of the material can show why it has such properties. Therefore, thin sections of the marble were examined with Polarized Light Microscopy (PLM) at 10x magnification. The texture, grain size, grain size distribution, grain boundaries, grain shape, and porosity were examined. All of this information can contribute to a better understanding of why and how the marble displays an inherent tendency to bow. According to some research, the "interlocking of the grains and the lattice preferred orientation"[62] are the important factors in determining if and how marble will deform, so particular attention was given to these properties. Also, particular attention was given to determine the grain size and boundary type, since "marbles with larger grain sizes show thermal cracking at significantly lower temperatures [and] marbles with straight or only slightly curved grain boundaries are much less resistant against thermal treatment…"[63] Since the grain structure can

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[62] Alnaes et al., 6.

[63] S. Siegesmund, T. Weiss, and E. K. Tschegg, "Control of Marble Weathering by Thermal Expansion and Rock Fabrics," in Proceedings of the 9th International Congress on

change when marble is exposed to heat and moisture, it is important to examine thin sections of the marble samples both before and after testing for comparison purposes.

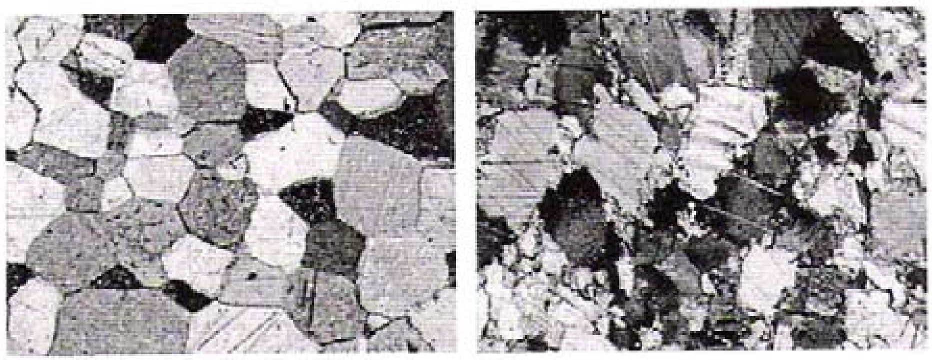

Figure 2.8 Calcitic marbles. Left: Granoblastic; Right: Xenoblastic. (Photos from Alnaes, et al., 3.)

Limitations

As the bowing potential test requires nearly two months of daily cycling, it was important to keep the tests simple, straightforward, and limited, confined to only the essential tests in order to draw relevant conclusions and results. Additionally, funding was not unlimited, so several types of marble and stone could not be tested. Also, tests were modified (i.e. number of samples, design and construction of assemblies, materials used for measurement, etc.) in accordance with budgetary constraints. Study

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Deterioration and Conservation of Stone, Venice, June 19-24, 2000, ed. Vasco Fassina (Amsterdam: Elsevier Science Publishing Company, 2000), 211-212.

of other properties of the marble should be conducted (i.e. water vapor transmission, water absorption, linear strain) to understand all of the physical properties.

CHAPTER III: ANALYSIS AND OBSERVATIONS

General Marble Examination

Initial examination of the general characteristics of the marble was conducted prior to treatments and testing.

Figure 3.1 Carrara marble sample.

Color

The Carrara marble tested is white (Munsell color 5PB-9/1) with charcoal gray veining (Munsell color 10PB-6/1). Each piece of marble displays different veining, but the colors remain consistent.

Texture

The marble is polished on one side, while the reverse is unpolished. Since the bowing potential test will be conducted with the heat lamps facing the polished side, this may have some effect on how much the marble will bow.

Hardness

Because this white Carrara marble is largely composed of calcite, the hardness on the Moh's scale is 3 out of 10. This means it is relatively soft.

Dimensions

The marble tested was cut to 15” x 4” x ¾”. These dimensions are appropriate for both the Bowing Potential and Flexural Strength tests, according to, respectively, the Nordtest Method NT Build 499 Bowing Potential and ASTM Designation: C 880-98 Flexural Strength test standards. Also, this is a much smaller scale than marble panels that would be used on buildings, due to space and logistic constraints, as well as the above-mentioned needed dimensions for the tests. Larger pieces may take longer to bow and may have greater flexural strength.

Microscopic Examination

Porosity

The Carrara marble is not very porous or permeable. The pores range between 0.0125 and 0.025 mm in width.

Grain Size

The grain sizes of the Carrara marble are approximately 0.2 mm in diameter. All of the grains are of similar size/homogenous with straight grain boundaries.

Grain Shape

All of the grains are subrounded and are all in different orientations. It is quite evident when looking at the thin section with the analyzer and accessory plate that there is high birefringence. Additionally, the thin section was stained with Alizarin red for calcite, and the marble is definitely calcitic (98%) homogeneous and isotropic, the only portions of the thin section not stained being the pores.

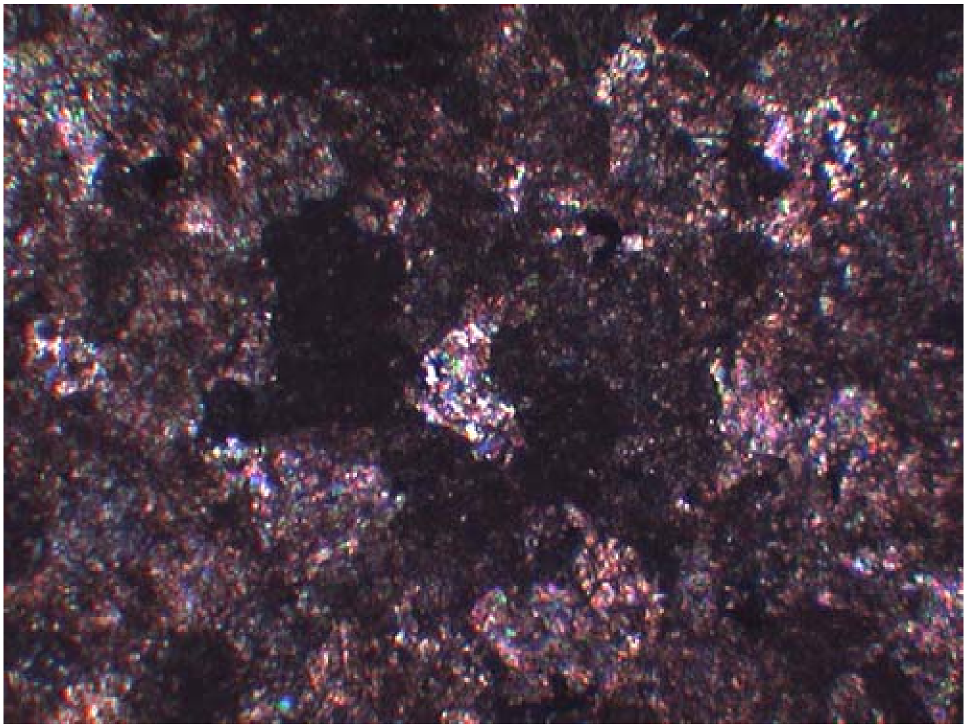

Figure 3.2 Fresh Carrara marble thin section, 10x with analyzer and accessory plate.

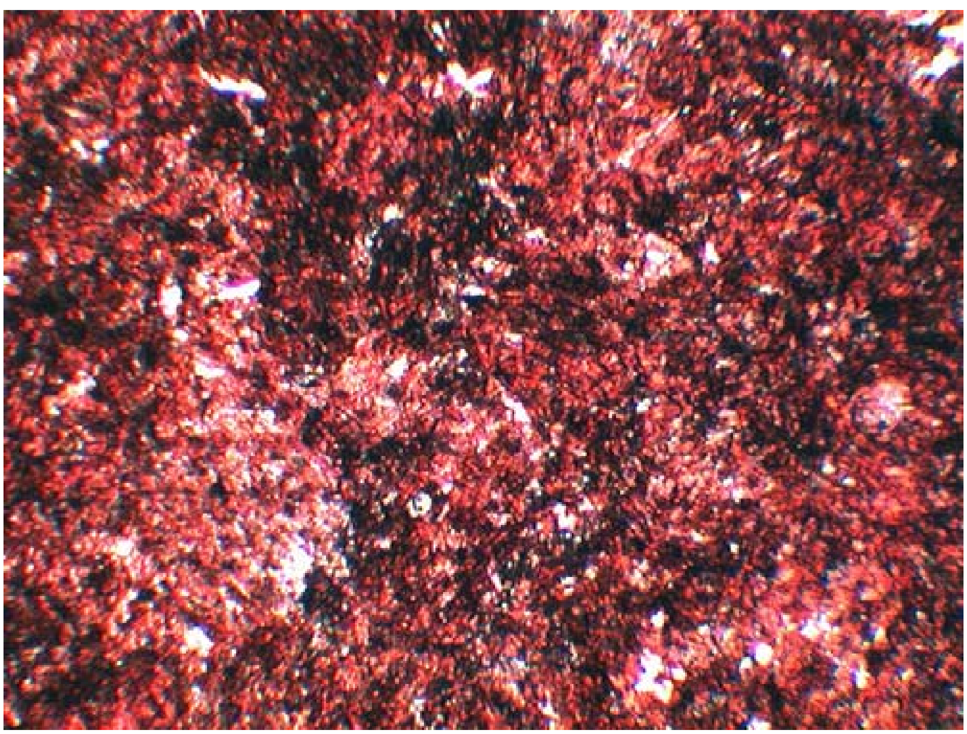

Figure 3.3 Fresh Carrara marble thin section, stained with alizarin red, 10x.

Treatments

Method of Treatment

The first step in the treatment process was to clean the surfaces of the carbon fiber straps, the polypropylene honeycomb, and the marble samples with acetone and cotton. This ensures that both surfaces are clean and free of dirt, oils, and other contaminants, so that the epoxy will adhere.

Next, Acryloid B-72 dissolved in toluene was applied to the side of the marble to be treated. The solution was a one to one, weight to weight ratio.[64] (Seventy grams of toluene was measured in a beaker and placed in a small glass container. Then seventy grams of B-72 were weighed and placed in cheesecloth that was tied with string, and immersed in the toluene, suspended above the bottom of the container, so that the B-72 would dissolve in the covered container over a 24-hour period). Next, the B-72 solution was applied with a brush to one side of the marble sample, and allowed to dry for one week.

Once the treatment materials and the marble were cleaned, the next step was to apply the Sikadur AnchorFix 3 epoxy gel. This is easily accomplished by inserting the cartridge into a caulking gun, and then squeezing the trigger. For the marble treated with carbon fiber straps, five

[64] Podany, et al., 21.

Figure 3.4 Step one: Apply epoxy to the marble panel.

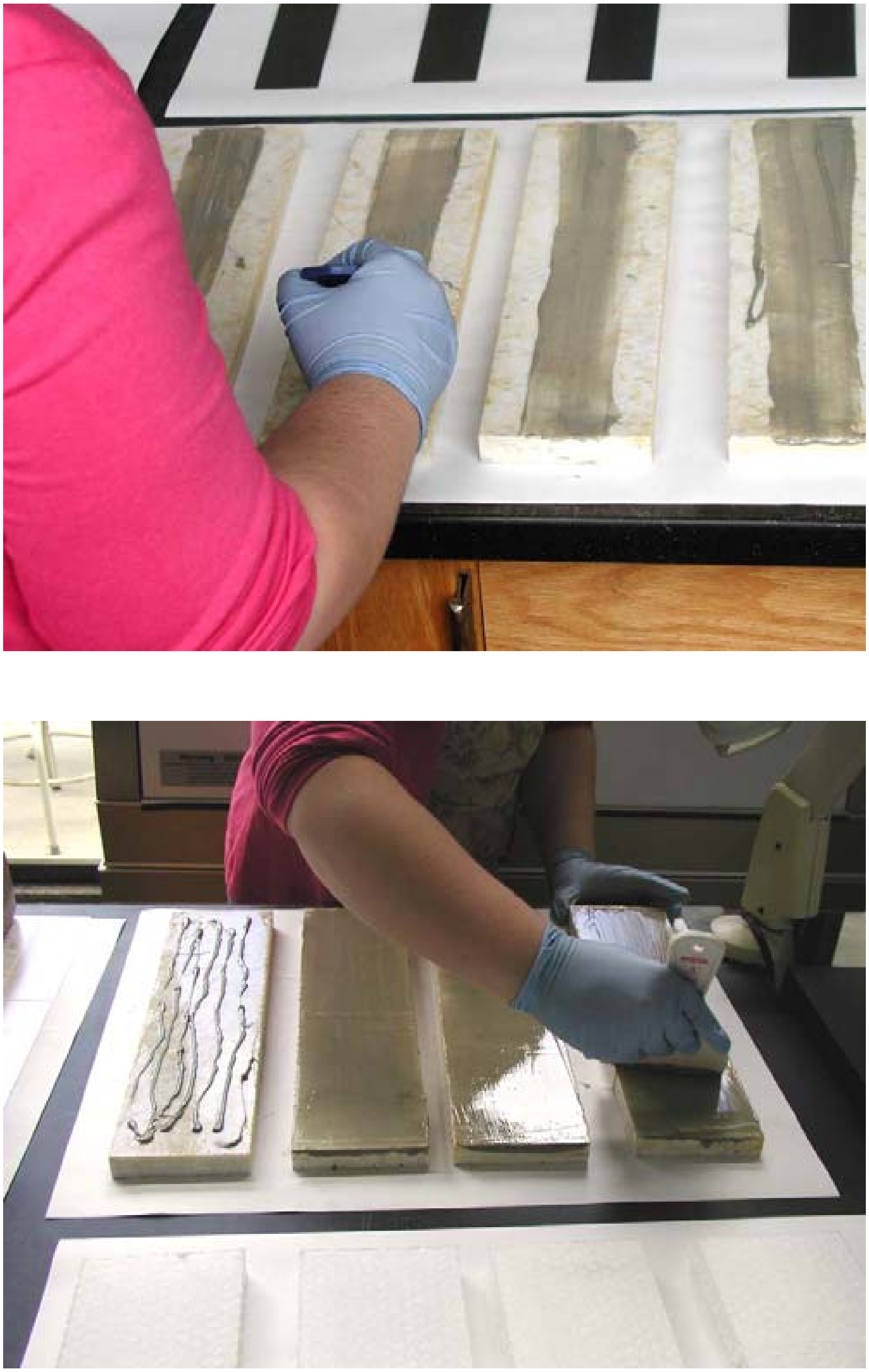

Figure 3.5 Step two: Spread the epoxy over the marble panel.

