
Soft Capping of Archaeological Masonry Walls

Far View House

Mesa Verde National Park

Alex Byungwook Lim

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Faculty Advisor:
Frank G. Matero
Professor of Architecture

Reader:
Michael C. Henry, PE, AIA
Adjunct Professor of Architecture

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*To My Parents,
For their Sacrifice and Faith*

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List of Abbreviations

MVRC: Mesa Verde Research Center

NCDC: National Climatic Data Center, United States Department of Commerce

1. INTRODUCTION

1.1. Topic Introduction and Justification

Exposed archaeological ruins are subject to various weathering conditions that accelerate their deterioration. Of particular importance are moisture levels and temperature variance. Combined with intrinsic material characteristics, age, building design, and past restorations, these factors can significantly threaten the durability of ruin sites. In order to conserve and manage archaeological structures effectively, one needs to understand the sources and effects of these environmental variants and to identify remedial and preventive conservation methods to minimize their damaging impacts upon features and sites.

Compound masonry walls are a common construction feature in many archaeological sites. They are usually constructed of two veneer "leaves" filled in-between with rubble, mortar or soil. In exposed archaeological ruins, the preservation of compound walls poses a particular challenge due to the lack of protection from fragmentation and direct exposure to the weather. Such exposure leads to severe moisture penetration and thermal movement. Over time, these continued cycles of weathering bring about irreversible damage which causes material attrition and displacement and can ultimately lead to wall collapse.

In the past, a hard capping of lime, cement, and modified soil mortars has conventionally protected exposed compound walls. This method has been popular due to its minimal intervention to the standing wall and the relative ease and economy of its

initial application. In reality however, the procedure requires persistent repairs and maintenance that can increase cost and risk to the wall. Hard caps tend to crack under prolonged compressive and tensile stress from thermal movement and ground subsidence. Cracks allow easy access for water to further penetrate and concentrate inside the cavity (Ashurst 2007: 98). At the same time, the cracked cap retards drying and desorption of moisture from the top of the wall. Increased moisture can cause dissolution of core mortars or soil and damage the masonry through freeze/thaw cycling and salt damage, each of which eventually weakens a wall. In addition, the damaged cap must be replaced through the removal of the previously installed cap or if this is not done, repaired or capped over by a new one. In either case, hard capping does not usually adequately address the long-term management of moisture and thermal damage that will continue to stress the wall. Instead of protecting the compound wall as initially designed, hard capping can actually accelerate deterioration of the wall over time.

A procedure called 'soft capping' aims to counter such problems posed by hard capping. Introduced in recent years at several archaeological sites in England, Turkey and elsewhere, soft capping replaces hard caps with vegetation planted on top of a layer of soil, with optional layers of gravel, and geosynthetics (Ashurst 1998, 2007; Sass and Viles 2006; Stokely 2007; Viles and Wood 2007; Wong and Stokley 2008; Wood 2004, 2005). Taking advantage of plants' transpirative ability to utilize the water, it seeks to

prevent water penetration, reduce thermal fluctuations, and provide a protective barrier on the wall top.

Geosynthetics provide further protection from moisture and temperature control. Often used in landfill waste control for their low permeability of water and toxic solutions, geosynthetics provide a moisture barrier and drainage system, in addition to functioning as filter layers and soil support. Over the years, architects adopted geosynthetics for use in "green" roof technology in architecture while archaeologists used the material for reburial of sites.

Far View House in Mesa Verde National Park offers an excellent opportunity to test the application of soft capping and to further improve its design and performance. Far View House is a mesa top site and is therefore exposed to the extremes of climate. Daily, it is subject to highly fluctuating air and surface temperatures due to heating from the sun. Seasonally, it is subject to extreme temperatures as well as dry and wet conditions in summer and heavy snow in winter. Over forty exposed rooms divided by compound walls experience such weathering conditions at Far View House. Over the years, these walls have undergone numerous stabilization campaigns utilizing a variety of mortar caps and repointing. While temporarily effective against precipitation, they do not benefit the walls in the long term as they require frequent repair. Unintended consequences such as cracks lead to serious destabilization of the wall by allowing water to attack the interior earthen bedding mortars. Far View House requires

reconsideration of conventional methods of wall protection coupled with monitoring in order to improve site preservation.

1.2. Limitations

The extent of the past stabilization of the interior core of the study wall is yet to be determined. Limited funding prevented carrying out long-term monitoring to evaluate the intervention method.

1.3. Definitions

(Koerner 1998; Kavazanjian 2004)

- Drainage core - Either a net composed of strands of polymeric materials or a membrane-like polymeric panel and sheet with raised nodules or pedestals.
- Fabric, non-woven - Geotextile manufactured by placing and orienting the fibers or yarns on a conveyor belt and bonding them by needle punching or heat bonding.
- Fabric, woven - Geotextile manufactured using traditional weaving methods and a variety of weave types.
- Geocells - Diamond-shaped cells fabricated into a sheet by welding together relatively stiff, rectangular panels of polymeric material at regular intervals. Used for erosion resistance and earth reinforcement.

- Geocomposite - A manufactured material using geotextiles, geogrids, geonets, and/or geomembranes in laminated or composite form.
- Geogrid - a net or a web of high-strength polymeric material used in earth reinforcement applications.
- Geomembrane - A polymeric sheet with a very high resistance to flow perpendicular to the sheet. Used as a flow barrier, separation and protection. Gore-Tex® is a type of geomembrane that retains liquids but remains pervious to vapor transport.
- Geosynthetics - A manufactured planar material employed for geotechnical engineering purposes. Fabricated in panels, sheets and/or rolls, and typically composed primarily of polymeric materials. Includes geotextiles, geomembranes, geosynthetic clay liners, geonets, and geogrids.
- Geosynthetic Clay Liners (GCL) - Composed of a relatively thin (6mm) layer of very low-permeability soil, typically bentonite (sodium montmorillonite), either bonded to a carrier geomembrane or encased between two carrier geotextiles. Used as an infiltration barrier.
- Geotextile - A fabric made from polymeric fibers.
- Gore-Tex® - A type of geomembrane that retains liquids but remains pervious to vapor transport.
- Hard Capping - A protective layer or fill using lime, cement or mortar that hardens upon application.

- Hydraulic conductivity - The rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperatures (20 deg C).
- Permeability - A generic term for the property that reflects the ability of a material to conduct a fluid or vapor through a porous media such as soil or geotextiles. Also called hydraulic conductivity.
- Permittivity - For a geotextile, the volumetric flow rate of water per unit cross-section area, per unit head, under laminar flow conditions, in the normal direction through the fabric.
- Polyvinyl chloride (PVC) - A synthetic thermoplastic polymer prepared from vinyl chloride. PVC can be compounded into flexible and rigid forms through the use of plasticizers, stabilizers, fillers, and other modifiers; rigid forms used in pipes and well screens; flexible forms used in manufacture of geomembranes.
- Soft Capping - A protective layer using vegetation and growing medium.
- Tear strength - The maximum force required to tear a specified specimen, the force acting substantially parallel to the major axis of the test specimen.
- Tensile strength - The maximum force required to cause tension failure in a given test specimen.
- Transmissivity - For a geotextile, the volumetric flow rate per unit thickness under laminar flow conditions, within the in-plane direction of the fabric

1.4. Assumptions

- Cracks in the hard cap may extend into the core of the wall, providing access for water to penetrate into the wall.
- Soil core of the compound wall has been partially lost, resulting in void spaces inside the compound wall.
- Soil contains intergranular voids that can contain air, water vapor, liquid water and ice crystals.
- Local grass will successfully grow with 15 to 25 cm of growing medium layer, under normal climate in the test region.
- Growing medium will hold enough moisture to provide water for vegetation.
- The differential fill in Room 28 is exerting lateral pressure on the study wall, causing the bulge on the wall veneer facing Room 13, and more severely the cracks through the wall stones.
- Soil grade on both sides of the wall is providing moisture to the bottom of the study wall through capillary action, resulting in mortar losses and weakening the wall.

1.5. Research Hypothesis

Different capping methods based on mortar and vegetation will result in a measurable difference in moisture content in and over the wall and in the thermal response of the wall top. In order to test this hypothesis, a sample section of compound

wall at Far View House will be selected for testing. The wall will be divided into two areas, a control employing a renewed hard cap and a test area with soft vegetative cap.

2. LITERATURE REVIEW

Without proper protection against weathering, exposed archaeological ruins face significant environmental threats. There is abundant literature available that details actual deterioration processes, and this literature review will specifically focus on the trend in the development of soft capping techniques and on environmental monitoring as a way to diagnose and evaluate the soft cap system.

2.1. The Development of Capping Techniques

Several intervention methods exist to protect masonry and other construction at archaeological sites including sheltering, hard capping, reburial, clay capping and soft capping. A brief review of the existing literature will focus on their functions and limitations.

2.1.1. Sheltering

2.1.1.1. Definition

Sheltering introduces new construction over an archaeological site and provides indirect protection against outdoor exposure. One immediate and temporary method to shelter sites is the construction of a roof. Casa Grande National Park in Arizona (U.S.A) and the Temple of Apollo at Bassae in Greece are well known examples of sites protected by more permanently constructed shelters. In 2003 the Getty Conservation

Institute published an annotated bibliography on the conservation and management of archaeological sites including shelters (Demas).

There are mainly two types of protective sheltering: open shelters and closed shelters (Schmidt 1988). Both shelter types use a variety of materials ranging from wood, metal, concrete and even plastic. Open shelters tend to utilize light frames in order to open up the viewing space. They may utilize advanced construction technology such as metal cables or tensile skins such as at Bassae in Greece. On the other hand, closed shelters incorporate ruin sites within the newly constructed walls and roof envelope. The use of glass as an envelope allows visual access into the ruin while creating a physical barrier.

2.1.1.2. Limitations

While sheltering protects archaeological sites from rain, snow, surface runoffs and solar heat, it generally can undermine the aesthetics of the sites and distorts interpretation (Bahn 1996). Regardless of the design, the introduction of a shelter generally intrudes on the landscape and disrupts the contextual authenticity of an archaeological site. One of the few notable exceptions is the movable shelter on rails at the Semna temples in Sudanese Nubia (Hinkel 1968). Such innovative designs, however, usually have a short life span due to limited funding and maintenance support. The construction of a protective shelter generally forces a compromise between visitor experience and site protection (Doumas 1997). In terms of functionality, protective shelters--especially closed ones--either lack effective micro-climate control or face

increased construction and maintenance cost due to the introduction of external micro-climate control systems (Ashurst 2007: 178-179). The most significant problem with protective sheltering, however, is the general lack of evaluation of its functional and aesthetic effectiveness based on established criteria (Demas 2004). As a result of these limitations, recent trends suggest a search for alternative methods of providing protection with minimal intrusion into landscape while improving functionality.

2.1.2. Hard Capping

2.1.2.1. Definition

The use of hard capping also dates back to the early years of archaeology. Hard capping utilizes lime, cement or soil mortars that are applied to horizontal surfaces in a plastic state when hardened create a weatherproof surface. With improvements in cement and mortar technology, reduced cost, and ease of application, hard capping had become popular in protecting wall tops as well as sometimes providing drainage on the walls and stabilizing the tops for visitors to walk on (Davison 1974, Neville 1981). Unlike sheltering that may or may not have direct contact with the historic fabric, hard capping is directly applied to the building. While the literature on the materials used in capping is numerous, a study specifically looking at the effectiveness of hard capping has been limited.