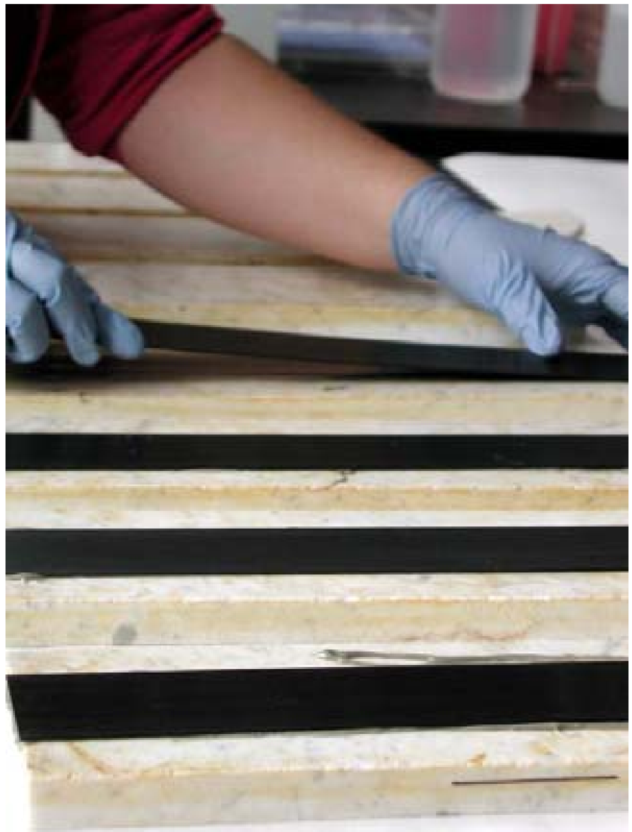

Figure 3.6 Step three: Apply treatments to the marble on top of the epoxy.

Figure 3.7 Step four: Roll the carbon fiber strap or the polypropylene honeycomb over the epoxy to ensure even contact.

thick lines of epoxy were squeezed onto the marble, and for those treated with the polypropylene honeycomb ten thick lines of epoxy were required for even coating. A putty knife was used to the spread the epoxy evenly and smoothly over the surface of the marble to a depth of approximately 1/16".

Finally, the treatment material was carefully placed on the marble and pushed firmly so as to ensure even contact with the epoxy. Then a sheet of Mylar and a large block of limestone were placed on top of the treated samples as weights for the 24-hour drying period at room temperature.

Problems Encountered

The first problem encountered in the treatment process was that the B-72 in toluene is quite sticky, and much care should be taken when applying this to the marble for a thin, even coating. Also, it took longer than expected to dry.

Secondly, since the epoxy consists of two-components, the instant they are in contact they start to react. This can be a problem when applying the epoxy because it can start to dry within the application mixing tube if the epoxy is not applied quickly. That is why it is recommended to have several applicator tubes at hand when conducting these treatment procedures. This also includes spreading the epoxy evenly and quickly on the marble, since as the more time goes by, the harder it is to spread.

Finally, the carbon fiber straps were not perfectly straight, so a large weight is required to ensure even adherence with the epoxy.

Results

By conducting practice treatment sessions, the problems and limitations could be accounted for and the procedure modified. Thus, the mechanical treatment of the samples was successful.

Bowing Potential Test

Construction of Assemblies

Based on the recommendations in the Nordtest BUILD 499 standard for the Bowing Potential test, a modified schematic was drawn for the number and size of the samples required for this thesis, as discussed in Chapter 2. In collaboration with Dennis Pierattini, Fabrication Laboratory Supervisor at the University of Pennsylvania, four test assemblies were designed and built for the purposes of this test. Each test assembly consisted of a plywood base, two plywood t-frame pieces, and one plywood support that is adjustable, all of which were cut, sanded, and varnished. Also, there are two wired light sockets for the infrared heating lamps. Three pieces of marble were placed on top of ½" depth of glass marbles and sand in one steel pan (17" x 16" x 2 ½"). One of these set-ups was needed for the three samples that were cycled for twenty days, and three assemblies were needed for the nine samples that were cycled for forty days.

Figure 3.8 Constructed bowing potential assemblies.

Gauge Set-Up

The Nordtest BUILD 499 test standard for bowing potential indicated that an invar steel gauge set-up was used to measure the dimensional change after each cycling. To construct a gauge set up with invar steel would have been costly and time-consuming, so in the interest of saving time and money a modified gauge set-up was designed in collaboration with Dennis Pierattini. A large granite base insured stability, so that consistent readings could be obtained each day. Additionally, two one-inch steel bars served as the supports, and were checked each day confirming that

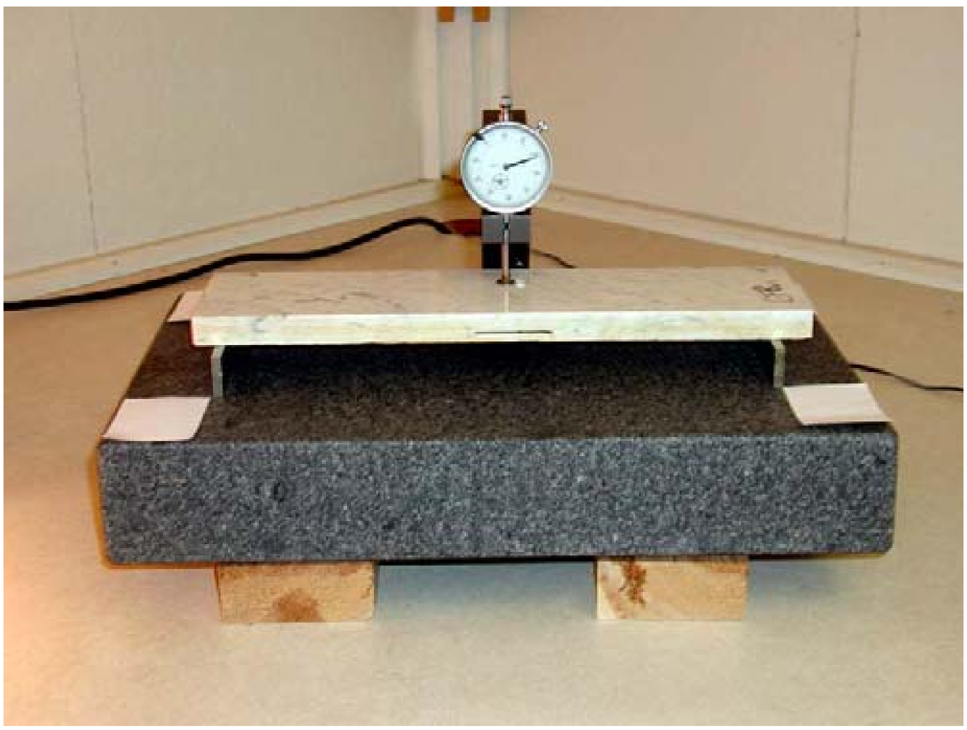

Figure 3.9 Bowing potential thickness gauge set-up.

they were within the boundaries marked on the granite so that the marble would be placed in the same spot for each measurement. A thickness gauge, with an accuracy to the nearest thousandth of an inch, measured the dimensional change in the marble, by placing the tip of the gauge on a marked spot in the middle of the marble for each measurement. Although this gauge set up may not have been as precise as the one recommended in the test standard, consistent and accurate readings were obtained after each cycle.

Method of Testing

As discussed in Chapter 2, the marble was placed on a ½" bed of glass marbles, filled with de-ionized water up to ½" below the top of the marble, and then the infrared heat lamps were turned on for four hours. The surface temperature of the marble started at 68 degrees Fahrenheit and ended at around 200 degrees Fahrenheit, which is slightly higher than the recommendation of the test standard. The lights would then be shut off, and the whole process would begin again twenty hours later, so that there would be one cycle each day for forty days. Prior to each cycle, the marble was measured with the thickness gauge to the nearest thousandth of an inch to determine the amount the marble bowed. For the first twenty cycles, all of the marble was left untreated, so as to determine if the marble would bow, by how much, and to account for any differences there may be inherently in the marble itself. After twenty cycles, three untreated samples continued to cycle, three samples were treated with carbon fiber straps, and three samples were treated with polypropylene honeycomb, and cycled for another twenty days. Additionally, two samples that had been cycled for twenty days were treated, one with carbon fiber and one with the polypropylene honeycomb, so that they could be tested for flexural strength with the others, and used for comparison purposes.

Limitations and Uncertainty

There were a few problems with the modified test assembly and gauge set up. Firstly, since there were only two heat lamps for three samples, some of the samples were more exposed than others. However, this problem was accounted for by rotating the placement of the samples in the tray for each cycle, so that each was exposed to the heat for the same amount of time and intensity. Secondly, the room in which the test was conducted was not climate-controlled, so that some days the marble would start at higher or lower temperatures than other days. Thirdly, once the treatments were applied to the marble, this increased the thickness, and therefore the distance between the heat lamps and the surface of the marble. This was corrected by adjusting the plywood support on the plywood t-frame, so that the lamps were 5 ½" higher than the surface of each piece of marble. Fourthly, the steel supports could move on the granite, but this was corrected by placing guides on the granite base.

Finally, in order to measure the marble, the thickness gauge was placed on top of the marble, and the exact spot could change slightly day to day. That is why the marble was measured several times with the gauge, to ensure consistent and accurate readings.

Results

After forty days of cycling, all of the marble panels displayed bowing. The direction of bowing was concave on the side that was in contact with the water and convex on the side that was facing the heat, as predicted.[65] The temperature difference between the heated surface and the surface in contact with moisture was approximately 130 degrees Fahrenheit, which is similar to in situ conditions because when accounting for air-conditioned interior spaces in the summer and heated interior spaces in the winter there can be a temperature difference of at least 100 degrees Fahrenheit.[66] In general, the dimensional change of all of the marble panels was quite similar. Most of the bowing occurred within the first twenty days,[67] and continued to bow for the last twenty days, albeit at a

[65] Gere, 230.
[66] Ian R. Chin and C. B. Monk, Jr., "Design of Stone Curtain Walls to Resist Weathering," in Proceedings of the Fourth International Congress on the Deterioration and Preservation of Stone Objects, July 7-9, 1982, ed. K. L. Gauri and J. A. Gwinn (Louisville: The University of Louisville, 1982), 91.
[67] Albert Jornet, Tiziano Teruzzi, and Philipp Ruck, "Bowing of Carrara Marble Slabs: Comparison between Natural and Artificial Weathering," in Understanding and

much slower pace.[68] An average of the dimensional change of the three marble samples within the three groups (C: untreated, CFV: treated with carbon fiber straps, and PH: treated with polypropylene honeycomb) was calculated after twenty days, after forty days, and within the last twenty days of cycling. The reason for the averages is to account for the differences inherent in each piece of marble. After twenty days of cycling, when all of the marble was untreated, the marble later used for the control (**C**) bowed 0.024 inches, the marble later used for the carbon fiber treatment (**CFV**) bowed 0.018 inches, and the marble later used for the polypropylene honeycomb (**PH**) bowed 0.027 inches, all of which are quite similar changes. At this point, one sample untreated (**C4**), one sample treated with carbon fiber (**CFV4**), and one sample treated with polypropylene honeycomb (**PH4**) were set aside, after these twenty

	20 Cycles	40 Cycles	Difference Between 40 and 20 Cycles	% Increase
C	0.024"	0.029"	0.005"	3.8%
CFV	0.018"	0.023"	0.005"	3.1%
PH	0.027"	0.034"	0.007"	4.5%

Figure 3.10 Calculated data from the bowing potential test of treated and untreated Carrara marble.