2.1.2.2. Limitations

While hard capping may seem less invasive in preserving the authenticity and integrity of a site's ruins and landscape, due to the direct application, it can significantly alter the material integrity of a structure and may drastically exacerbate the condition of that structure and the site. The area immediately below cement – rich wall capping have been known to deteriorate (Ashurst 2007: 93). For example, the walls at Kenilworth Castle in England had been severely damaged by concentrated water run-offs due to the cement-based mortar wall capping (ibid. 98). The part of the adobe walls at Fort Union National Monument in New Mexico developed erosion, especially in area under the soil-cement hard caps (Oliver 2000: 84). At Chaco Canyon in New Mexico (U.S.A.) Ford observed how hard capping damaged historic building materials (2004). Applied to prevent sandstone masonry from falling off the walls, cement mortars had damaged an entire section of wall. All examples highlight the danger of applying hard capping to the building materials without careful consideration of compatibility and long term performance.

Various deterioration conditions develop in hard capped areas. Cracks can develop from chemical deterioration, volume change from freeze/thaw, and incompatible thermal expansion with historic materials (Pavia 2005). As a result, accelerated water entry and saturated wall system lead to structural collapse. In addition, salts introduced from Portland cement, such as calcium sulfate dehydrate (gypsum) can damage porous materials.

2.1.3. Reburial

2.1.3.1. Definition

An alternative to sheltering and hard capping methods has been the partial or complete reburial of excavated sites. According to Demas, reburial is "an attempt to reinstate the original buried environment of an excavated site, and thereby re-establish a state approaching equilibrium" (2004: 139). Reburial does not stop deterioration but it aims to significantly slow it down (ibid. 140). Reburial usually fills a space once excavated but may selectively cover exposed features and ruins. Reburial protects the site in two ways: one, by shielding the site from direct damage by water, wind, vegetation, light, animals and humans; and second, by establishing a stable environmental equilibrium where moisture and temperature fluctuations are reduced and the location of evaporation and salt crystallization are distanced from the ruin materials (ibid. 140).

Reburial is often used for sites with valuable historic and aesthetic values that cannot be separated from the context. These include mosaics (Burch 2004), wooden timbers (Ford 2004), and other traces of human activities, such as prehistoric human foot prints (Agnew and Demas 2004). In particular, the reburial project at Laetoli focused on the preservation of the hominid foot prints details the methodology for the design and evaluation of the intervention technique. In addition, it provides technical and strategic guidelines for designing a reburial intervention program.

Archaeological walls may be reburied in whole or in part, although when the wall is considerably high or when visitor interpretation can be interrupted, partial reburial is

an option (Ashurst 2007: 161). Constant monitoring and vegetation control should accompany afterward to effectively manage the reburied walls.

2.1.3.2. Materials Used

Reburial of archaeological sites requires an understanding of two key components in its design: geosynthetics and soil.

2.1.3.2.1. Geosynthetics

The literature on geosynthetics is extensive. Geosynthetics are commercially available as flexible woven or needle-punched textiles, nets or meshes, and solid semi-rigid sheets for use in geotechnical applications including separation, reinforcement, drainage, erosion and infiltration control, and filtration (Koerner 1998; Kavazanjian 2004). Five criteria should be met in choosing geosynthetic materials for use in reburial (Demas 2004; Kavazanjian 2004): First, it should be impermeable to liquid water but permeable to water vapor to allow ventilation; second, it should be durable enough to withstand fills above it and to be easily pulled off to allow for reversibility of the design; third, it should be flexible to conform to the contours of archaeological features; fourth, it should prohibit the growth of roots; and finally, it should be chemically resistant. Gore-Tex® and Tyvek® seem promising geotextiles based on their selective permeability and flexibility. However, they require more strength and durability in order to improve their function under soil fills. Geomembranes, on the other hand, exhibit strength and

durability suitable for rigorous application, but they are not elastic enough to be flexible for application on various building shapes and sizes.

Complex multi-composite systems such as geosynthetic clay liner (GCL) is composed of a relatively thin layer of very low-permeability soil, typically bentonite (sodium montmorillonite) that can absorb water and expand, exhibiting great moisture retention. It is either bonded to a carrier geomembrane or encased between two carrier geotextiles. GCL is an excellent water barrier until it gets saturated. In addition, it shows some vapor permeability. However, GCL requires enough overburden and neutralized soil in order to avoid complication from freeze/thaw and cation exchange (Kavazanjian, pers. comm.)

2.1.3.2.2. Soil

Soil buffers the damaging effects of moisture, temperature and vegetation. The porosity, pH and insulation performance also contribute to the performance of soil. Clays that retain moisture such as vermiculite, perlite and bentonite have been incorporated into the design of geosynthetic materials (Matero and Moss 2004). Kavazanjian has done a detailed study on evapotranspirative cover systems that take advantage of soil layers of different grain sizes to control movement of moisture (2001). Research has been done to understand chemical processes, such as oxygen level, pH and Redox potential in the reburial environment (Caple 2004; Corefield 2004) as well as biological process, in particular, the effect of wet-dry cycles on organic decomposition (Hopkins 2004).

2.1.3.3. Limitations

While visually less intrusive than protective sheltering, reburial limits future access and the experience of the site by blocking direct interaction of the visitors with the buried archaeological site (Demas 2004). Sites with modular systems could accommodate partial reburial of a site to allow visitor interpretation but it is not suitable for small sites without repetitive structures. Reburial without proper control of moisture movement has also proven more damaging than helpful for preservation of wooden structures (Ford 2004). The use of drainage systems and geosynthetic layers may keep moisture out but they may also trap moisture and encourage bio-growth.

The lack of monitoring, maintenance and evaluation is again the major problem facing reburied sites (Demas 2004). In particular, unchecked vegetation growth weakens the building materials through mechanical damages by root penetration, increased moisture retention that invites freeze/thaw and salt damage. The trackway at Laetoli illustrates how damaging vegetation can be to the preservation of an archaeological site even when buried (Agnew and Demas 2004). Mosaic pavements and earthen walls are also vulnerable against the poorly managed reburial program.

2.1.4. Clay Capping

2.1.4.1. Definition

Clay capping is similar to reburial in that it uses soil and geosynthetics. However, unlike reburial that covers spaces surrounded by walls or historic pavements such as mosaics, clay capping targets the surface areas of historic constructions. The use of clay

aims to take advantage of its ability to hold water and to help the system to gradually reach an equilibrium level with its surroundings, thus preventing any sudden changes in moisture and temperature levels. Since clay may be easily eroded, geosynthetics provide erosion controls to avoid wash-offs. Matero and Moss have evaluated the performance of perlite-vermiculite protection systems used as an immediate and temporary solution to slowly stabilize and help equilibrate the newly excavated earthen walls at Çatalhöyük, Turkey with measurable success (1999).

Goodman had installed temporary clay capping on terrace buildings at Gordion, Turkey to protect composite masonry-earthen walls (2002). His research is critical in several ways. First, it lays out a clear guideline in introducing stabilization through clay capping. He singles out reversibility, aesthetics, legibility, and ease of the installation among others that are critical for intervention design. Second, he clearly identifies the key areas for future intervention and suggests the future direction of the research. Third, he shows flexibility in employing different means to meet the goal of preservation. For example, he inserted sacrificial cast coupons of ash-modified lime mortar highly susceptible to frost action as a way to monitor freeze/thaw action in the protected wall core. After serving its immediate need, the clay capping was removed for introduction of a better system.

2.1.4.2. Limitations

The lack of follow-up research is scarce to quantitatively evaluate the effectiveness of the stabilization system. Since 2006, environmental monitoring has taken place at Gordion's Terrace Building 2, but the data suffered from gaps and malfunctioning equipment that makes an objective analysis difficult (Stokley 2007).

2.1.5. Soft Capping

2.1.5.1. Definition

Soft capping utilizes a plant's natural evapotranspirative ability to take up water through its roots and emit it as water vapor through the pores in its leaves. It not only limits the level of moisture in the growing medium but also manages any excessive water through the soil's ability to hold water for plant use or evaporation. A liquid water-impermeable but vapor-permeable geomembrane provides additional protection against water penetration into the masonry below. The installation of soft capping is most effective after all the excavation has been done and the site requires permanent sheltering strategy in order to retard its deterioration. The application of soft capping reduces the need to install a protective shelter that most often negatively impacts the visitor experience of the site. Soft capping is minimally intrusive to the landscape, and one may even argue that it contributes to the natural ruined feel of an archaeological site. Since it is retreatable, it may be removed when needs arise to allow for additional archaeological investigation of the site or improvement in intervention technology. In

addition, soft capping does not hinder visitor access. Soft capping provides sustainable protection against root penetration, moisture infiltration and erosion of soil. Due to its wide implications for use, the development of soft capping could protect not only exposed archaeological ruins, but any cultural site that requires protective roofing to work as a buffer against environmental elements, such as moisture and temperature.

2.1.5.2. Green Roof Technology

The development of the soft capping method has benefitted from research in other disciplines, including architecture, biology, soil mechanics and civil engineering. Different components of soft capping, from vegetation layer to geosynthetics, derive from the advancement in the corresponding fields of green roof and geosynthetics technologies. The application of the hybrid technology from these disciplines has fueled additional research in the development of soft capping tailored specifically toward the preservation and management of archaeological ruins.

The advancement of green roof technology holds great promise in its adaptation to soft capping techniques at archaeological sites and elsewhere. Over the past few decades, the literature on green roof systems has increased significantly. Its greatest strength lies in its sensibility toward the protection of the environment by reducing acid water runoff in urban areas, by reducing CO₂ levels in the air through avoidance of calcined energy consuming materials like lime and cement, and by increasing the aesthetics of the landscape. Since the emphasis on sustainability and energy efficiency

coincides with the aim of preservation of archaeological sites, the conservation and management of archaeological sites could benefit much from the adaption of green roof system.

The Internet offers rich information on schematics of green roof design. The research conducted by K. Liu and B. Baskaran for Institute for Research in Construction in Canada details the methodology in analyzing energy efficiency of green roof design with data on heat flow and temperature variance (2003). The paper is particularly helpful in understanding the methodology for designing a green roof and for evaluating its performance.

2.1.5.3. Soft Capping Research

2.1.5.3.1. Initial Development

English Heritage was the first organization to scientifically investigate and evaluate the applicability of vegetation as a capping method in mitigating the damaging effects of moisture on ruins. Begun in the 80's on low lying ruin walls, their research focused on the English climate with mild winter weather and year-long precipitation, that may be easier to design for and potentially more successful due to the consistently high percentage of atmospheric moisture, permitting a high survival rate among the native plant materials (Ashurst and Dimes 1990: 9-11; Ashurst 2007: 93-108; Viles, et al. 2002; Viles and Wood 2007; Wood 2004).

Wimble and Thompson noted the growth of flora on the walls of Jervaux Abbey, England as having been the stimulus for developing a more systematic approach (1993). As a pilot study they set up an experiment on the walls of eighteenth-century Garrison on the Island of St Mary. The granite walls provided a setting to engineer the use of vegetation growing in the oceanic climate. The chosen vegetation was applied in three types, turfed, sown lightly with seed moisture, and completely sown and were directly applied on top of the masonry tops. With caution, the researchers reported the result of the study to be excellent but emphasized the need for several years of monitoring. The follow up reports have not been found.

Rachel Tilling introduced a capping of turf, clay and mortar on masonry wall tops at Black Castle in Moulin in Scotland (2004). Once the wall top had been repointed with mortar, she laid down 125mm thick clay and coarse sand mix, on top of which she laid a turf layer dug from the local woods. In this research, the author recognized the value of plant turfs that provide immediate protection against moisture penetration in the wall system despite the destructive nature of plant roots penetrating into the masonry. However, Tilling does not provide any quantitative data to critically evaluate the effectiveness of the system.