Managing of Stone Decay, eds. Richard Prikryl and Heather A. Viles (Prague: The Karolinum Press, 2002), 161. The authors stated that, "the more significant changes occur already after the first 50 cycles."
[68] Malaga, et al., 6. TEAM also found this to be the case, writing that "…(bowing) is not a continuously increasing movement (on fresh marble)…this means that fluctuation of bowing decreases with the time of exposure of a panel."

cycles with no further cycling, for the flexural strength test. After forty cycles the untreated marble (**C1-C3**) bowed 0.029 inches (a difference of 0.005 inches and a 3.8% dimensional increase), the marble treated with carbon fiber straps (**CFV1-CFV3**) bowed 0.023 inches (a difference of 0.005 inches and a 3.1% dimensional increase), and the marble treated with the polypropylene honeycomb (**PH1-PH3**) bowed 0.034 inches (a difference of 0.007 inches and a 4.5% dimensional increase). The mechanical treatments appear to have had little effect on decreasing the bowing potential of the marble, since all of the marble panels, treated and untreated, continued to bow at similar rates. The differences in dimensional change, in this case, could simply be attributed to slight differences within the marble itself, such as veining, porosity, and grain shape and size. However, what is proven is that when exposed to heat and moisture, the marble will bow quite significantly, enough that it is even visible to the naked eye. Also, since the mechanical treatments did not have much effect on decreasing the bowing potential, this also indicates that the marble will bow because of hysteresis. The carbon fiber straps lowered or reduced the bowing potential by decreasing the amount of deformation. However, it did not change the shape of the curve on the graph. The polypropylene honeycomb increased the bowing potential. One possibility is that the water may have been trapped in the pores of the marble for longer than with the other marble samples. However, this is a topic that ought to be investigated further. After treatment, with all samples and both treatments, bowing continued with no bond failure. This indicates that the epoxy is a strong adherent and that the treatment materials were flexible enough to move with the marble as it changed.

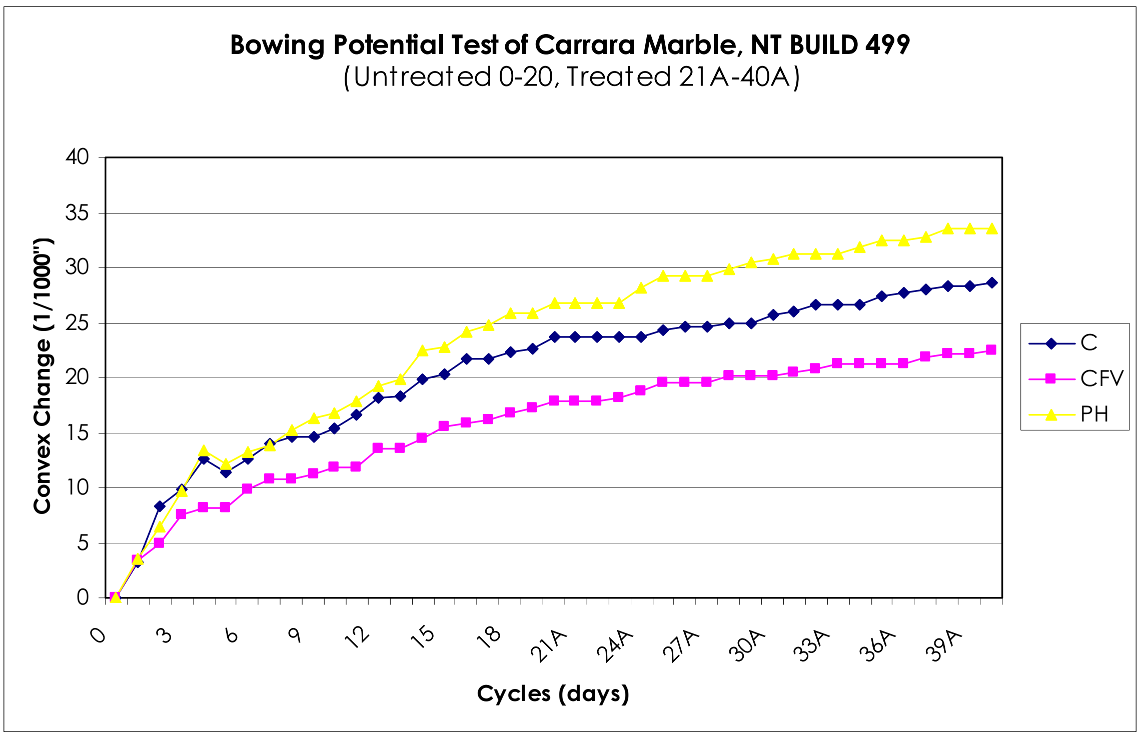

Figure 3.11 Bowing potential of treated and untreated Carrara marble.

Flexural Strength Test

Method of Testing

Figure 3.12 Flexural strength, quarter-point loading Instron test assembly.

All of the marble panels were taken to LRSM at the University of Pennsylvania, and tested for flexural strength with Dr. Alex Radin. The test assembly was discussed in Chapter 2, whereby an upper knife with a span of 3 inches is lowered onto the centered marble panel that sits on a lower knife that has a span of 8 inches. This Instron flexural strength test set-up is quarter-point loading because the two knives are in contact with the marble in four places on both sides, and a load limit of 500 pounds (limit was increased to 2000 pounds for sample CFV4: treated with carbon fiber strap after 20 cycles) was added on top of the marble at a rate of 0.02 inches per minute until the marble fractures. The load and displacement data is recorded by the computer, entered into a Microsoft Excel database sheet, and graphed to determine at what load the marble fractured.

Limitations and Uncertainty

Since this test assembly did not really have to be modified from the ASTM C 880-98 standard for flexural strength testing, there were few problems with accuracy and precision. Once appropriate span lengths for the upper and lower knives were determined in collaboration with Dr. Alex Radin, of the University of Pennsylvania's LRSM, the chance of the marble failing at a load that was not at the full capacity strength of the stone could be eliminated. Additionally, to ensure that all four points of the upper knife would be in even contact with the marble, a steel ball was placed beneath the knife as it was lowered onto the marble, so that the upper knife could move slightly to adjust to the surface of the marble. The weight of the upper knife (two pounds) had to be taken into account when determining the amount of load the marble could withstand without fracturing. The 500-pound load limit was enough for the majority of the samples, although the fresh marble samples (**U1-U3**) required a load limit of 1,000 pounds and the sample treated with carbon fiber after 20 cycles (**CFV4**) needed a 2,000-pound load limit, therefore requiring that the test needed to be started again to account for the increase in load capacity. However, the one large problem encountered was that the marble panels treated with polypropylene honeycomb needed two steel supports (two inches wide) between itself and the lower knife. This is because once the load was applied, the lower knife would cut into or crush the polypropylene honeycomb, thereby interfering with an accurate load capacity reading. Yet, when looking at the results, this may have negatively affected the amount of weight the marble treated with polypropylene honeycomb could withstand without failing, as will be discussed below.

Results **(for graphs see Appendix 4)**

The flexural strength, σ, of each marble panel, both treated untreated was calculated by the equation:

$$\sigma = (3WL)/\ (4bd^2)$$

where:

σ = flexural strength (psi)
W = maximum load (pounds)
L = span (inches)
b = width of specimen (inches)
d = depth of specimen (inches).

Samples	Maximum Load (pounds)	σ (psi)	Average σ (psi)	Average Change from Fresh Samples U1-U3 (%)
C1	281	748		
C2	310	827	808	-45%
C3	318	848		
C4*	251	670		-55%
CFV1	266	708		
CFV2	429	975	942	-36%
CFV3	366	942		
CFV4*	1,631	4,350		+194%
PH1	197	524		
PH2	214	571	541	-63%
PH3	198	528		
PH4*	335	893		-40%
U1	500	1,333		
U2	670	1,787	1,482	
U3	498	1,327		

Figure 3.13 Flexural strength test data for treated and untreated samples. (*Samples cycled for twenty days, treated, and no longer cycled prior to flexural strength tests).

The flexural strength tests showed that the bowing significantly reduced the flexural strength of the marble panels by an average of 45% for the untreated cycled for forty days, 36% for those samples treated with the carbon fiber and cycled for forty days, and 63% for the marble samples treated with the polypropylene honeycomb and cycled for forty days.

However, the marble sample that was cycled untreated for twenty days, then treated with the carbon fiber with no further cycling, actually increased the flexural strength by 194%. The carbon fiber straps and the polypropylene honeycomb did, in fact, increase the flexural strength of the marble that was cycled for twenty cycles and then treated when compared to untreated marble that was cycled for twenty and forty days. Although the marble samples treated with carbon fiber straps and cycled for an additional twenty days (**CFV1-CFV3**) also increased the flexural strength of the marble when compared to weathered marble samples with no treatment (**C1-C3**); for some reason those treated with

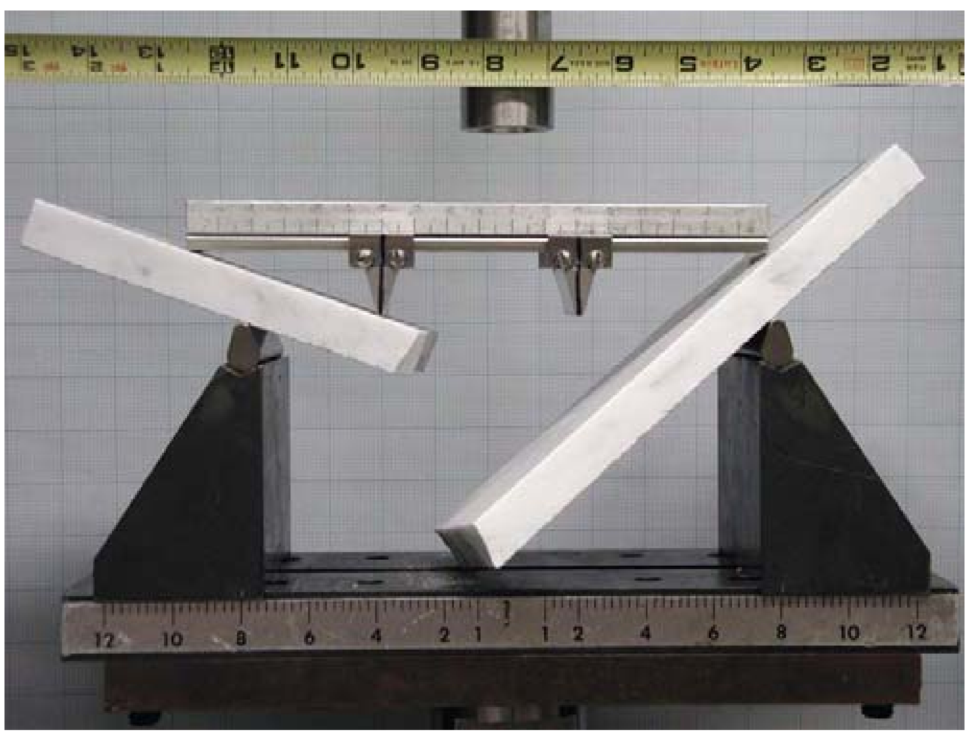

Figure 3.14 Failure mode of Sample U2 during the flexural strength test.

the polypropylene honeycomb and then cycled for another twenty days (**PH1-PH3**) actually decreased the flexural strength capacity of the marble. As stated above, this could be due to the steel supports beneath the polypropylene honeycomb or because the honeycomb had doubled the thickness of the samples. It is obvious from the flexural strength test results that the fresh Carrara marble samples (**U1-U3**, i.e. those that have not undergone any heat and moisture cycling) are the strongest in flexural strength, with a flexural strength of 1,482 psi, with the exception of the one sample that underwent 20 cycles, treated with a carbon fiber strap, and