2.1.5.3.2. Research at the University of Oxford

Two universities, the University of Oxford and the University of Pennsylvania, have been conducting research on improving soft capping techniques. The most active

research on soft capping is at Rock Breakdown Laboratory at the University of Oxford in the school of Geography and the Environment, with funding from English Heritage among others. Currently, researchers have done comparative study of non-capped and soft capped walls at Byland Abbey, Kirkham Priory and Hailes Abbey, England (Sass and Viles 2006; Viles and Wood 2007). The field data from the months of March and July in 2005 at Byland abbey demonstrated thermal blanketing effect of soft caps (Viles and Wood 2007). In particular, the soft caps maintained temperature above freezing in cold weather below freezing. In addition, it reduced the amplitude of the diurnal temperature fluctuation in the summer by maximum of one fourth from 25 deg C temperature change to approximately 5 deg C. Equally significant, it maintained relatively constant temperature between 20 and 25 deg C. The result from the laboratory testing also substantiated the findings from the field. Using a more severe temperature regime, ranging from -1.5 to 30 deg C, the researchers have shown that soft caps have an advantage over hard caps in lessening the amplitude of temperature fluctuation.

The research in England has also shown that soft caps can control the amount of water available to the walls below. Electrical resistivity tomography (ERT) allowed researchers to understand the two dimensional distribution of moisture using a non-destructive method and to visualize the effectiveness of the soft capping technique in controlling moisture penetration (Sass and Viles 2006). Wooden dowels to measure moisture confirm the usefulness of the ERT method.

The data from Byland Abbey shows that soft cap reduced the amount of water available to the wall significantly (Viles and Wood 2007). The graph shows that hard cap provided some protection against precipitation during the actual rain event as indicated by lower moisture content (ibid. 316-317). However, hard cap still got wet. It did not dry fast but held moisture underneath it, resulting in relatively high moisture content for an extended period of time. Soft cap, on the other hand, showed the opposite performance. While the moisture content temporarily increased drastically during rain events, soft cap did a better job in reducing the overall moisture content afterward due to its high drying ability. As the soft cap rapidly expelled moisture from the system, it eventually brought the moisture level below that of hard cap and maintained it that way until another precipitation event increased its moisture content. The data shows that as long as rain events are not frequent in order to provide soft cap a recovery time to dry and keep the moisture level low, soft cap will perform better in the long run in the management of water.

In addition to the functional design of the soft capping, the English have shown great sensitivity toward the aesthetic impact of the capping installation on heritage sites. The discussion of 'the return to the picturesque' reminds the preservation philosophy of John Ruskin who advocated the age value of sites (Wood 2005).

2.1.5.3.3. Research at the University of Pennsylvania

In contrast to the British counterpart, research at the University of Pennsylvania has been focused on the application of soft capping in arid climates. While the concept of using vegetation for protection is the same, several differences in the environmental condition, wall types, and the capping design distinguish these university projects. First, unlike the relatively high moisture levels in the British Isles, the conditions in arid climates are usually marked by extreme wetting and drying conditions. This makes moisture retention for the survival of vegetation challenging, especially since the allowable amount of growing medium to hold moisture is limited on wall top due to the dimensions and load that adds extra weight to the wall. The use of geosynthetics in addition to the vegetation layer to provide additional protection from moisture and temperature fluctuation is also a fundamental difference between the two research programs.

Since 2006, pilot project has been conducted at Gordion, Turkey to test the viability of the soft capping in dry weather. So far, three years of study have yielded enough data to evaluate and analyze the performance of the soft capping at Gordion. In 2008 field report, Wong compared the performance of three capping methods: white felt geotextile fabric with rubble/stone covering, grey Typar® geotextile fabric with *poa* mudballs, and polyethylene sheet with transplanted *poa* plant. She concluded that the use of Typar® is effective against root penetration but found that when placed against vertical walls with reburial, it created air pockets that allowed the recrystallization of salts in the masonry walls.

Based on comparative analysis between the data from 2007 and 2008, the effectiveness of the soft capping technique is yet to be determined. In particular, a simple soft capping technique does not seem to provide effective protection against moisture, at least based on the recorded data. A huge moisture level spike in December 2007 recorded by all the dataloggers indicates that the capping system was overwhelmed by the sudden increase in moisture level. During both test seasons the water content level gradually rose starting in January and reached its peak in May. While the test site received less precipitation in 2007 on average from January to May than during the same period in 2008, the data from capping sites in 2007, especially in spring, tend to show a higher level of water content compared to 2008. In other words, the moisture content in the wall may have been the design problem rather than the climate.

While a detailed discussion on the possible mechanisms for such failure would shed more light on the effectiveness of the design of the soft capping system, one can suspect moisture entry through the sides where the capping does not provide protection as one of the causes for malfunctioning. Another possibility is the entry of melting snow into the wall system from the foundation level through capillary action. This type of water saturation can raise the level of moisture content in both liquid and vapor form, culminating in the highest moisture content level in May.

2.2. Environmental Monitoring

Environmental monitoring is critical for diagnosing the pathology of ruin sites, designing effective soft capping techniques and evaluating design performance. Regardless of the capping type, monitoring is fundamental for understanding the site.

Various environmental monitoring techniques are available to record the physical environment of the site. In particular, information on daily and seasonal fluctuations in moisture and temperature levels allows researchers to identify the problem and to seek solutions. Since the test site for this thesis is located in an arid climate, the literature review focuses on environmental monitoring done in similar climates. Of particular interest are areas with overall dry conditions but with seasonal moisture increase through snow melt as well as temperature variance below and above freezing temperature. Maekawa reported on the methodology for conducting environmental monitoring through projects at Chaco Canyon in New Mexico (U.S.A.) (2004), the Mogao Grottoes in China (1997), and the Tomb of Nefertari in Egypt (1993) among others.

Maekawa's soil moisture program at Chaco Canyon (2004) is significant for a soft capping project in two ways: first, it is one of the first articles that uses extensive data collection from environmental monitoring *in situ* to substantiate the idea of using plants to manage the evapotranspirative process in soil. While other authors have suggested the use of vegetation for capping and even installed them on ruin sites, they do not provide effective long-term evaluation methods to test whether such installation has

indeed contributed to the protection of heritage sites. Based on the soil moisture map of the test site, Maekawa suggests that snow accumulation on an archaeological site constantly feeds the system with moisture until it completely dries in spring. As temperature fluctuates above and below freezing temperature, snow melts, penetrates into the wall and re-freezes as ice, exerting great volumetric pressure. The cyclical process damages the wall mechanically throughout winter as long as there is snow to be melted. It also damages the wall chemically via transportation of soluble salts. Maekawa observed that the soil is wettest not on the top surface but about 30cm below, where drying and wetting reach an equilibrium at a level that maintains wetness. Soil below this depth usually exhibits dry conditions without much fluctuation in soil moisture and temperature level.

Maekawa's study indicates the significant danger from cycles of snowmelt and freezing. Water expands and exerts significant volumetric pressure upon freezing. It transports soluble salts and becomes a medium for chemical deterioration. It also hosts biological growth for plants to grow roots forcing mechanical deterioration. When left untreated, daily and seasonal damages seriously weaken and destroy masonry walls.

The development of monitoring guidelines is also needed to evaluate the effectiveness of soft capping. They include comparative information regarding the parameters measured, accuracy, ease of use, cost and other variables (Teutonico 2004). Maekawa has consistently shown exemplary methodology in monitoring moisture level,

Relative Humidity, CO₂ levels, and temperature at various sites that could be adopted for the current project at Far View House, Mesa Verde National Park.

2.3. Summary and Conclusion

The literature review provides technical and scientific background with which to carry out a design for soft capping and an environmental monitoring program. It helps to identify areas for documentation and treatment and to raise awareness and funding to initiate and maintain a successful program for site protection. Based on the review, a soft capping project could greatly benefit from improvements in five areas. First, the identification of a flexible yet durable geosynthetics system would increase the applicability of the design for use in diverse archaeological sites, where the actual available surface area is limited and the wall tops can hold only a certain amount of static load on top; second, the identification of geosynthetic materials that conduct vapor moisture but block liquid moisture could significantly increase the ventilation and drain performance of the system; third, the identification and use of appropriate vegetation and growing medium combination would allow customized design to meet the needs of the environmental condition of a particular site; fourth, the visualization and quantification methods of environmental monitoring need to be improved to evaluate the effectiveness of the overall system; and finally, the design should be reversible but simple to accommodate easy use by local personnel. Despite these needs, soft capping may prove a highly feasible and easy-to-use alternative for hard

capping and protective sheltering. Continued monitoring of the test wall at Far View House would greatly contribute to the understanding of the deterioration mechanism, the improvement of soft capping design, and the preparation of an informed management plan.

3. CASE STUDY: FAR VIEW HOUSE

3.1 Introduction

Far View House is one of many front country sites open to the public within Mesa Verde National Park, Colorado, designated a World Heritage Site in 1978 (ICOMOS 1978) (Figure 1). At Mesa Verde National Park there are two major large site types: those located in cliff alcoves and those on the open mesa tops. The alcove sites or alcovates such as Spruce Tree House and Cliff Palace are naturally protected by the deep alcoves in which they are situated. Mesa top sites, on the other hand, are open and exposed to the weather. Far View House belongs to the latter.



Figure 1. Far View House in Winter (Lim 2008)

Located at 2345 m above sea level, Far View House sits on the northern end of Chapin Mesa, between Soda Canyon on the east and the East Fork of Navajo Canyon on

the west (Figure 2). The site is a part of the Far View Sites Complex comprised of several villages and a reservoir.