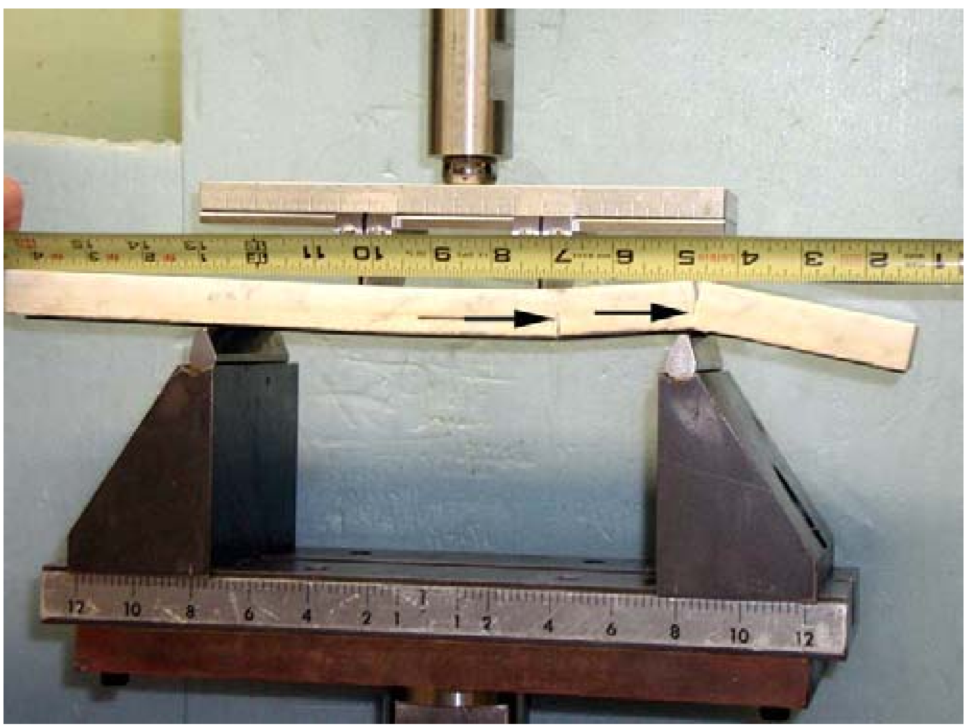

Figure 3.15 Failure mode of Sample CFV4 during the flexural strength test.

was tested with quarter-point loading without any further cycling (**CFV4**) that had a flexural strength of 4,350 psi. Thus, the carbon fiber straps do, in fact, provide the marble with increased flexural strength, even when weathered. The carbon fiber straps that were placed on the marble after 20 cycles and then cycled for an additional 20 days (**CFV1-CFV3**) on average were stronger than the 20-cycle untreated sample (**C4**), the 40-cycle untreated samples (**C1-C3**), the 20-cycle polypropylene honeycomb treated sample (**PH4**), and the 40-cycle polypropylene honeycomb treated samples (**PH1-PH3**), with a flexural strength of 942 psi. This means that no matter if the sample is treated with the carbon fiber strap after the marble is weathered with no further cycling or if the marble is cycled with the carbon fiber afterwards, it will increase the flexural strength of the marble. Since the marble panel that was treated with the carbon fiber strap after twenty cycles with no further cycling increased the flexural strength by a drastic amount, it might be prudent to determine a way to inhibit a weathered piece of marble to deteriorate any further once treated.

One unexpected result was the case where the marble panel that was untreated and cycled for only twenty days (**C4**) had a lower flexural strength of 670 psi than those that were untreated and cycled for forty days (**C1-C3**) with an average of 808 psi. This is probably due to anomalous microstructure of that marble panel.

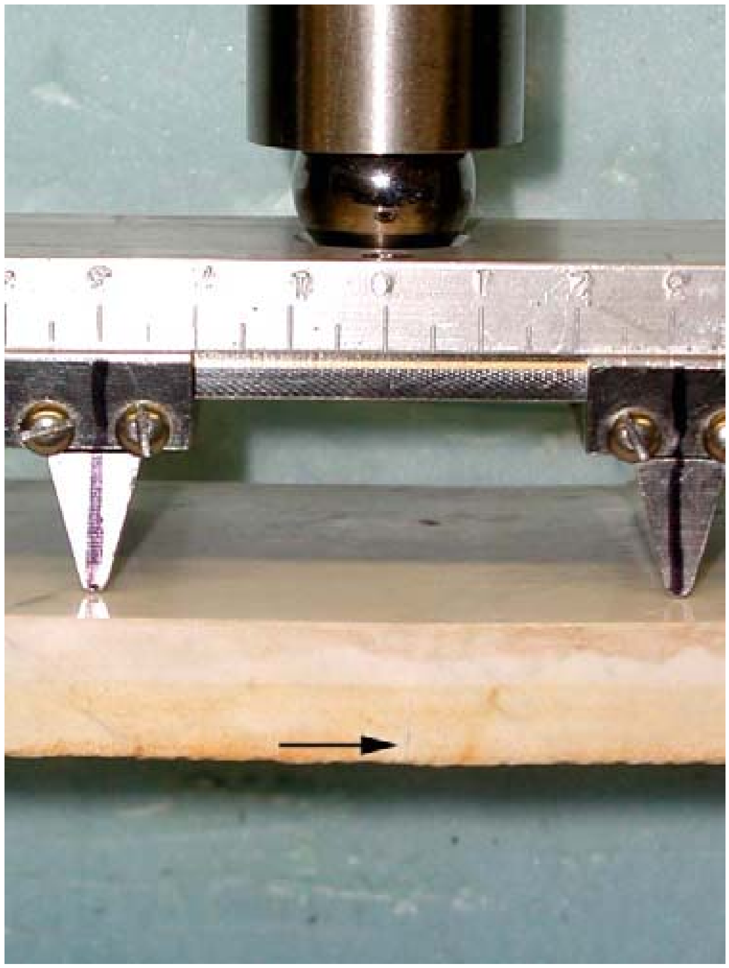

Figure 3.16 Failure mode of Sample C2 during the flexural strength test.

The biggest surprise with the flexural strength testing occurred with those marble panels treated with polypropylene honeycomb. Those marble panels that were treated with the polypropylene honeycomb and then cycled for an additional twenty cycles (**PH1-PH3**). These samples had lower flexural strengths than even the untreated twenty- and forty-

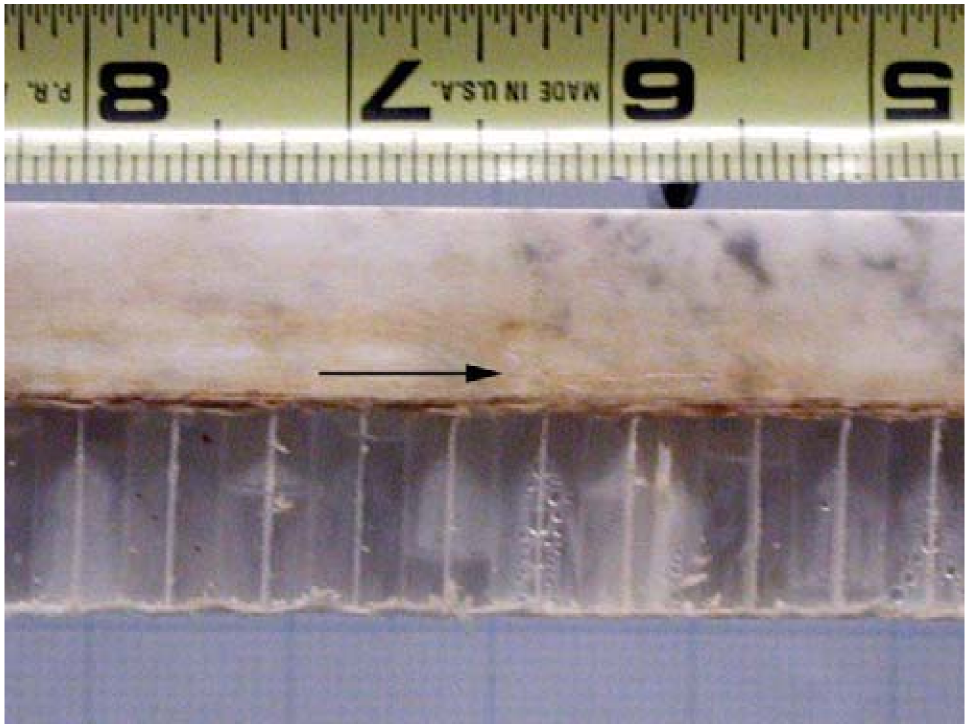

Figure 3.17 Failure mode of Sample PH2 during the flexural strength test.

cycled marbles (**C4** and **C1-C3**) with an average flexural strength of 541 psi. The marble sample that was treated with the polypropylene honeycomb with no further cycling (**PH4**) performed slightly better with a flexural strength of 893 psi. One explanation stated above was that maybe the two-inch supports added while testing may have had a negative effect, in addition to the double thickness of these samples due to the thickness of the honeycomb. A modified method of testing should be considered for more accurate and reliable flexural strength testing results regarding the polypropylene honeycomb treatment.

In general, with weathered and deteriorated marble, carbon fiber straps seem to be a good option when considering mechanical treatments that can enhance the flexural strength capacity of the marble.

CHAPTER IV: CONCLUSIONS

Microscopic Examination

Based on the thin section analysis, it is not surprising that the Carrara marble easily bowed when subjected to heat and moisture cycling, even despite one side being polished. This is because, as was discussed in Chapter 2, marbles with larger grains, slightly curved grain boundaries, homogeneous grain size and shape, and consisting mainly of calcite, are prone to hysteresis that other marbles, and stones in general, are not. A way to mitigate hysteresis is currently unknown, and the mechanical treatments applied and tested in this thesis seemed to have little effect on lessening the impact of hysteresis, since this is inherent within the marble. One suggestion would be to examine various chemical treatments that could be used to impregnate the marble, or, if in situ, a way to maintain exterior and interior temperatures so that the thermal gradient is not so great between the two sides of the marble could be tested.

Treatments

Cost

Based on cost, the polypropylene honeycomb is much cheaper than the carbon fiber straps. The Sika CarboDur Carbon Fiber Reinforced Plates, Type S, that are two inches wide, are $25 per foot. This means that for the four samples that were treated it would have cost $125 just for the carbon fiber. The Polypropylene Structural Honeycomb from Nida-Core costs $1.79 per square foot. This translates to $35.80 for the four samples that were tested in this thesis. Also, when the samples are larger, more carbon fiber straps are required, not only in one direction, but additionally criss-crossing is required for optimum reinforcement. Therefore, the carbon fiber straps are expensive.

Retreatability

As stated in Chapter 2, each of the marble samples that were treated with carbon fiber straps and polypropylene honeycomb first had a layer of B-72 dissolved in toluene applied to the side of the marble to be treated. This aided in the possibility of retreatability. However, when conducting the flexural strength tests, all of the marble samples failed within the marble, not within the adhesive or the treatment. This may be a huge drawback for retreatablity and practicality. Therefore, it is recommended that a weaker epoxy be applied, one that is sacrificial to the marble, so that retreatability could be an option. However, if one is more concerned about public safety on buildings, this strong epoxy may be more desirable, since the marble will not debond from the treatment.

Ease of Application

Both of the treatments were relatively easy to apply to the marble panels. The only problem is that with the AnchorFix 3, it is a two-part epoxy and once the two components come in contact with each other, they immediately start to set, even within the application tube, therefore requiring several application tubes in order to apply treatments to more than one sample. This is also a problem when applying the epoxy to the marble because one must be quite quick when spreading the epoxy so that it does not start to set prior to placing the treatment on the marble considering that complete contact is required for effectiveness. Placing the treatments on the marble is straightforward, but one must be sure to place a heavy weight on top, so that the entire treatment material comes in even contact with the epoxy. Also, one or two days must be allowed for the epoxy to completely set before any further cycling or testing can continue.

Damage to Marble

As discussed above, the epoxy may affect retreatability of the marble; also of consideration is the potential of the failure mode being within the marble itself, as opposed to within the epoxy or treatment material. Additionally, though, the epoxy and polypropylene significantly affect certain critical properties of the marble, such as water absorption and water vapor transmission. This could easily be remedied by restricting the surface area of the adhesive to attachment points or spot welds. A honeycomb that did not have the scrim flap on either side could offer a better treatment option, since it would not restrict water vapor transmission of the marble.

Bowing Potential

Based on the results of the bowing potential test in Chapter 3, neither of the mechanical treatments had a significant impact on decreasing the bowing potential of the marble panels. This may be because the effects of hysteresis are inherent within the marble, due its grain size, shape, distribution, boundaries, porosity, and mineralogical construction. Therefore, one suggestion for mitigating the problems of hysteresis is to consider chemical treatments that could alter the physical properties of the marble, impregnate the marble, and perform the bowing potential test again, with or without the mechanical treatments.