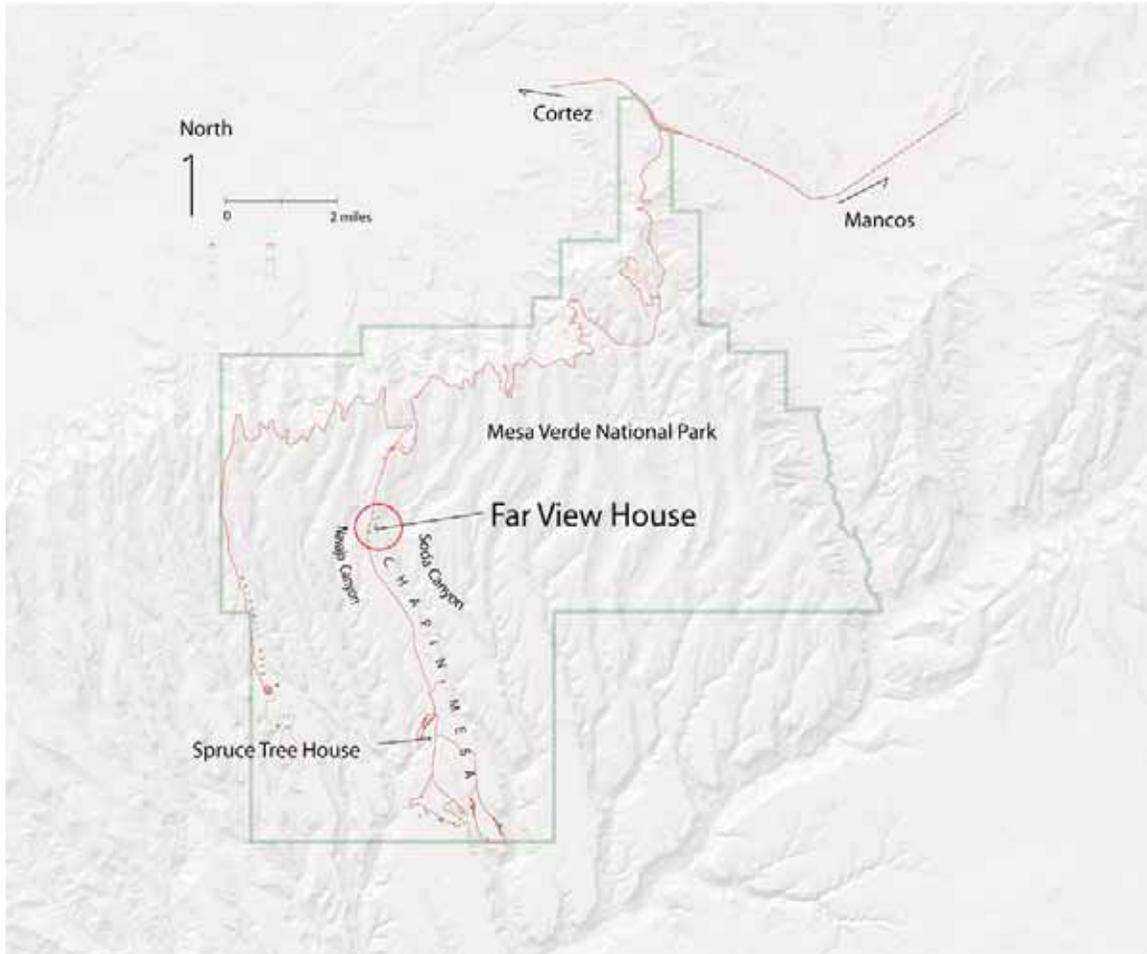
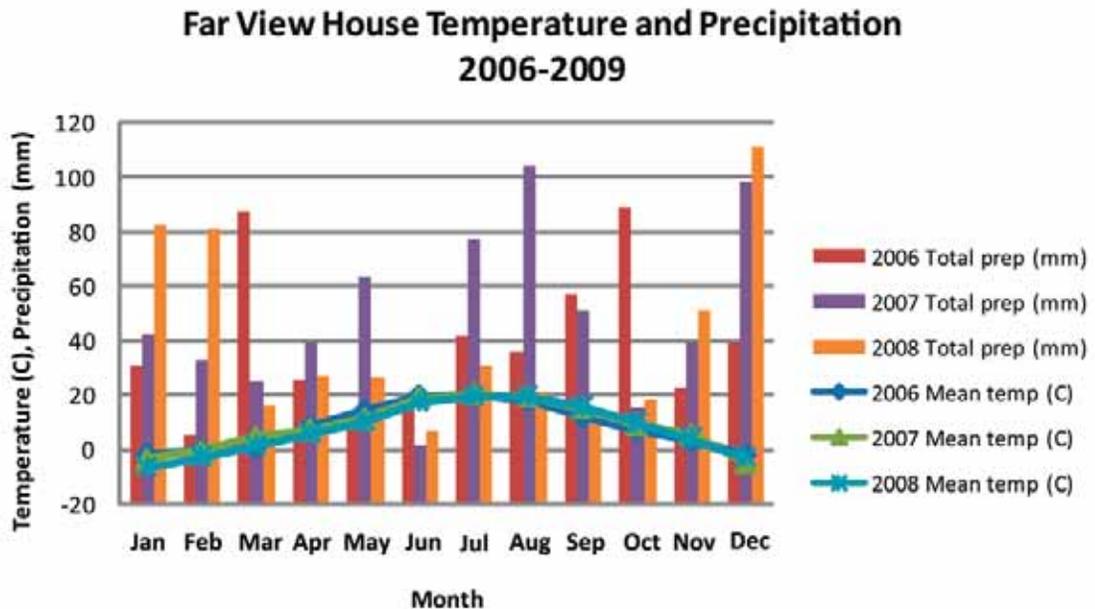


Figure 2. Map of Mesa Verde National Park (Based on a map from [http:// www.nps.gov/meve](http://www.nps.gov/meve))

3.2. Environment

Mesa Verde is located in a semi-arid region. The temperature throughout the year ranges on average from a maximum high of approximately 25 deg C in summer to a minimum of approximately - 5 deg C in winter, although the daily extremes can be much

more severe. The daily temperature range is most extreme in spring and fall, covering from below freezing to a high of 15 deg C (Graph 1).



Graph 1. Far View House Annual Temperature and Precipitation Data (NCDC 2009)

Annual precipitation is relatively low. Most of the precipitation is in the form of heavy snow in winter and early spring. A brief period of heavy rain in late summer also adds to the annual precipitation. When the temperature rises in the spring, standing snow melts, rapidly increasing the moisture content in the soil. June is constantly the driest season of the year.

The watertable level at Far View House is very low, since water percolates through the mesa top consisting of porous sandstone and soil. One hydrologist concluded that there is no permanent water table on Chapin Mesa and even the perched water table as a result of melting snow and rain runoff occurs very infrequently

(Wright 2006: 72). Water on the Mesa top was managed by Ancestral Puebloans through check dams and reservoirs for farming and for domestic use through percolation into natural springs and collection in cupules pecked in the bedrock.

Far View House experiences constant wind regardless of season unlike semi-protected alcove sites. Wind speed ranges from 8 to 16 km/h per day.

3.3. Design

Far View House is a rectangular shaped pueblo with similarities to the great house pueblos at Chaco Canyon in New Mexico (U.S.A.) (Fewkes 1917a: 469, 1917b: 82). A pueblo is a terraced community building constructed in the open and not attached to cliffs (Fewkes 1917a: 463). About forty rooms and three kivas are centered on one major kiva at the center in a rectangular fashion with one additional kiva in the southeast corner of the court (Figure 3). The pueblo faces south.

The rooms at Far View House are mostly rectangular in shape, except for four circular kivas and triangular recesses between rectangular rooms and circular kivas. The height of Far View House increases gradually toward the north as more stories are added. The north wall is about 34.5 meters in length and originally assumed to be approximately 6 meters high (Fewkes 1917a: 471). Wall thickness varies depending on location, ranging from a few inches to one or two feet in width. The rooms north of the large kiva contained wooden floor beams and roof rafters when excavated. Today there are no existing wooden beams except for signs of viga sockets.



Figure 3. Far View House Aerial View (Ruins Stabilization Report 1976)

3.4. Construction

In general, the walls of Far View House are mostly of compound masonry construction comprised of two opposing stone veneers with soil-rubble infill, although walls of a single wythe of stone also exist. The stone units are well shaped, many with a smooth or pecked faces and roughly coursed.

Fewkes reported that the masonry technique was generally fair but not very advanced (1917a: 471). Stones are relatively small, easily portable by a single laborer. An exception is in an area in the southwest inner corner where large, flat, thin and unworked stones are set on edge. Joints are unbroken, and corners were not property bonded or tied to the other walls. The adjoining surfaces of the superposed stones are not worked flat; the stones are set in mud with chinking stones inserted.

3.5. Use History

Baron Gustav Nordenskiöld, one of the first scientific explorers of Mesa Verde, first mentioned the mound as “the ruins of a considerable village” with walls “leveled with the ground, leaving only huge heaps of stone to mark the site.” (1893: 74) The area is quite densely populated with cedars, piñon trees, sagebrush, and other flowering plants, indicating rich soil and enough moisture for vegetation. Based on these observations and the presence of several reservoirs, Fewkes suggested that a farming community may have populated the area using water from the reservoir as well as natural precipitation (1917a: 464).

The exact date of construction is unknown but it is generally believed that the pueblo was occupied between A.D. 1100 and 1200 and was abandoned before the 13th century (Rohn 241-243).

In 1916, Walter J. Fewkes of the Smithsonian institute began excavation of the site at the request of the Secretary of the Interior (Fewkes 1917a) (Figures 4 – 5). The first excavation season lasted for three months from July to September. At the time of

the excavation, the remains of fallen walls were especially extensive along the north reducing the height to about six feet. Beginning from the northwestern corner, Fewkes and his crew removed the soil from the rooms, and discovered ceramics, stone hatchets and mawls, arrowheads, animal figurines and other minor small objects. Few human remains were found by Fewkes and other archaeologists in later years; the majority was found instead in a mound southeast of the site.



Figure 4. Fewkes' Crews Excavating Far View House (Fewkes 1916) MVRC



Figure 5. Dr. Fewkes and His Crews at Far View House (Fewkes 1916) MVRC

3.6. Material Analysis

There is no specific petrographic data on the sandstone from Far View House. However, based on its location on the mesa top, it is likely the stones were extracted from the upper formation known as the Cliff House Sandstone (Griffitts 1990). Petrographic analysis of the Cliff House sandstone was performed on stones from Spruce Tree House, located four miles south of Far View House and situated in the formation. The two major types of sandstone found in the region and at Spruce Tree House are quartz-bonded and calcite-bonded sandstones (Petuskey 1995: 149-152).

Mineralogical analysis on samples from Spruce Tree House indicate that the typical quartz-bonded sandstone consists of 82% quartz (SiO_2), 6 % feldspars (Na and K), 5% clays (kandite, and illite), 2% carbonates (Ca, Mg, and Fe), 4% iron compounds and less than 1% of other phases such as apatite, rutile, magnesium oxide, and zircon (Figure 6).

The typical calcite bonded sandstone consists of 68% quartz (SiO_2), 5% feldspars (Na and K), 4% clays (kandite, illite), 20% carbonates (Ca, Mg, and Fe), less than 1.5% each of iron compounds and other phases such as apatite, rutile, magnesium oxide, and zircon (Figure 7).

Of particular importance is the high porosity of the siliceous sandstone compared to the calcareous sandstone. Siliceous sandstone exhibits very high levels of porosity, around 25% in stark contrast to only 5% for calcareous sandstone.

Previous XRD studies on mortar samples from various sites at Mesa Verde point to the use of various types of clay. The samples from Mug House contained 70% kaolinite, 10% illite and 20% of illite/smectite mix (Dix 1996: 84). The samples from Cliff Palace contained 40% of illite/smectite mix, followed by 30% of kaolinite, 20% illite and 10% montmorillonite (Slater 1999: 48).

Quartz-Bonded Sandstone Phases Percentage by Weight

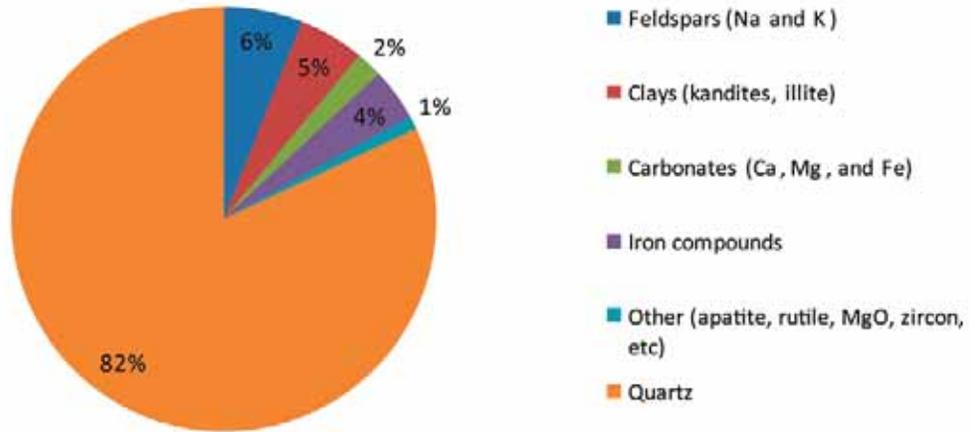


Figure 6. Quartz-Bonded sandstone (Petuskey 1995)

Calcite-Bonded Sandstone Phases Percentage by Weight

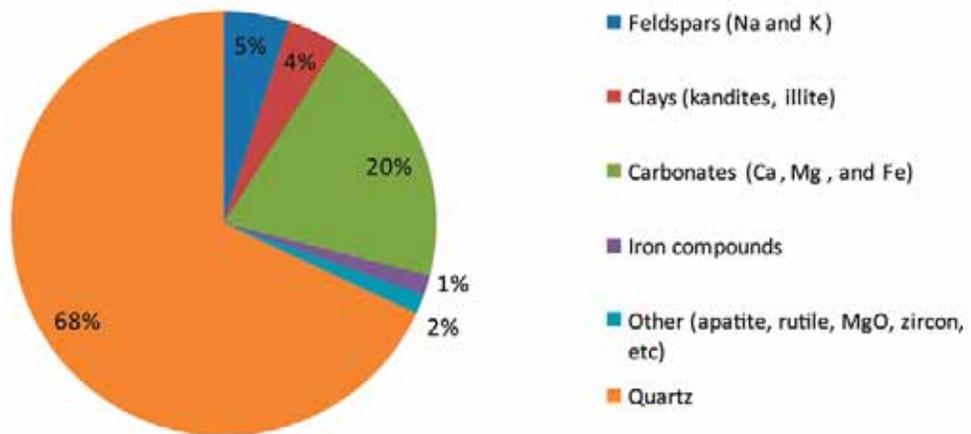


Figure 7. Calcite-Bonded Sandstone (Petuskey 1995)

3.7. Past Interventions

According to the *Superintendent's Reports* for Mesa Verde National Park, numerous stabilizations have been carried out at Far View House since excavation. Although the written documentation usually lacks the specifics of exact locations and the extent of work, when combined with visual documentation, they provide rich information on the history of previous preservation.

In the past, the interventions were mainly focused on stabilizing the ruin walls and repointing the deteriorated wall surfaces. Portland cement-based wall caps were initially installed by Fewkes to protect and drain the wall tops from weather and to allow visitors to walk on the walls for viewing the structure. Repointing mixes were made from soil and cement and attention was given to aesthetics by trying to match the mortar color with the original building materials. No reports have been found yet, however, on the composition of the original mortar mixes.

When Fewkes excavated Far View House from 1916 until 1921, many of the walls had either already fallen or collapsed during the work (1917a). At Sun Temple excavated a year earlier than Far View House, Fewkes had a similar experience with falling stones from wall tops especially due to violent rains in the summer or the infiltration of snow water with subsequent freezing during and between excavation seasons. In order to stop the wall tops from falling, Fewkes applied Portland cement mortars on top of the walls laid on mud mortar with a foundation of broken stones or rubble. The hard capping shed water from the wall top and provided a walking surface for visitors.



Figure 8. Repair by Fewkes (Markley, 1934) MVRC

Fewkes applied the same intervention methods on the wall tops of Far View House (Figure 8). He stabilized walls by adding a few courses of masonry on the exposed wall tops and applied a Portland cement and coarse sand mortar of unknown component ratios. He mentions the addition of sand as well as “coarse grout” when

applied to the tops of the walls of the kivas excavated in the summer of 1916. He showed a certain sensitivity toward wall integrity when introducing the intervention methods, by setting the added courses back from the original wall plane thus demarcating the extent of the repair work. Wall tops were left irregular but built to allow visitors to walk along them.

In addition to capping, he buttressed the west and south walls of the side that had leaned severely using stud walls of ancient appearance. Using mud mortars, he also temporarily tied the west ends of the partition walls on the west tier of rooms to the inner side of the west wall, in order to prevent them from falling.

After Fewkes' work, the site was left open with only minor repairs. In 1923, Al Lancaster, an archaeological foreman at the time, led a repair team to stabilize areas of immediate need. However, the inadequate funding limited the scope of the work. It was not until 1934 that major stabilization work was undertaken.

A year before the major stabilization project began in 1934, C. Marshall Finnan, the superintendent of Mesa Verde National Park requested appropriations to carry out repair and stabilization of major ruins, including Far View House (1933). He noted that prior to the excavation, "natural conditions had contributed to what we call the remarkable preservation of the ruins" (ibid. 1). However, "with the complete removal of this protective soil covering of the ruins enumerated," he continued, "walls were exposed to the elements, and in the intervening years considerable damage has resulted from the destructive effects of water and wind" (ibid. 2). Visitors also walked on top of the walls, posing serious safety and wall collapse issues.

Based on the observations, Finnan singled out moisture as the most destructive force to the ruins:

Capillary action takes place very rapidly in the sandstone and adobe [soil] mortar. As a result, moisture is pulled from the ground and rises sometimes several feet in the wall. Foundations and lower building stones disintegrate rapidly under this action. Late summer rains and early fall snow will keep the lower portion of wall saturated. With freezing weather begins the destruction, and that portion of the wall has been destroyed to the depth that the frost has penetrated. The damage or affected outer rock disintegrates or crumbles away in a few months. The process then repeats itself. We must give immediate consideration to this type of damage, since it affects the entire structure and could, in the course of a few years, completely destroy our finest archaeological remains... (ibid. 4)

The request had a profound impact, as a special team was soon formed to address the problems. The observations Finnan made were insightful, although the continued use of Portland cement based capping, an inheritance from the Fewkes' era, would have a serious long term consequence. It appears that managers had only a basic understanding of the deterioration mechanisms. While some of the proposed treatments described below have no documentation, they provide glimpses into the lack of clear understanding of compatible materials.

To protect these lower walls it would be necessary to install tile drains, both inside and outside, so that ground water and stored moisture will be carried off immediately and capillary action will not take place in the sandstone walls. As a feature of precaution the foundations and lower section of the walls should be protected by a concrete bib. (ibid. 4)

Among the various sites at Mesa Verde National Park, Far View House was chosen by Jesse L. Nusbaum, the director of the Laboratory of Anthropology, Santa Fe, New Mexico, as a field test site in 1934 since it was easy to measure due to its location

and design. At the same time, the site was used to practice methods and to train personnel for later applications at other sites in the park.

The first course of action was to record the site through an extensive field survey. In 1934, Stanley E. Morse and Jesse L. Nusbaum of the Department of the Interior led a comprehensive measuring and recording program for Far View House. Nusbaum defined the purpose of the project, first mentioned in a letter to Morse which was later reiterated in the official report.

The purpose of this survey is to assemble data which in the future may be used as authentic source material in connection with the repair and preservation of ruins as they stand at the time of the survey, or in their restoration, should certain walls or details be destroyed by visitor travel or natural forces. (1934: 1)

A guideline prepared by Stanley E. Morse in a letter to Mr. Meem, an architect based in Santa Fe, New Mexico, on January 30th, 1935 is equally illuminating. He emphasized the need for a complete record and inventory of the ancient material before and during the excavation that would become publicly available. In general, he urged absolute caution and reconsideration of the need before applying any restoration, repair and repointing works. Intervention was to be avoided, unless it provided immediate reinforcement to the original failing structure or surface protection. Even when applied, these interventions were to be “distinguishable from the bordering ancient work in some manner”, although they may be “no more evident than a slight discoloration of the mortar joints.” (Morse 1935)

Site plan drawings, photographs and detailed notes on each room were prepared (Ruins Survey 1935). Black and white clothesline cords were used to distinguish intact

original wall areas from rebuilt or repointed wall areas. Cord was placed surrounding the two smaller types of areas, isolating the third and largest type area (Figure 9).

Monthly ruin repair reports provide detailed accounts of the problems at the site. In his September 1934 report, Morse wrote.

...more than twenty weak or fallen spots were replaced or strengthened among the interior walls of the Pueblo. Some of these places were very deceptive. Where only a few loose stones showed in the face courses of the masonry, their removal revealed great cavities behind, sometimes reaching to the opposite veneer of the wall. Plugging of such holes took much more time than was anticipated... (ibid)



Figure 9. Room 5 North Wall in 1934 before Stabilization (Markely 1934) MVRC

The Ruins Survey report, written by Robert Burgh, identified several causes of wall deterioration. It is interesting to note that he found no damage at the base of the

walls despite constant contact with snow for several months of every year, an observation contradictory with earlier reports. However, his analysis on the performance of the capping is significant.

The upper courses of stone in the walls have been somewhat affected. The direct striking of rain on the surface washes the chinking from between the joints and the lack of stone to stone contacts causes the walls to slump. In places where the concrete capping is cracked or fallen water has penetrated into the interior of the walls. This results in the washing away of clay mortar, and the spreading of the poorly tied walls by the action of freezing. (Burgh 1935: 5)

The report further identifies that rat tunneling of the wall interior as well as tourists walking on top of the walls are significant threats to the wall stability. In addition, mechanical damage by plant roots as well as water penetration through the channels made by roots were considered deleterious to the ruin.

Perhaps the biggest challenge to the stability of the site was its foundations. The study found that the whole site was built on top of unstable soil, especially toward the west side. Built on a huge refuse mound comprised of ashes and rubbish, the walls have settled and slumped outward, necessitating the construction of supporting structures by Ancestral Puebloans. Current investigation by Park archaeologists suggests an earlier construction phase below.

The unstable walls identified were stabilized by Al Lancaster with the help of Navajo workmen led by Sam Akea (Lancaster 1935) (Figure 10). For unstable walls, stones were taken from the wall while the clean stone surface was sprinkled before resetting the new stones in cement mortar. The cement mortar was prepared with 1

part Portland cement to 3 parts Shiprock sand. The joints were raked 3/6" for pointing with local mud and spalls. For walls two stones or more in thickness, the stones on the outside course were set in cement mortar, while the stones on the inside courses were set in mud. The inside courses were bonded every three feet with a header tied in cement mortar.



Figure 10. Room 5 North Wall in 1934 after Stabilization (Markely 1934) MVRC

In addition to structural and surface problems, the aesthetic concern in choosing the repair materials continued to be an issue. In a letter to Nusbaum, Morris mentioned the effort to secure the formula for adobe-colored cement (1934). Due to the lack of funding, he wrote, the team instead decided to employ a flat paint custom made by Florman Company. He revealed that there was an attempt to paint a textured cement

plaster on the walls. The team repaired and rebuilt parts of the site and recorded in detail the extent of their work.

In 1940, the Director's Committee on Ruins Stabilization, held in Santa Fe, New Mexico, prepared a report after serious discussions on the status of the ruins led by Jesse L. Nusbaum, Senior Archaeologist of Region III and others, including Erik K. Reed, Dale S. King, Lyle Bennett, A.R. Kelly, and Edmund F. Preece.

Citing the uncontrolled excavation programs by Fewkes from 1908 to 1923 at Mesa Verde National Park, the committee faulted the lack of adequate stabilization of newly excavated sites as the reason for terminating the Fewkes program (Report of the Director's Committee on Ruins Stabilization 1941). Nusbaum was acutely aware of the continued falling walls at Far View House, observed only three years after the stabilization work (Letter to Franke 1937). The cement capping by E.H. Morris at various sites in the Southwest was soon discovered to be "unsatisfactory as regards preservation and obnoxious as regards appearance." (1941: 6) These caps were removed and replaced at Pueblo Bonito but the report does not indicate whether this was the case for all the sites that received such work. The report prompted an active materials research program into soil-cement for use as a repair mortar for archaeological sites in the Southwest Region. This eventually became an integral part of the NPS Southwest Region stabilization program until 1976. Other new synthetic materials such as silicone ester were also mentioned.

Despite these efforts, the saturation of walls with water and eventual collapse continued to undermine the integrity of Far View House well into the 1940's. The 1942

report mentions the collapse of a wall after the earth fill between the walls became saturated during the heavy rainy season in 1941 (Complete Report on the Ruins Stabilization Program). Cement mortar was washed away as well. The fallen stones were re-laid in cement mortar and repointed with soil mortar. A cement trough was constructed on top of the fill to provide more rapid drainage and reduce saturation. The entire west wall and other select areas on the north and south walls were repointed with soil mortar. In addition, all loose cap-stones were reset in cement mortar.

The ruins stabilization record prepared by Al Lancaster in 1950 again refers to the chronic problems of leaning walls and disintegrating basal stone courses. Lancaster ascribed the damage to the design of the wall and the ready availability of moisture.

Most of the walls were double-coursed, with a dirt or rubble fill. Water entering at the top has washed this fill away, leaving some of the walls hollow. Since the two faces of these walls were seldom tied together this loss of fill in the corner constitutes the greatest threat to their stability. (1950: 2)

The use of cement continued during Lancaster's almost annual minor repairs. It was used in stabilizing the walls to secure adjoining walls after pulling them back using rods and turnbuckles (ibid. 2). Resetting loose stones and repointing open joints with mud or cement continued. Fewkes' caps were left alone to do the temporary job of protecting the wall tops, although Lancaster recommended removing them all and recapping the walls. All Portland cement was colored to match local soils.