Flexural Strength

As discussed in Chapter 3, the best option for mechanical treatments with this type of Carrara marble appears to be the carbon fiber strap. This seemed to be the most effective regarding flexural strength because it actually did increase the flexural strength of the weathered marble. In the case of the marble that was cycled for twenty days and had the carbon fiber strap applied with no further cycling, the increase in flexural strength was so great that it would be extremely useful to find a way to inhibit the weathering of the marble once the carbon fiber strap is applied. Equally important was the fact that the carbon fiber straps did not induce greater marble panel damage by restricting the bowing potential.

Alternative Approaches

In hindsight, there are a few things that could have been done differently. First of all, various types, sizes, and thicknesses of both the carbon fiber strap and the polypropylene honeycomb should have been examined prior to application and testing. This is because there may be some mechanical treatments that would have been more effective, such as a polypropylene honeycomb that did not have scrim flaps. Secondly, several other adhesives should have been tested to determine which would be sacrificial to the marble. Finally, chemical impregnation could have been examined so as to mitigate thermal gradients between the two sides of the marble, so that it would not have bowed so dramatically.

Further Research

Information is still needed to form any solid recommendations regarding treatment of bowed marble. For example, it would be interesting to test several different types of marble, and even other dimensional stone, for bowing potential and flexural strength. This would not only aid in determining what types of stone to use as cladding in new construction, but could also provide conservators with a prediction of how cladding already on buildings might weather now and in the future. Similarly, testing various mechanical treatments, chemical treatments, and both together, could provide information regarding the most effective ways to mitigate bowing due to hysteresis, while also increasing flexural strength. Additionally, it would be useful to conduct other tests, such as water vapor transmission, water absorption, bond strength, and linear strain tests on the marbles in order to determine if certain treatments negatively or positively affect or alter these physical properties of the marble. Finally, testing of proposed treatments should be on naturally bowed and deteriorated marble samples to ascertain the same treatment trends.

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MATERIALS AND SUPPLIERS

Carrara Marble

Cava International
2007 Washington Avenue
Philadelphia, PA 19146
215.732.0907
www.cavaintl.com

Construction Materials and Miscellaneous Supplies

McMaster-Carr Supply
473 Ridge Road
Dayton, NJ 08810
1.732.329.3200
www.mcmaster.com

Polypropylene Structural Honeycomb (Rigid-Elastic Technology)

Nida-Core Structural Honeycomb Materials
541 NW Interpark Place
Port S. Lucie, FL 34986
1.772.343.7300
www.nida-core.com

Sika CarboDur Carbon Fiber Reinforced Plates, Type S
Sikadur AnchorFix-3, Sikadur Injection Gel FS

The Sika Corporation
201 Polito Avenue
Lyndhurst, NJ 07071
1.800.933.SIKA
www.sika-construction.com

Thin Sections

Spectrum Petrographics, Inc.
3315 NE 112th Ave Ste B98-99
Vancouver, WA 98682
1.877.838.2950
www.petrography.com

NORDTEST Method

NT BUILD 499
Approved 2002-05

CLADDING PANELS: TEST FOR BOWING

UDC 620.179.13:691.21

Key words: Cladding panels, bowing, test method

1 SCOPE

This Nordtest method describes a laboratory procedure for determining the bowing potential of natural stone panels intended for building facades. The method shall therefore be used to select natural stone types that are fit for cladding purposes, without demonstrating this phenomenon.

2 FIELD OF APPLICATION

The method is used for indicating thermal and moisture induced bowing of various natural building stones, especially carbonate rocks such as marble and limestone.

3 REFERENCES

1. Schouenborg, B., Grelk, B., Brundin, J-A. & Alnæs, L. SP RAPPORT 2000: 28 Nordtest project 1443-99: Buktningsprovning av marmor för fasadbeklädnad (Bow test for facade panels of marble).
2. prEN 12670 – *"Terminology of Natural Stone"*.
3. prEN 12440 – *"Denomination of Natural Stone"*.
4. NT BUILD 500 (Field method for measurement of bowing of cladding panels).

4 DEFINITIONS

Bowing: In this test method, bowing is used as a term for a slab that has changed from an original flat and plane shape to a curved or dished shape in a concave or convex direction. Other terms commonly used for the same phenomenon are warping and dishing.

Concave: Centre part of the specimen is bowing upwards, away from the moist substratum. Compare NT BUILD 500 where the centre part of the panel is facing inwards (to the facade).

Convex: Centre part of the specimen is bowing towards the moist substratum.

Object testing: Testing of panels taken directly from the production of cladding elements or from buildings.

5 SAMPLING

The method of sampling shall be stated in the test report and shall be chosen so that the samples are representative of the batch to be tested. For material characterisation purposes samples shall be selected from three perpendicular orientations (e.g. parallel, normal and perpendicular to foliation). For "object testing" it is sufficient to test one set of samples with the same orientation as the slabs to be used on the facade.

One test set consists of five specimens of size 400 mm by 100 mm, thickness as in use. For material characterisation the specimens shall have a thickness of 30 mm. The specimens shall be randomly chosen for the tests. At least one side of the samples (the side exposed to moisture) shall be smooth but not polished.

6 TEST METHOD

6.1 Principle

Bowing is measured on test samples exposed to moisture from one side and infrared heating on the other side. The temperature interval is from 20 to 80°C, one cycle each 24 hours.

The moisture gradient is produced by letting the samples rest on an approx. 5 mm thick wet heat stable filter cloth or a 5–10 mm thin bed of sand that gradually dries under the influence of the infrared heater. The temperature of the sand is not controlled by other means than the temperature of the laboratory, i.e. 20 ± 2°C.

6.2 Equipment

- A suitably sized, non-corrosive container for water immersion of the specimens.
- A thermometer at least ranging from 15 to 85°C, with a tolerance of ±2°C.
- A watch or a timer.
- A container to moisten the specimens on one side and to expose them to heating on the other side (see example in Figures 1 and 2).

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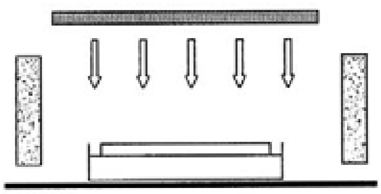

Figure 1. Schematic sketch of an insulated container for testing the potential bowing properties of natural stone. The test specimens are placed in a pan, on top of a filter cloth (needle felt) or a sand bed. The heat is distributed from above. The walls are preferably insulated.

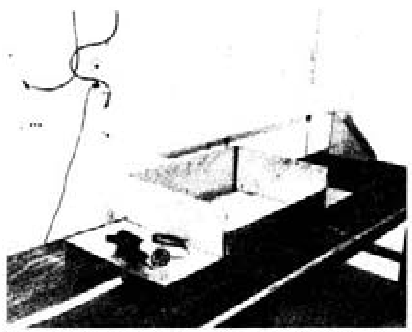

Figure 2 A. Test container with infrared heating lamps above.

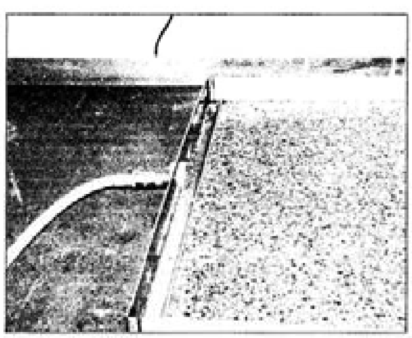

Figure 2 B. Inner pan with sand bed and a water hose. Here complemented with an adjustable water level outlet.

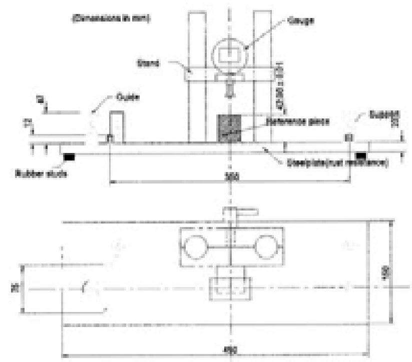

Figure 3. Schematic drawing of a bow-test rig.

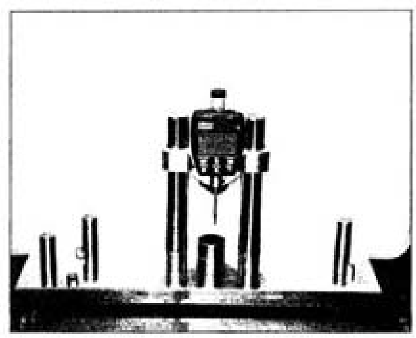

Figure 4. Example of a bow-test rig with a digital gauge and a reference cylinder for zero setting. The reference piece (a cylinder) is preferably made of invar steel and has a height of 30 mm, i.e. the same as the thickness of the specimens.

- Heat stable filter cloth (needle felt) or sand to place the specimens on in the above container. No specification for the sand other than a capillary suction greater than the thickness of the sand bed.
- Radiant heating devices, capable of keeping the specimen's surface at 80°C.
- A "bow-test rig" for measuring the amount of bow (see example in Figure 3 and 4). The dial/digital gauge for measuring the amount of bow shall be readable to thousands of one mm. It shall have an accuracy better than ±0,01 mm.
- A thermometer capable of measuring the surface temperature of the specimens.

6.3 Pre-conditioning of test samples

All loose material shall be washed from the surface of the specimens using tap water.

Dry the specimens in 40°C for one week. Some marble types are sensitive for higher temperature. Changes of the stone properties shall not be included during the pre-conditioning.

After drying, cool the specimens to room temperature 20°C ± 2°C. Each specimen is then labelled with a durable marking.

Each specimen is placed in an open container, partly immersed in distilled or filtered water to a depth of 10 mm ± 2 mm below the top of the specimen. The specimens are placed in the container at a distance of minimum 5 mm from each other and the distance to the sides of the container shall be at least 10 mm. Alternatively, the specimens may be placed in a single container provided that there is a minimum of 10 mm between the specimen and the sides of the container. The specimens shall be kept in the container for 24 hours at a water temperature of 20 ± 2°C.

6.4 Test procedure and data processing

Before the specimens are exposed to temperature cycling, the difference in height between the top surface in the middle of the specimen (h) (see Figure 3) and the reference cylinder is measured with an accuracy of ±0.01 mm.

The container with the specimens is placed in an open insulated box under a group of radiant-heating devices (see example in Figure 2 A). The heaters are placed approximately 0.5 m above the specimens. A temperature-measuring sensor is placed on the top surface of one of the specimens. The heaters shall be arranged or adjusted by a regulator to provide a maximum surface temperature of 80°C ± 2°C on top of the specimens at the hottest stage of the temperature cycling. Check that the heat is evenly distributed by placing the temperature sensor on different places in the container.

The increase in the surface temperature of the specimens from 20°C ± 2°C to 80°C ± 2°C shall take place in not less than 1 hour and not more than 3 hours. The maximum temperature shall be maintained for 3 hours (Figure 5). The heater is then switched off, and the specimens are left in the container for at least 16 hours to cool down to ambient temperature (20°C ± 2°C).

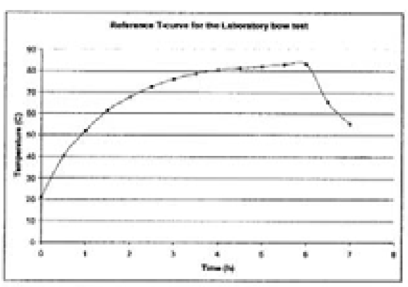

Figure 5. The preferred temperature cycle, measured on the surface of the specimens.

Before each temperature cycle (2 ± ½ hours), it is necessary to remoisten the specimens by filling the container with distilled or filtered water in such a way that the specimens once again are partly immersed in water to a depth of 10 mm ± 2 mm below the top of the specimens.

After each temperature cycle (approx. 22–24 hours) the change in height (h) of each specimen is measured at a temperature of 20°C ± 2 °C. After the 10th cycle, measure the change in height every second cycle.

At least 40 cycles shall be carried out. After the last temperature cycle the height (h) is determined on both sides of the specimens to ensure that the result does not represent an increase in volume due to immersion in water but pure bowing. Any such volumetric expansion shall be subtracted from the final bow result.

The magnitude of bowing is calculated as the difference between the first gauge reading and the final reading divided by 350 mm, i.e. the length between the supports under the specimens.

$\tau = \Delta h / L$ (length) mm/m

Δh: Change in height in mm (after 40 cycles)
L: Length between the supports (0.35 m).

6.5 Applicability

The validation of the test method relies on the fact that stone types that show bowing damage on building facades also bow in this test. Stone types that are known to not have produced bowing on facades (e.g. granite) do not bow in the test.

6.6 Uncertainty

The precision data presented are preliminary and have been obtained within an earlier Nordtest project, in which some varying procedures have been used.

r_1 is here calculated as 2,78 times the pooled standard deviation (s_1) of 3 marble types and one limestone. The test on each stone type was performed on 4–6 test specimens. s_1 was determined to 0,025 and r_1 to 0,07 mm.