Between 1964 - 1976, Al Decker was actively engaged in stabilizing Far View House. The use of Portland cement continued. Walls were repointed using soil cement mixture of white and red mineral soils, Portland cement Type I/II, sand and cement

coloring. In 1964, a metal drainage system of unknown description was installed in the walls of the interior rooms (Fiero 1983). In order to improve drainage, a plastic membrane was installed below the floors in 16 rooms and 3 kivas. The stabilization report in 1976 mentions a minor rock spalling at the base walls of the kivas in the fall. It attributed the damage to freezing of water absorbed during late spring and summer. Stones were reported to be replaced.

In 1983, after a long period of minor repairs, Kathy Fiero conducted major repair work between May and September of 1983. While detailed documentation is lacking for each room, photographs of every room before and after intervention provide a good record of conditions of the site. Eroded repointing, unstable walls, capstones and clogged drains led her team to engage in an extensive repair campaign during the summer. The following was done:

1. *All walls in the ruin were repointed*
2. *Six walls were partially rebuilt*
3. *Eroded and missing stones were replaced*
4. *Loose stones were reset in soil cement or Rhoplex mortar*
5. *Cap stones were reset in cement mortar*
6. *Drains were cleaned and repaired*
7. *Subfloor black plastic membrane was removed and replaced with Mirafi[®] geosynthetics*
8. *A concrete cap on the walls of two kivas and three rooms was removed and replaced with flagstones*

Soil cement was applied as repointing material in kivas A and B, Rooms 1-5, 7, 13, 25, 27, 30, and 40. It consisted of 7 parts soil, 3 parts sand, 1 part white Portland cement, and Tamms Colorant 3311 Medium Buff. Amended mud mortar consisted of 3 parts sand, 2 parts yellow soil, 1 part red soil, and water/Rhoplex E330 mix (4.5 parts

water to 1 part Rhoplex E330). Cement mortar consisted of 4 parts sand, 1 part white Portland cement with a colorant (Tamms Colorant 3621 Desert Tan) (All parts by volume). Soils came from sources nearby the site: red soil was from the heliport area, yellow soil from the south end of Chapin Mesa, and the sand from Mancos, Colorado.

In areas where the walls had to be rebuilt, Fiero observed that the use of concrete mortar for repointing prevented moisture accumulated within the walls from escaping. She suggested that after penetrating through the cracks the trapped moisture subjected the walls to constant frost heaving, slumping and stone erosion.

She had also discovered black plastic sheetings buried about 3 inches below the floor of 16 rooms and kivas that were installed in 1964 when metal drains were placed through the walls. While intended to drain water, they also created a constantly moist environment below the plastic. She suspected that they might have accelerated the erosion of the basal stones in the walls of these rooms. She replaced them with Mirafi[®] geosynthetics, a woven geotextile permeable to both liquid and vapor water and air. They were placed in several rooms including Room 28.

Since then, minor repairs have occurred including silicone crack repair and cap replacement. Walls continue to slump and lean; caps crack; and joints open.

4. CONDITION ASSESSMENT

4.1. Test Wall Selection

A test wall for the pilot study was selected meeting the following criteria:

- A compound wall constructed of two veneers and a rubble core with an exposed top surface
- A straight, not curved wall to avoid complications in measuring movement
- Easy access for work
- Evidence of past damage and stabilization campaigns using hard caps

Based on the above criteria, the east wall of Room 13 was selected in August 2008 (Figure 11). In addition to the criteria above, the wall is subject to rising damp and differential fill that further contributes to its deterioration.

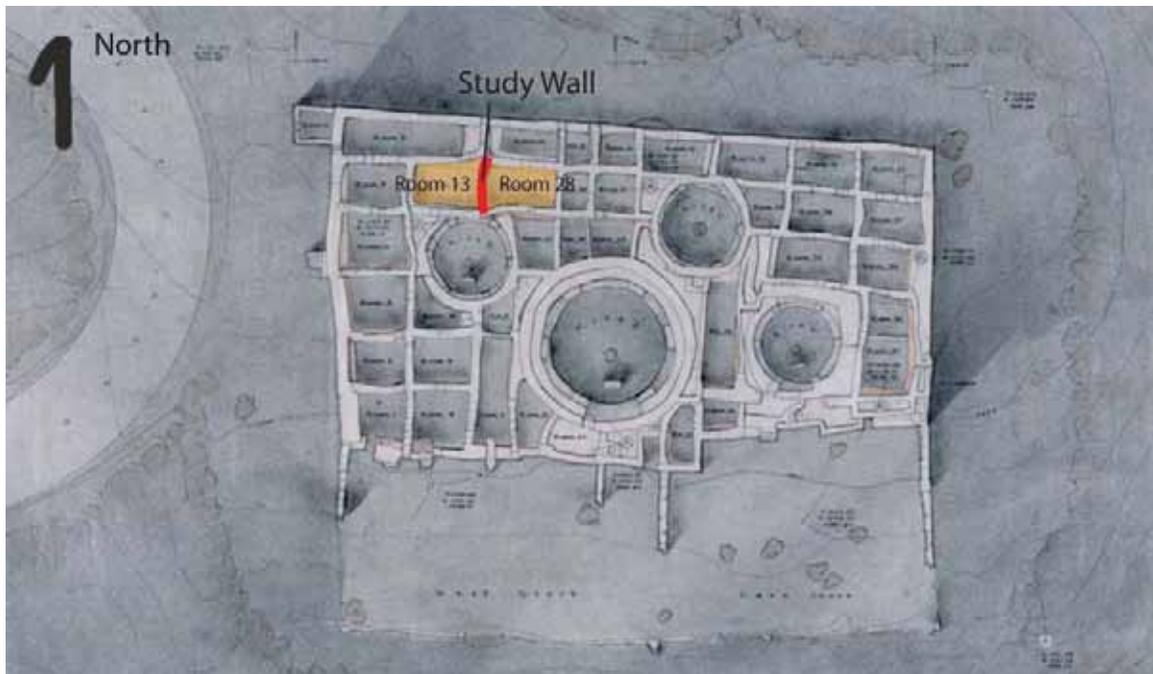


Figure 11. Site Plan of Far View House (Nusbaum 1934) MVRC

4.2. Wall Description

The test wall is of three leaf construction: a double veneer of sandstone masonry with a core of unknown composition, although it is probably soil and rubble fill. The western wall elevation is trapezoidal in shape and faces west and east. To the west is Room 13 with grade level fill; to the east, Room 28 has a differential fill up to the second floor level. The sandstone units are approximately 6 inches wide x 9 inches long x 4 inches high in size, roughly coursed with occasional headers to tie the veneer wall to the core, and laid in their original earthen mortars with various stabilization repointing mortars. Original surface mortar was described in 1934 as “fired black” (Ruins Survey 1934). Recent analysis also suggests they contain ash.

Numerous stabilization campaigns have left a variety of intervention materials. The top of the wall is covered in hard caps of cement and soil mortar. While Fewkes used Portland cement, it is not clear whether later cementitious mortars included other ingredients (e.g., calcium aluminate).

4.3. Past Interventions

Since its excavation, the test wall underwent extensive repairs consisting of part reconstruction and numerous repointing. The comparison of historic photos combined with written reports reveals much about its past intervention history.

While a detailed description of the repair work by Fewkes in 1916 on the test wall has not been found, the photograph taken in 1934 of the west face of the test wall

(Room 13 East Wall) shows three different areas, offering clues to the extent of Fewkes' repair (Figure 12).



Figure 12. Room 13 East Wall in 1934 before Stabilization (Markely 1934) MVRC

The top half of the wall can be divided into two sections, one of rebuilt courses and the other repointed area. Using recycled stones set in cement mortar, Fewkes rebuilt the top courses, and then laid Portland cement cap on top. He also filled the gap between the slumping north wall and the test wall. The other section below the rebuilt top was repointed with soil mortar with some use of chinking stones. The bottom half of the wall, roughly below the Room 28 grade level, shows dense original chinked mortar in stark contrast to the repaired top. Settlement cracks are visible on stones. Viga sockets also remained since the excavation. However, all the wooden members mentioned in 1916 Fewkes report are no longer present.

The comparison to the accounts in 1934 survey report provides additional information. Noting every wall as unstable, the report concludes that the walls were burned, indicated by reddened stones and fired mortar and some uncharred ends of vigas in the beam sockets. Major vigas ran north and south with perpendicular minor vigas running east and west. A refuse silt layer was found beneath the walls. The top courses of all walls show a mixed use of burned and unburned stones, unmatched halves of stone and the use of red mud mortar, all indicating rebuilding. The restoration team plugged the major viga sockets with masonry while minor viga sockets in the east wall of Room 13 remained.



Figure 13. Room 28 West Wall in 1934 before Stabilization (Markely 1934) MVRC

The east face of the test wall (Room 28 West Wall) shows severe structural instability as evidenced by the sloped courses and significant lack of pointing (Figure 13). According to the report, the east face showed no signs of burning. The test wall, along with other walls at the site, was reported to have been either eroded by water or tunneled extensively by rodents, leaving the walls very unstable. The report found no evidence of original wall.



Figure 14. Photo showing Upper Part of Room 28 East Wall (Lancaster 1956) MVRC

After 1934, there exist few photos that partially document the condition of the wall. The one taken in 1956 by Lancaster, in particular, shows the wall top contour changed to a broad U-shape pattern (Figure 14). Except for the north and south ends where the test wall adjoins other walls, the stone courses show significant change compared to 1934 photos. The photo suggests that the rebuilt portion suffered from stone falling or underwent at least one more repair before the photo was taken. A photo by Decker in 1967 also shows a very similar configuration (Figure 15). The wall

pointing is maintained to a minimum, revealing recesses between sandstones. Viga sockets are no longer visible.

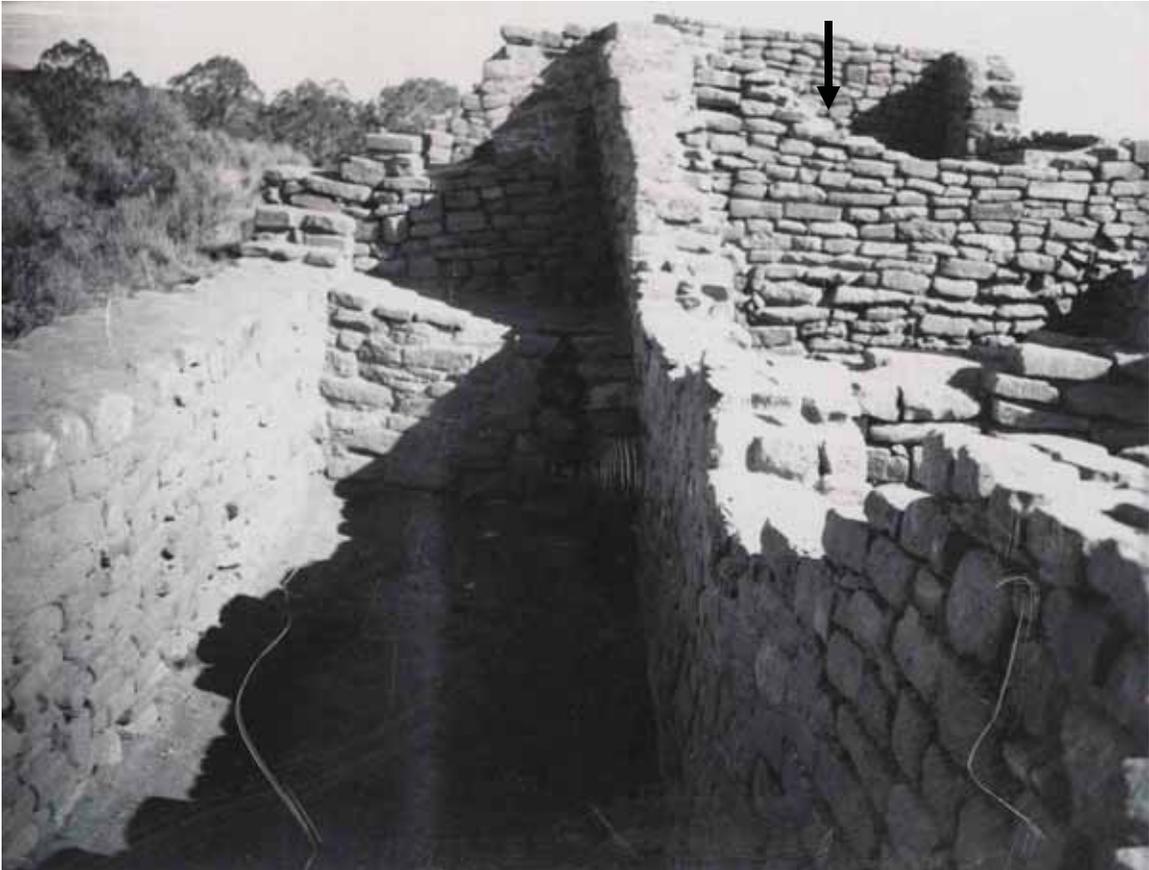


Figure 15. Photo showing Upper Part of Room 28 East Wall (Decker 1967) MVRC

By 1983, most of the chinking stones have disappeared and replaced by a patch work of repair mortar (Figures 16-17). The pointing mortar has eroded, resulting in recesses between sandstones. Overall, the wall retained most of the stones visible on 1967 photo.



Figure 16. Room 13 East Wall in 1983 before Re-Stabilization (Fiero 1983) MVRC



Figure 17. Room 28 West Wall in 1983 before Re-Stabilization (Fiero 1983) MVRC

Between June and September of 1983, Kathy Fiero carried out major repair work at Far View House. The walls, including the test wall, were heavily repointed with soil cement consisting of 7 parts red soil, 3 parts sand, 1 part cement of unidentified source and buff colorant (Figures 18-19). In September, soil mortar mixed with Rhoplex™ E 330 was additionally used for repointing. This replaced an earlier purple mortar of unknown composition and application date. Amended mortar consisted of 3 parts sand, 3 parts yellow soil, and 1 part red soil mixed with Rhoplex E 330 and water in a 1 to 4 ratio for Room 13 and a 1 to 4.5 part ratio for Room 28. About three quarters of Room 13 east wall was repointed during this campaign.



Figure 18. Room 13 East Wall in 1983 after Re-Stabilization (Fiero 1983) MVRC



Figure 19. Room 28 West Wall in 1983 after Re-Stabilization (Fiero, 1983) MVRC

4.4. Current Condition of the Wall

The condition of the site was assessed through field survey in August and December 2008 and subsequent laboratory testing of mortar and stone samples. In addition, photographic documentation taken roughly every two months established a visual change and weather conditions on the test wall.

4.4.1. Test Wall

As of August 2008, the test wall showed significant bulging and displacement toward Room 13 in the lower half of the wall below the level of lateral fill in Room 28 (Figure 20). The enlarged joints, cracked repair mortar (1984), vertical cracks on the

sandstone, and the deformation of the wall into a convex shape all indicate that the bulging has been active since at least 1934 and is still active posing a serious problem to the stability of the wall.



Figure 20. Room 13 East Wall in 2009 (Hovezak 2009) (Note: Red circle indicates bulging)

In addition to bulging, the bottom courses of masonry at grade exhibit stone erosion and disaggregation as well as detachment of repointing mortar, resulting in smaller weathered units and open joints. In the middle of the south part of the wall, recesses have again begun to appear approximately the same level as the differential fill in Room 13. The area of basal erosion roughly follows the edges of standing snow in winter and therefore is water related. Some of the detached mortar is still visible at grade level. Ground vegetation, discoloration by lichens, and dark brown spots resulting

from the oxidation of ferrous minerals suggest that the area remains in contact with moisture for a prolonged period of time.

4.4.2. Materials Characterization

In order to understand the performance of the test wall, masonry samples were taken to the Architectural Conservation Laboratory at the University of Pennsylvania for physical and chemical analysis (Tables 1-3).

Table 1. Far View House Original Building Materials Properties

Sandstone	Test Results	Test
Color	Brownish Yellow 10yr 6/6	Munsell Soil Color Chart
Texture	320 grit, fine	The Matero Texture Calibration System
Hardness	1.5-2.5	Mohs Hardness Test
Density (g/cm ³)	1.79	ASTM C97-96
Porosity (% volume)	21.98	Normal 7/81
Water absorptivity g/(cm ² sec ^{0.5})	0.0648	Normal 11/85
Drying (g/(cm ³ hr))	0.022	Normal 29/88
Frost resistance	High	RILEM Test No V.3
Modulus of rupture, Dry (psi)	414	ASTM Standard C99-87
Modulus of rupture, Wet (psi)	181	ASTM Standard C99-87
Modulus of rupture, After Frost (psi)	187	ASTM Standard C99-87
Dry-wet strength ratio	2.285	
Compressive strength, dry (psi)	2650 (//), 2220 (L)	ASTM Standard C170-90
Compressive strength, wet (psi)	1950 (//), 1210 (L)	ASTM Standard C170-90
Dry-Wet Strength Ratio	1.4 (//), 1.8 (L)	
Soluble salt	Sulfates	Ion Strip (Merck)
Original Soil Mortar		
Color	Brown, 7.5 yr 5/4	Munsell Soil Color Chart
Hardness	1.5-2.5	Mohs Hardness
Plastic Limit (%)	20	Atterberg Test
Liquid Limit (%)	34	Atterberg Test
Plasticity Index	14	Atterberg Test
Soluble salts	Nitrates	Ion Strip (Merckoquant®)

(//: Parallel to rift, L: Perpendicular to rift)

Table 2. Far View House Original Building Materials Comparison

(Blue: Sandstone, Original Mortar: Orange)

Type	Characteristics					
Physical	HARDNESS	High				Low
	DENSITY	High				Low
	POROSITY	High	Orange	Blue		Low
	ABSORPTIVITY	High	Orange	Blue		Low
	DRYING	High	Blue	Blue	Orange	Low
Mechanical	FROST RESISTANCE	High	Blue	Blue		Low
	MODULUS OF RUPTURE, DRY	High		Blue		Low
	MODULUS OF RUPTURE, WET	High				Low
	COMPRESSIVE STRENGTH, DRY	High		Blue	Blue	Low
	COMPRESSIVE STRENGTH, WET	High			Blue	Low
Chemical	SHEAR STRENGTH	High		Orange		Low
	SOLUBLE SALT CONTENT	High	Orange	Blue		Low
	CLAY CONTENT	High	Orange	Blue		Low
Thermal	ALBEDO	Dark		Orange		Bright
	THERMAL CONDUCTIVITY	High		Blue	Orange	Low

(Based on a table by S. Harris)

Table 3. Far View House Mortars

Name	Soil Mortar #1	Soil Mortar #2	Current Joint Repair	Cement Repointing
	3" under Modern Repair	3"-8" from Surface. SW lower corner. 6th Course from Grade		Upper Core Bedding Mortar
Surface Appearance	Fine fibrous organic material, burnt charcoal, fine white particles	Fine fibrous organic material, burnt charcoal, fine white particles	White angular, coarse grains, brown and black sub-round, coarse grains	White particles, other dark gray and brown particles
Overall Color	Brown 7.5 yr 5/4	Brown 7.5 yr 5/4	Reddish Yellow 7.5 yr 6/6	White 2.5 yr 8/1
Texture	Fine, 320 grit	Fine, 320 grit	Medium. 80 grit, some 30 and 120 grits	Medium. 80 grit, some 30 grit
Hardness	1.5 -2.5. pale yellow finger nail scratch	1.5-2.5. pale yellow finger nail scratch	1.5 - 2.5. pale yellow finger nail scratch	7. white streak by steel knife

Based on the results of the testing program, the following observations can be made about the building materials from Far View House:

4.4.2.1. General:

1. The sandstone readily absorbs water and dries rapidly.
2. The sandstone has high frost resistance when not restricted.

3. The sandstone significantly loses strength when water saturated. This has significant implications for sandstone walls, since wetting under lateral pressure can lead to ruptures, compromising the stability of the wall structure.
4. The sandstone that has undergone cyclical freeze/thaw loses flexural strength. However, its modulus of rupture is very similar to that of wet samples, indicating that cyclical freeze/thaw has not affected the sandstone structurally.
5. The sandstone does not undergo severe reduction in compressive strength even after wetting. The sandstone performs relatively well under compression.
6. The clay content of the original soil mortar has high shear strength as demonstrated by its low to medium plasticity index. When combined with fibrous organic materials, the soil mortar complements the sandstone's compressive strength by imparting good shear and tensile strength (Houben and Guillaud 1994).

4.4.2.2. Sandstone:

4.4.2.2.1. Porosity

22% open porosity of the sandstone falls generally within the documented range for sandstones. Fitzner reports the use of sandstones with open porosity between 18% and 23% (1994: 53). Valdeon records an even higher number at 27% for sandstones used in Spanish building stones (1992: 912). High porosity indicates that the sandstone has a high capacity for water. When the stone surface available for draining or drying is reduced, blocking easy exit of moisture liquid or vapor, the high porosity and

permeability will have a negative impact on the durability of sandstone through cyclical freeze/thaw. High porosity also indicates easy penetration by soluble salts into the core and most certainly on surfaces. Therefore, high porosity sandstones are vulnerable to salt crystallization.

4.4.2.2.2. Absorption and Drying

The high absorption rate of the sandstone at Far View House indicates that when subjected to moisture, either as rain, melting snow, or rising damp from the ground, sandstones are likely to become saturated. The initial phase of absorption results from large pores absorbing water fast. The graph levels off after all the large pores have been filled, but the water absorption continues to rise at a significantly lower rate. This is due to the presence of small pores. However, compared to the volume of large pores, small pores take up a relatively small amount of water. Equally important, the test shows that sandstones dry rapidly. Since the temperature, air circulation and the surface area of the samples determine the drying rate, when tested *in-situ*, wind and heating from sun will accelerate the drying rate.

4.4.2.2.3. Frost Resistance

The comparison of the samples before and after the test shows that there is no significant damage to sandstone samples within the given cycles and time frame. While the overall color of the stone prism lightened, there is no evident disintegration of

grains on the surface. Dark brown spots became quite visible on the surface, similar in color to the bedding lines.

The lack of noticeable volumetric change indicates that the sandstone is quite resistant to the cycles of freeze/thaw when not restrained. The test result coincides with other reports that observed sandstones not easily experiencing damage from repeated freeze/thaw (Turkington 2004).

A cyclical freeze thaw induces the build up of internal pressure from the expansion of ice crystals. When liquid water freezes, it arrests the vibrating water molecules into a static state. As water molecules line up in order, the volume of water increases. When the sandstone is restricted in expansion, this volume expansion translates into internal disruptive pressure on grain bonding.

Based on the absorption data that suggests the presence of large and small pores, the sandstones from Far View House fit the characteristics of sandstones that are fairly resistance to frost. The porosimetry of the sandstone is most likely the reason why this deterioration does not occur. Torraca pointed out that it is the pore structure, not the total volume of water inside a porous stone, that affects the damage by frost action (1982: 31). In the case of the sandstone at Far View House, water can enter and exit the system easily. The intensive pore network with varying degrees of pore radii allow easy movement by the water molecules into, through, and out of the system (Thomachot and Jeannette 2002). As a result, the unfrozen liquid water can escape and does not contribute to the build up of pressure.

The discoloration of the samples --- notably a dulling with dark grains appearing on the surface can be explained as the oxidation of ferrous minerals present in the sandstone from the cycles of wetting and drying.