6.7 Test report

The test report shall include the following information (when relevant)

a) Name and address of the testing laboratory

b) Identification number of the test report

c) Name and address of the organisation or the person who ordered the test

d) Purpose of the test

e) Method of sampling and other circumstances (date and person responsible for sampling)

f) Name and address of the manufacturer or the supplier of the tested object

g) Name and other identification marks of the test specimens

h) Description of the test specimens

i) Date of supply of the test specimens

j) Date of test.

k) Test method

l) Condition of the test specimens (i.e. orientation of stone fabric in relation to the test object and the applied force), environmental data during the test if relevant (temperature, RH etc.)

m) Any deviations from the test method

n) Test results (in SI units), see section 6.4

o) Statement about the uncertainty of the test results

p) Date and signature.

Designation: C 880 – 98

Standard Test Method for Flexural Strength of Dimension Stone[1]

This standard is issued under the fixed designation C 880; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the procedure for determining the flexural strength of stone by use of a simple beam using quarter-point loading.

1.2 Stone tests shall be made when pertinent for the situation when the load is perpendicular to the bedding plane and when the load is parallel to the bedding plane.

1.3 As required, the flexural tests shall also be conducted under wet conditions.

1.4 The values stated in inch-pound units are to be regarded as the standard. The values given in parentheses are for information only.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 4 Practices for Force Verification of Testing Machines[2]

C 119 Terminology Relating to Dimension Stone[3]

3. Terminology

3.1 *Definitions*—All definitions are in accordance with Terminology C 119.

4. Significance and Use

4.1 This test method is useful in indicating the differences in flexural strength between the various dimension stones. This test method also provides one element in comparing stones of the same type.

5. Apparatus

5.1 *Testing Machine* (Fig. 1), conforming to the requirements of the applicable sections of Practices E 4. The quarter-point loading method shall be used in making flexure tests of stone employing bearing blocks which will ensure that forces applied to the beam will be vertical only and applied without eccentricity. The apparatus should be capable of maintaining the span length and distances between load-applying blocks and support blocks constant within ±1.3 mm (±0.05 in.). The load should be capable of being applied at a uniform rate and in such a manner as to avoid shock.

6. Test Specimen

6.1 The test specimens shall measure 102 mm (4 in.) wide by 32 mm (1.25 in.) thick by 381 mm (15 in.) long, with a span as tested of 318 mm (12.5 in.). The sides of the specimen shall be at right angles with the top and bottom. The specimens shall have a fine abrasive finish on the planes perpendicular to the load and a fine saw finish on the other four planes. The dimensions of the specimen shall be measured and recorded to the nearest 0.3 mm (0.01 in.). A minimum of five specimens shall be tested for each condition of test. The average value of the test results is reported as the flexural strength of the stone.

6.2 Where this test method is specified in the physical requirements of an ASTM C-18 Standard Specification for a dimension stone, the test specimens shall meet the requirements under 6.1.

6.3 Where the job thickness has been set (for example, the thickness of the stone panels for the project has been established), it is often requested to perform flexure tests at the job thickness. The following shall govern the specimen size where it is requested to test at the job thickness and the job thickness is other than 32 mm (1.25 in.). The span as tested shall be 10 times the thickness. The specimen lengths shall be not less than 51 mm (2 in.) and not more than 102 mm (4 in.) greater than the span as tested. Where the thickness is less than 68 mm (2.67 in.), the width of the specimen shall be 102 mm (4 in.). Where the thickness is greater than 68 mm (2.67 in.) the width shall be 1.5 times the thickness. Where the thickness is other than 32 mm (1.25 in.) and the specimen size is in accordance with the job thickness criteria noted in the foregoing, the average value of the test results shall be reported as the flexural strength of the stone at the job thickness. All other requirements shall be in accordance with 6.1.

6.4 Where the job surface finish has been set (for example, the architectural finish on the panels for the project has been established), it is often requested to perform flexure tests on specimens with the finish the same as on the job. The following shall govern when it is requested to test at the job surface

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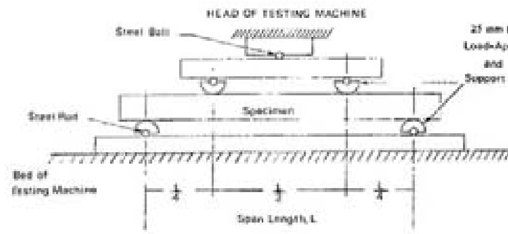
[1] This test method is under the jurisdiction of ASTM Committee C-18 on Dimension Stone and is the direct responsibility of Subcommittee C18.01 on Test Methods.

Current edition approved Sept. 10, 1998. Published March 1999. Originally published as C 880 – 78. Last previous edition C 880 – 96.

[2] *Annual Book of ASTM Standards*, Vol 03.01.

[3] *Annual Book of ASTM Standards*, Vol 04.07.



NOTE—Apparatus may be used inverted.

FIG. 1 Diagrammatic View of a Suitable Apparatus for Flexure Test of Stone

finish. The specimens shall have a finish on one plane perpendicular to the load in accordance with the finish specified for the job. Unless there is data to the contrary, the positioning of the specimen should be with the finished face in flexural tension. The average value of the test results shall be reported as the flexural strength of the stone at the job surface finish. All other requirements shall be in accordance with 6.1 and 6.3.

6.5 Where the specimens conform to the requirements of 6.3 and 6.4, the average value of the test results shall be reported as the flexural strength of the stone at the job thickness and surface finish.

6.6 Test results obtained by this test method are those of flexural strength properties. In specific applications, test specimens of different geometry may give useful results in terms of a modulus of rupture value.

7. Conditioning

7.1 Before testing the specimens in a dry condition, dry them for 48 h at 60 ± 2°C (140°F ± 4°F). At the 46th, 47th and 48th hour, weigh the specimens to ensure that the weight is the same. If the weight continues to drop, continue to dry the specimens until there are three successive hourly readings with the same weight. After removing the specimens from the oven, cool them to room temperature in a desiccator before testing them.

7.2 Before testing the specimens in a wet condition, immerse them in water for 48 h at 22 ± 2°C (72 ± 4°F). Test them immediately upon removal from the bath, wiping the specimens free of surface water.

8. Procedure

8.1 Assemble the apparatus and place the specimen on the span supports and adjust the quarter point loading blocks into contact with the specimen.

8.2 Apply the load at a uniform stress rate of 4.14 MPa (600 psi/min.) to failure.

9. Calculation

9.1 Calculate the flexural strength, σ as follows:

$$\sigma = \frac{3WL}{4bd^2} \qquad (1)$$

where:

σ = flexural strength, MPa (psi),
W = maximum load, N (lbf),
L = span, mm (in.);
L = $10d$,
b = width of specimen, mm (in.); $b \geq 1.5d$, and
d = depth of specimen, mm (in.).

10. Report

10.1 The report shall include the following:

10.1.1 Stone type.

10.1.2 Sizes of the specimens used.

10.1.3 Preconditioning procedure used.

10.1.4 Individual test results for each specimen.

10.1.5 Average value of the test results for each group using the following relation:

$$\bar{\sigma} = \frac{\text{sum of observed values}}{\text{number of tests}}$$

10.1.6 Standard deviation, s, of the test results for each group using the following relation:

$$s = \sqrt{\frac{\text{sum of (observed value} - \bar{\sigma})^2}{\text{number of tests} - 1}}$$

10.1.7 Any variations from the above procedural techniques.

11. Precision and Bias

11.1 Individual variations in a natural product may result in deviation from accepted values. A precision section will be added when sufficient data are available to indicate acceptable tolerances in repeatability and reproducibility.

12. Keywords

12.1 dimension stone; flexural strength; flexure; stone; test

Table of actual gauge readings from the bowing potential test for each cycle of each sample (1/1000"). *Top row indicates cycles; left column indicates samples.

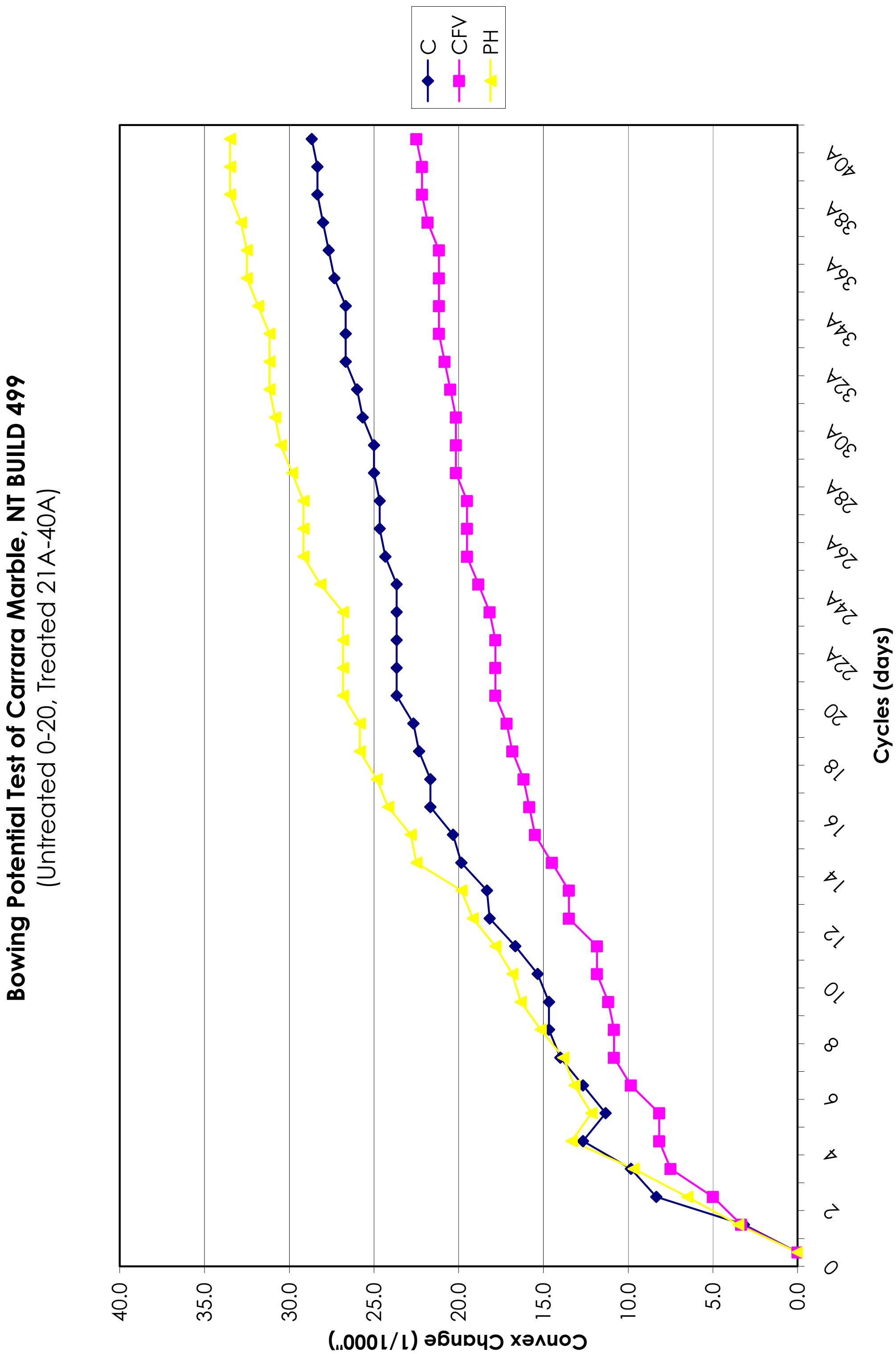
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21A	22A	23A	24A	25A	26A	27A	28A	29A	30A	31A	32A	33A	34A	35A	36A	37A	38A	39A	40A
C1	94	96	102	102	104	100	103	104	104	104	104	105	106	106	107	107	108	108	109	109	110	110	110	110	110	110	111	111	111	111	111	111	112	112	112	112	113	113	113	113	114
C2	114	119.5	124	125.5	129	129	129	131	132	132	133	135	136	136	138	139	141	141	142	142	143	143	143	143	143	144	144	144	145	145	146	146	147	147	147	147	147	148	148	148	148
C3	115	117	122	125	128	128	129	130	131	131	132	133	135.5	136	137.5	138	139	139	139	140	141	141	141	141	141	142	142	142	142	142	143	144	144	144	144	146	146	146	147	147	147
CFV1	114	122	125	132	132	131	135	135	135	136	137	137	141	141	143	145	145	146	147	147	148	148	148	149	151	152	152	152	152	152	152	153	153	153	153	153	153	154	154	154	154
CFV2	106.5	107	108	108.5	109	110	110	111	112	112	113	113	113	113	113	114	114	114	115	115	116	116	116	116	116	116	116	116	117	117	117	117	117	118	118	118	118	118	119	119	120
CFV3	111	112.5	113.5	113.5	115	115	116	118	117	117	117	117	118	118	119	119	120	120	120	121	121	121	121	121	121	122	122	122	123	123	123	123	124	124	124	124	124	125	125	125	125
PH 1	114	119	122	126.5	132.5	130	132	132	133	134.5	135	136	138	139	141	141	143	144	145	145	146	146	146	146	148	148	148	148	148	150	150	150	150	150	151	152	152	153	153	153	153
PH2	110	113	115	118	121	121	121	121	123	124	124	125	126	126	130	130	131	131	131	131	132	132	132	132	134	136	136	136	137	137	137	138	138	138	139	139	139	139	140	140	140
PH3	108.5	111	115	117	119	118	119	121	122	123	124	125	126	127	129	130	131	132	134	134	135	135	135	135	135	136	136	136	137	137	138	138	138	138	138	139	139	139	140	140	140

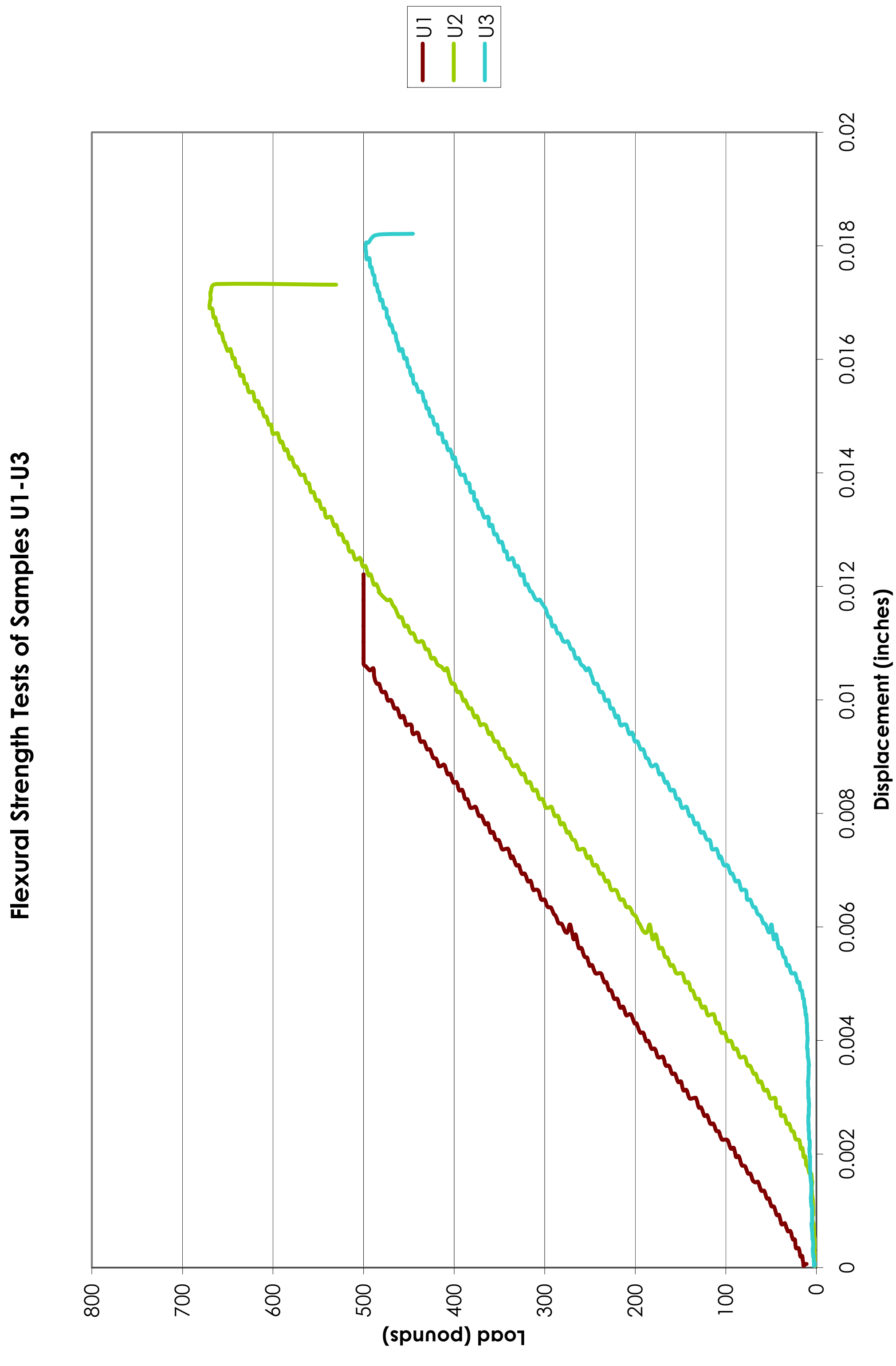
Table of calculated change from the bowing potential test for each cycle (1/1000"). *Top row indicates cycles; left column indicates samples.

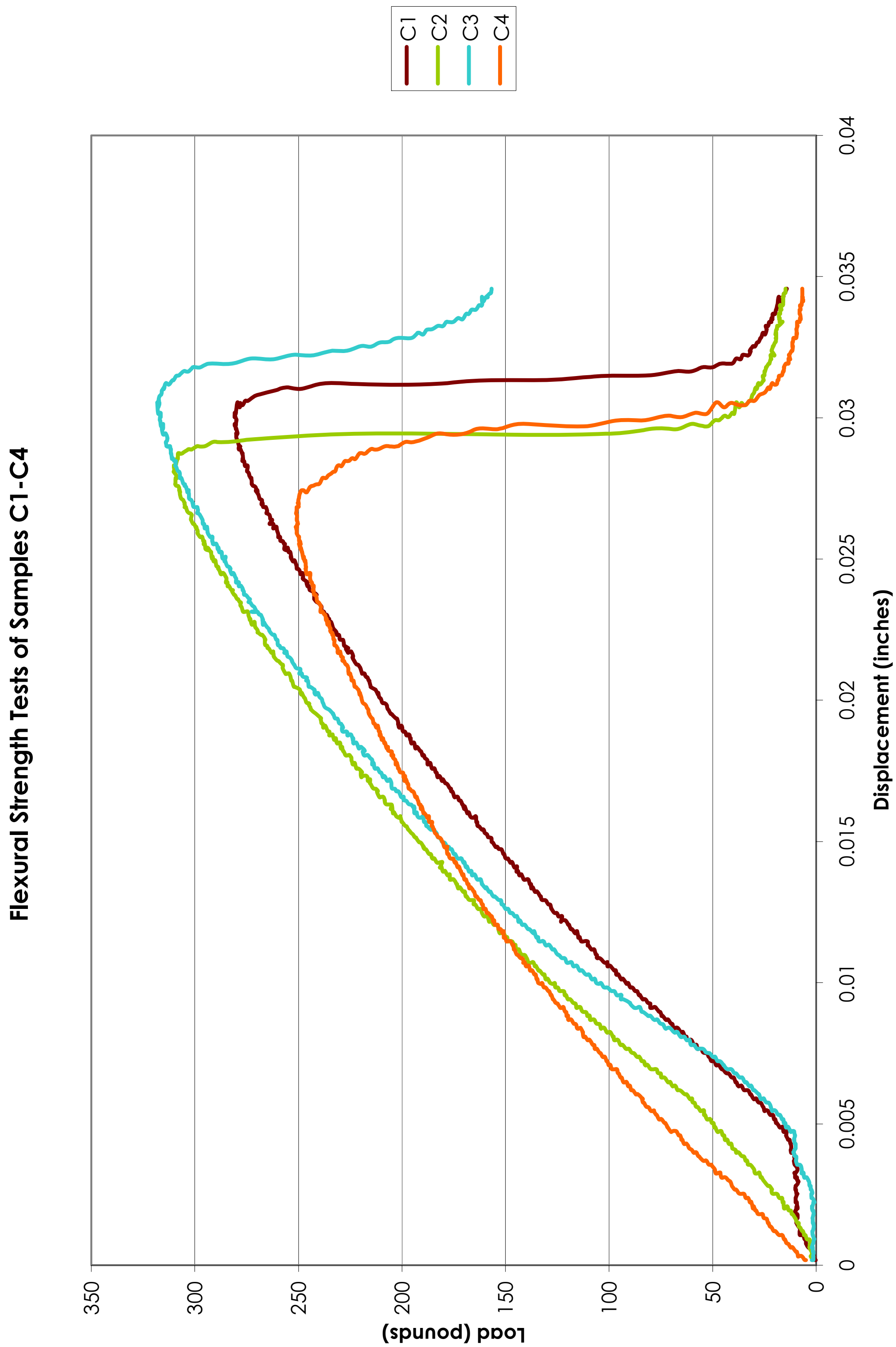
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21A	22A	23A	24A	25A	26A	27A	28A	29A	30A	31A	32A	33A	34A	35A	36A	37A	38A	39A	40A
C1	0	2	8	8	10	6	9	10	10	10	10	11	12	12	13	13	14	14	15	15	16	16	16	16	16	16	17	17	17	17	17	17	18	18	18	18	19	19	19	19	20
C2	0	5.5	10	11.5	15	15	15	17	18	18	19	21	22	22	24	25	27	27	28	28	29	29	29	29	29	30	30	30	31	31	32	32	33	33	33	33	33	34	34	34	34
C3	0	2	7	10	13	13	14	15	16	16	17	18	20.5	21	22.5	23	24	24	24	25	26	26	26	26	26	27	27	27	27	27	28	29	29	29	29	31	31	31	32	32	32
CFV1	0	8	11	18	18	17	21	21	21	22	23	23	27	27	29	31	31	32	33	33	34	34	34	35	37	38	38	38	38	38	38	39	39	39	39	39	39	40	40	40	40
CFV2	0	0.5	1.5	2	2.5	3.5	3.5	4.5	5.5	5.5	6.5	6.5	6.5	6.5	6.5	7.5	7.5	7.5	8.5	8.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	10.5	10.5	10.5	10.5	10.5	11.5	11.5	11.5	11.5	11.5	12.5	12.5	13.5
CFV3	0	1.5	2.5	2.5	4	4	5	7	6	6	6	6	7	7	8	8	9	9	9	10	10	10	10	10	10	11	11	11	12	12	12	12	13	13	13	13	13	14	14	14	14
PH1	0	5	8	12.5	18.5	16	18	18	19	20.5	21	22	24	25	27	27	29	30	31	31	32	32	32	32	34	34	34	34	34	36	36	36	36	36	37	38	38	39	39	39	39
PH2	0	3	5	8	11	11	11	11	13	14	14	15	16	16	20	20	21	21	21	21	22	22	22	22	24	26	26	26	27	27	27	28	28	28	29	29	29	29	30	30	30
PH3	0	2.5	6.5	8.5	10.5	9.5	10.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	20.5	21.5	22.5	23.5	25.5	25.5	26.5	26.5	26.5	26.5	26.5	27.5	27.5	27.5	28.5	28.5	29.5	29.5	29.5	29.5	29.5	30.5	30.5	30.5	31.5	31.5	31.5

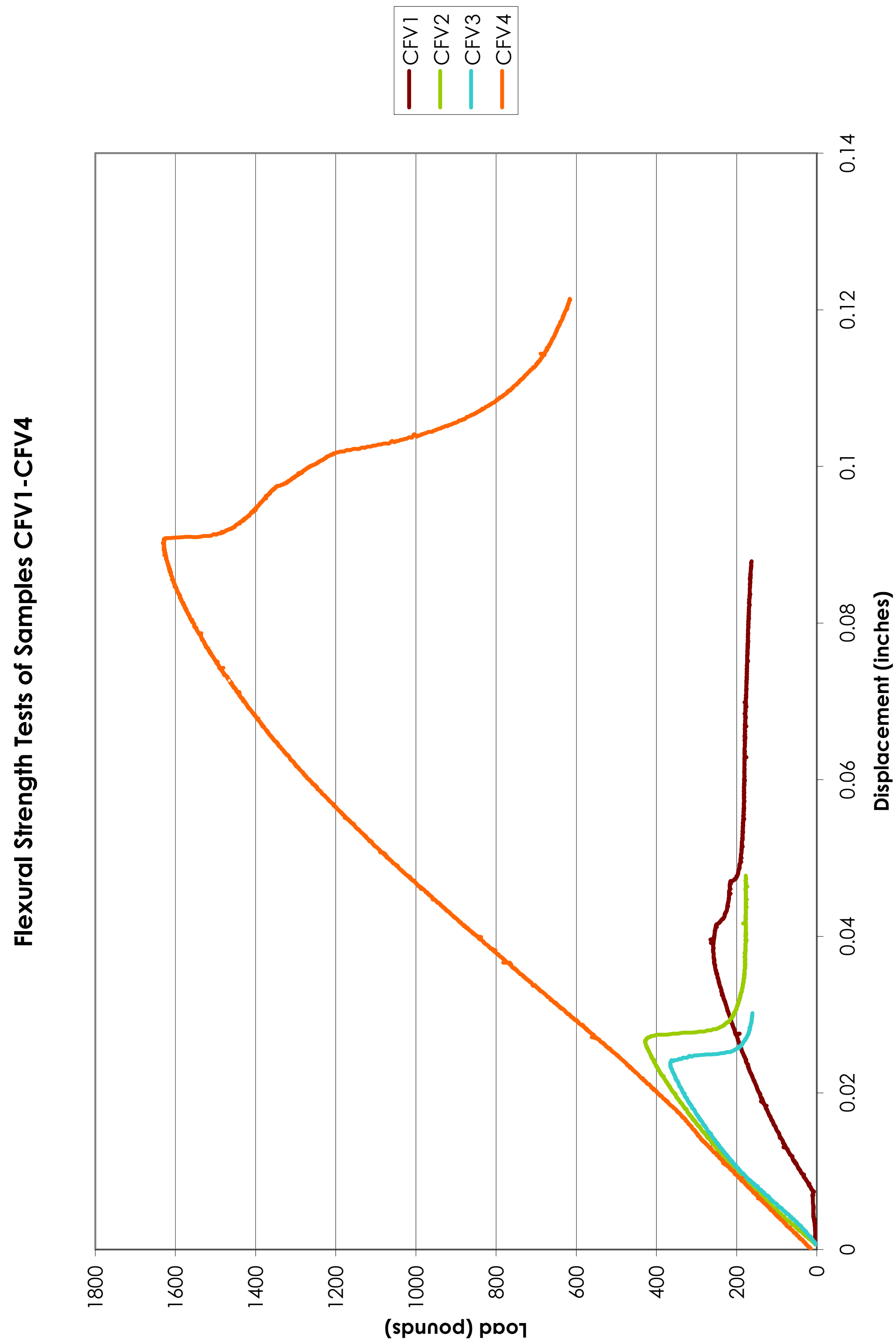
Table of calculated average change among each category of samples from the bowing potential test (1/1000"). *Top row indicates cycles; left column indicates samples.

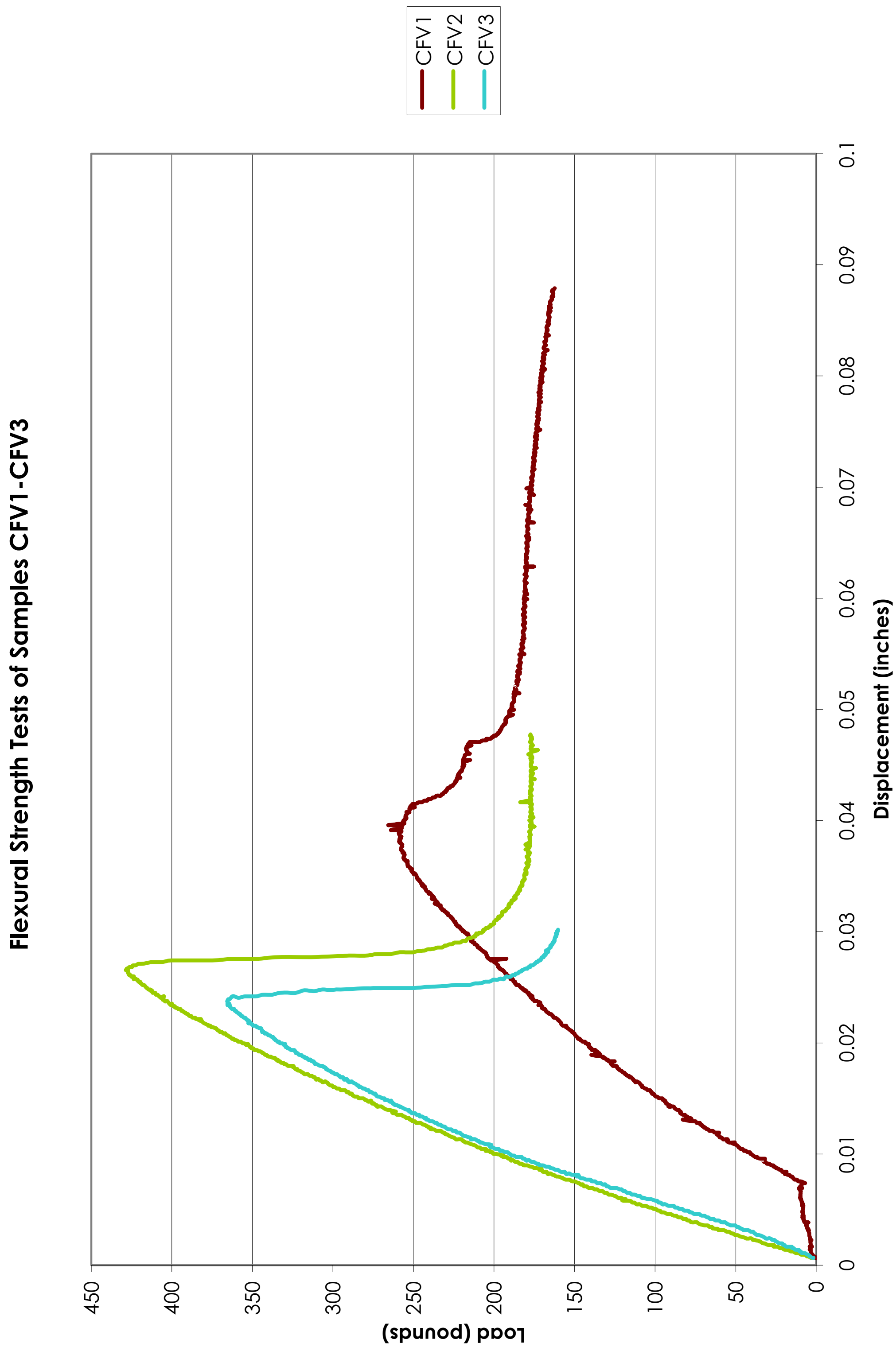
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21A	22A	23A	24A	25A	26A	27A	28A	29A	30A	31A	32A	33A	34A	35A	36A	37A	38A	39A	40A
C	0.0	3.2	8.3	9.8	12.7	11.3	12.7	14.0	14.7	14.7	15.3	16.7	18.2	18.3	19.8	20.3	21.7	21.7	22.3	22.7	23.7	23.7	23.7	23.7	23.7	24.3	24.7	24.7	25.0	25.0	25.7	26.0	26.7	26.7	26.7	27.3	27.7	28.0	28.3	28.3	28.7
CFV	0.0	3.3	5.0	7.5	8.2	8.2	9.8	10.8	10.8	11.2	11.8	11.8	13.5	13.5	14.5	15.5	15.8	16.2	16.8	17.2	17.8	17.8	17.8	18.2	18.8	19.5	19.5	19.5	20.2	20.2	20.2	20.5	20.8	21.2	21.2	21.2	21.2	21.8	22.2	22.2	22.5
PH	0.0	3.5	6.5	9.7	13.3	12.2	13.2	13.8	15.2	16.3	16.8	17.8	19.2	19.8	22.5	22.8	24.2	24.8	25.8	25.8	26.8	26.8	26.8	26.8	28.2	29.2	29.2	29.2	29.8	30.5	30.8	31.2	31.2	31.2	31.8	32.5	32.5	32.8	33.5	33.5	33.5

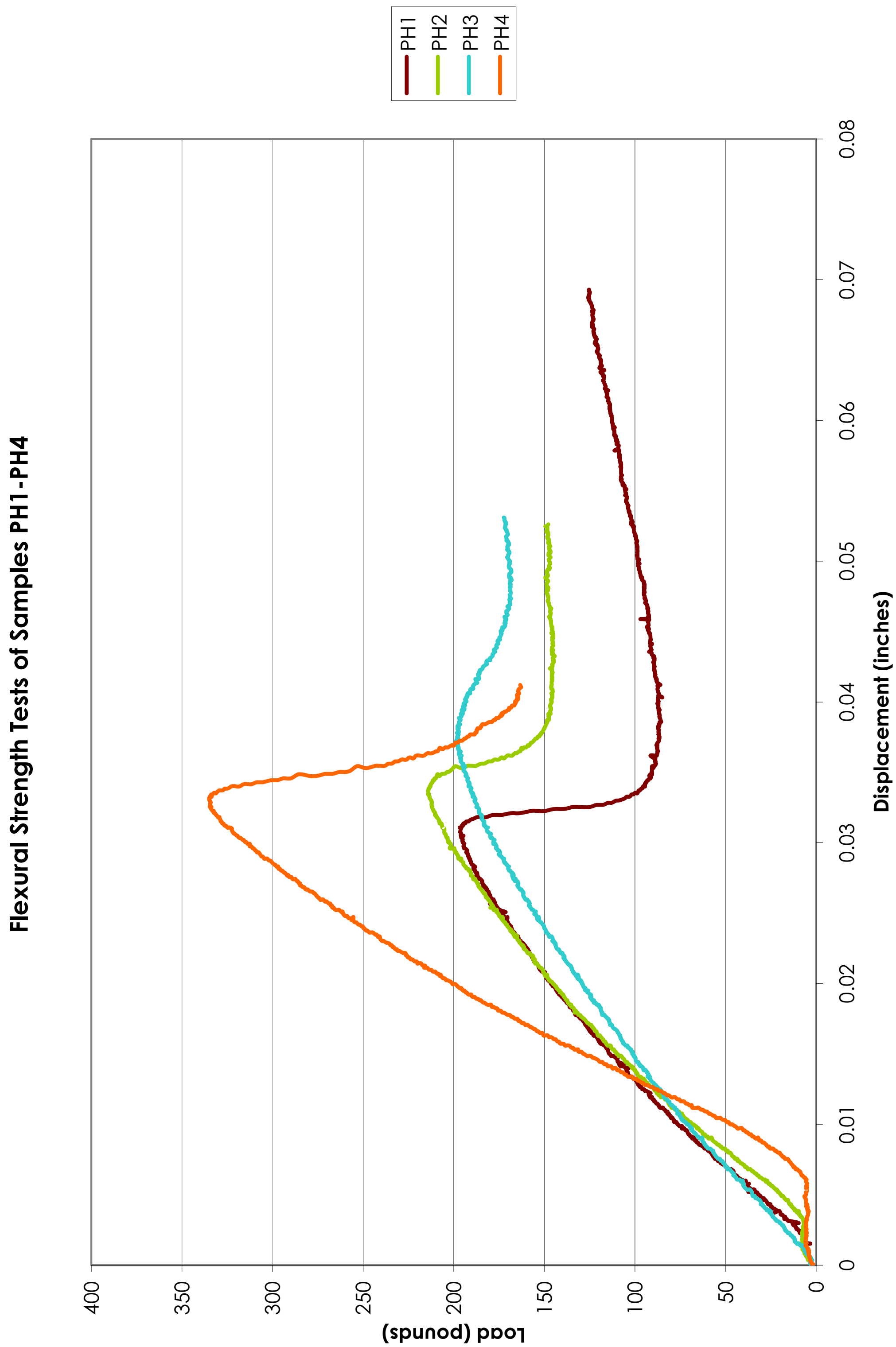

Bowing Potential Test of Carrara Marble, NT BUILD 499
(Untreated 0-20, Treated 21A-40A)
C
CFV
PH
Convex Change (1/1000")
Cycles (days)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
0
2
4
6
8
10
12
14
16
18
20
22A
24A
26A
28A
30A
32A
34A
36A
38A
40A


Flexural Strength Tests of Samples U1-U3
Load (pounds)
800
700
600
500
400
300
200
100
0
Displacement (inches)
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
U1
U2
U3


Flexural Strength Tests of Samples C1-C4
Load (pounds)
0
50
100
150
200
250
300
350
Displacement (inches)
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
C1
C2
C3
C4


Flexural Strength Tests of Samples CFV1-CFV4
Load (pounds)
0
200
400
600
800
1000
1200
1400
1600
1800
Displacement (inches)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
CFV1
CFV2
CFV3
CFV4


Flexural Strength Tests of Samples CFV1-CFV3
Load (pounds)
Displacement (inches)
CFV1
CFV2
CFV3
0
50
100
150
200
250
300
350
400
450
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1


Flexural Strength Tests of Samples PH1-PH4
Load (pounds)
0
50
100
150
200
250
300
350
400
Displacement (inches)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
PH1
PH2
PH3
PH4

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