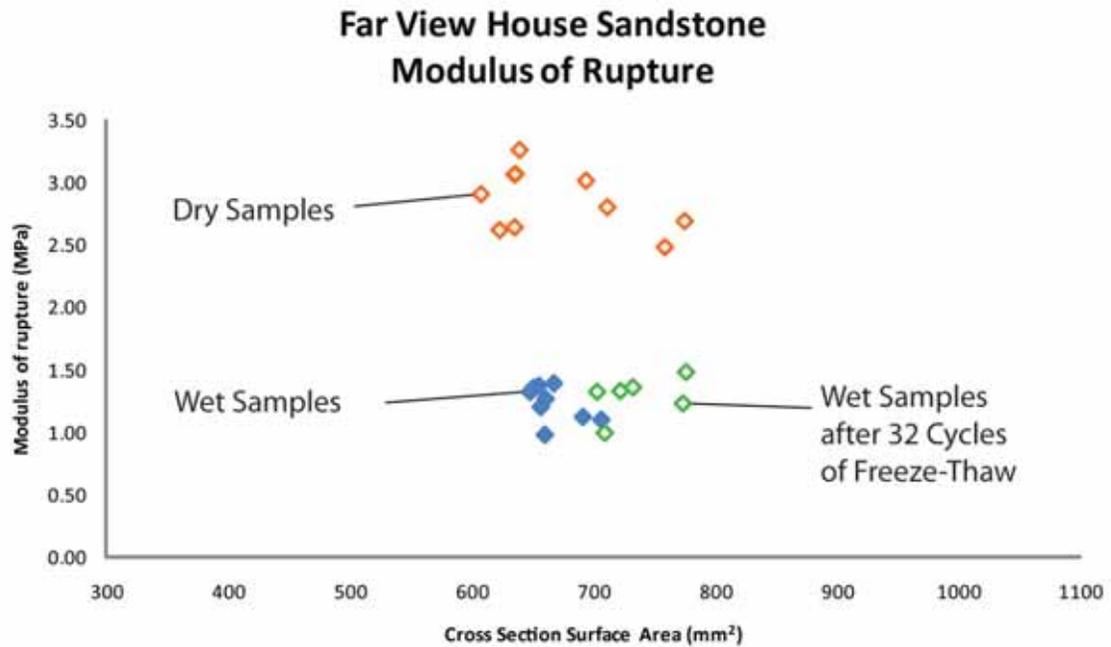
The high resistance to frost, however, does not explain the deterioration of the basal stone and mortar. The east wall of Room 13 shows the detachment of repair mortar and disaggregating stones where snow collects throughout winter.

The cause for this deterioration could be the sudden hygroscopic expansion of the clay minerals in spring from melting snow or salt crystallization of soluble ground/burial salts through repeated wetting and drying cycles. Sulfates were found in the stone and soil-cement repointing suggesting gypsum contamination from the Portland cement. Nitrates were found in all archaeological materials – mortar and soil fill – suggesting organic remains.

4.4.2.2.4. Mechanical Strength

The strength test shows that the sandstone becomes weak when saturated. In particular, the flexural strength of the wet samples was approximately one third that of the dry samples (Graph 2). When a saturated sandstone is subjected to force parallel to its bedding plane, it is more likely to rupture. The dry to wet strength ratio for flexural strength is 2.285. The inclusion of clay minerals in the sandstone especially seems to have weakened the bond strength (Winkler 1997: 52). The repeated freeze/thaw did not affect the modulus of rupture of the wet samples. The compression tests of the dry

stone showed similar compressive strength compared to the wet samples with dry to wet strength ratio of 1.4 for compressive force parallel to its bedding plane.



Graph 2. Modulus of Rupture of Far View House Sandstone

4.4.2.2.5. Soluble Salts

The positive detection of sulfates and nitrates is significant in providing necessary conditions for deterioration by salt crystallization. Overall the soil samples showed higher salt contents than the mortar samples. The difference may have resulted from water dissolving soluble salts available in the mortars and concentrating them in the soil over time.

The detection of nitrates in the original mortar taken from the lower right corner of the west face of the test wall is understandable based on the presence of organic

materials in the original soil and the subsequent burial deposits. NO_3^- ions present in all of the samples except in the cement mortar most likely have come from bio-organisms.

The presence of sulfates in sandstone and cement repair mortar is not surprising given the use of soil cement mortar as Portland cement contains gypsum ($\text{Ca}_2\text{SO}_4 \cdot 2\text{H}_2\text{O}$). The calculation shows that 1.36 % of calculated CaSO_4 is very close to 1.34 % of total concentration, suggesting sulfate ions may have come from clinker materials used in Portland cement. Further tests for cations would point more clearly to the type of salts that could crystallize out upon water drying.

4.4.2.3. Mortars:

4.4.2.3.1. Atterberg Tests

Plasticity Index is a measure of soil strength as well as soil swelling. The sample of original mortar has a medium range PI of 14 which indicates that the soil has high shear strength and a low to medium expansion potential. Since the original soil contains fibrous organic materials giving tensile strength to the mix, the use of soil-based repointing provides plasticity to easily rupturable sandstone masonry wall. The resistance to lateral pressure derives mainly from the performance of the original soil mortar repointing when wet either during burial or after excavation from rising and falling damp. It also suggests that the use of hard caps and other less inelastic repointing materials has not taken into account the behavior of sandstones and the

environmental pattern that provide moisture and thermal energy that activate various deterioration mechanisms.

4.4.3. Summary

The laboratory tests show that the sandstone and original soil mortar are compatible building materials. Despite their susceptibility to moisture absorption, when properly managed, they are well suited for the type of climate at Mesa Verde National Park. The fast drying rate compensates for fast absorption of water, since it rapidly reduces the amount of water retained by the wall in the dry climate. The soil mortar also should exhibit fast drying aided by fibrous additives that wick moisture and accelerate drying. In addition, the soil mortar provides shear and tensile strength to the wall system made of sandstones with relatively strong compressive strength but otherwise weak in tensile strength.

The use of cement based mortars, however, seems most likely not to be compatible with the original building materials. They are brittle and not as plastic, very likely introduce damaging salts, and expand differently when exposed to moisture. While they do not appear to be the cause of any damage to the sandstone, they display poor retention.

4.5. Analysis of Existing Conditions

The laboratory analysis on hygroscopic behavior of the wall materials indicates several deterioration mechanisms may be simultaneously at work. Based on the field

and laboratory assessment of the wall, the following symptoms and their sources are listed.

4.5.1 Symptoms

4.5.1.1. Crack Formation and deformation

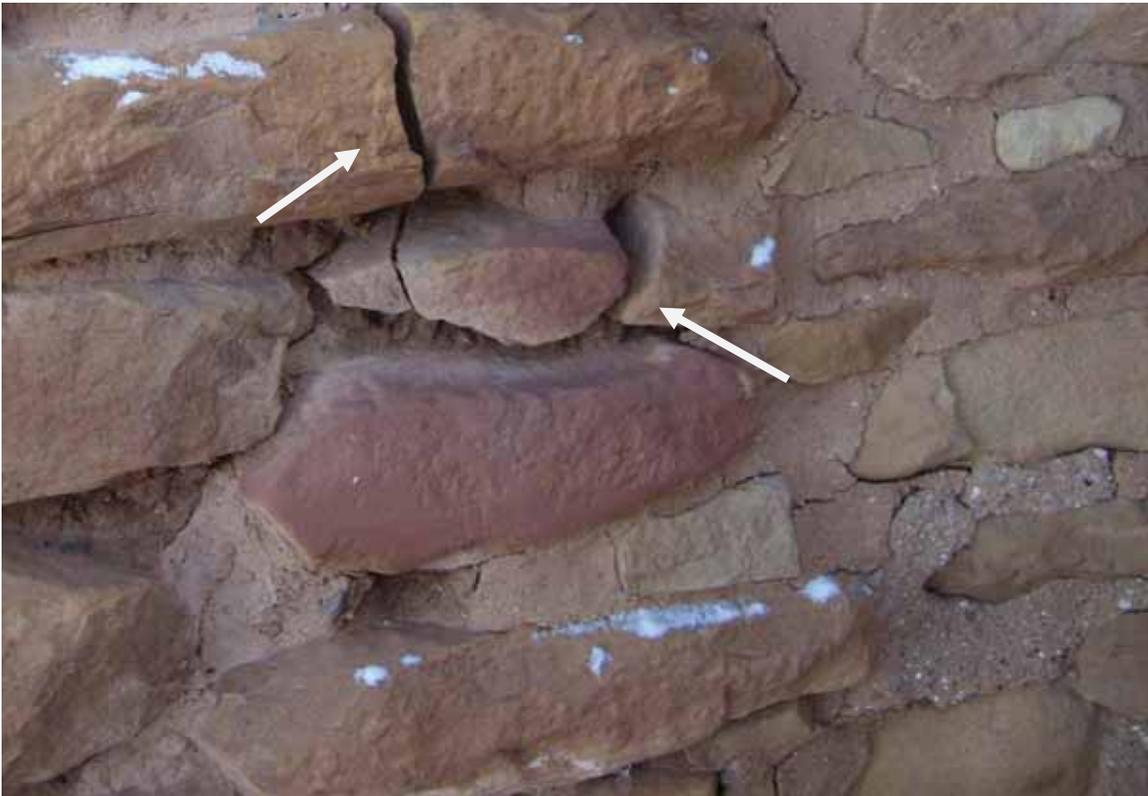


Figure 21. Enlarged Cracks (Lim 2008)

Cracks accelerate the rate of water entry into the wall system and interrupt the structural continuity of the wall assembly. There are several ways cracks may develop. The lateral pressure from the fill in Room 28 on the sandstone wall has contributed to the development of cracks and opened joints in the masonry units (e.g., step cracking) (Figure 21). Microcracks may also develop leading to increase in the number of pores,

further weakening the wall (Torraca 1988: 21). These are most prevalent in the area of greatest lateral force where the wall bulge occurs. The shrinkage of soil mortar also leads to mortar cracks and open joints (Alva 1984: 52).

A comparison of historic photographs with current conditions indicates that some of the vertical cracks observed today had already existed in 1934. While some of these cracks may be inactive, others are clearly enlarged and extended in length suggesting that the wall may be displacing as a result of lateral forces from the fill and renewed sources of water entry from open cracks in the hard caps and sides of the wall top.

4.5.1.2. Mortar Detachment

Unlike the original soil mortar that could wick moisture away from the sandstone masonry and tolerate change in shape and size due its plasticity (Harris 2001: 91), Rhoplex™ modified repair mortar exhibits less permeability to water and less flexibility. When combined with cement repointing that shows much less permeability to water and flexibility, the result appears to be the detachment and loss of mortars and open joints (Figure 22). With standing snow continually feeding water to the wall top and base, the pores become saturated. Rhoplex and cement mortar that do not allow water to escape easily, and the internal disruptive pressure that builds up either through expansion of ice crystallization or through hygroscopic expansion of clay minerals leads

to eventual bond failure. The soil-based mortars would deform until they reach the critical moment before bond failure.



Figure 22. Loss (Lim 2008)

The volumetric change of soil mortar is likely active. Soil mortar joints are vulnerable to loss from increased levels of moisture that leads to hygroscopic expansion (McKee 1973: 61). The continued loss of the surface mortars is translatable to the loss of shear strength of the wall, particularly when each stone does not contact each other. Without the soil mortar that provides shear and tensile strength, the wall is at serious risk. Again, continued monitoring is critical in understanding wall deformation.

4.5.1.3. Granular Disintegration

Surface loss of sandstone is most severe on the base of the wall and in association where the mortar has detached. Stones at the wall base are visually smaller in size from overall surface and granular disintegration is visible. This is most likely due to salt crystallization.

4.5.1.4. Discoloration



Figure 23. Discoloration (Hovezak 2008)

Red, purple and even dark sooted stone discoloration indicates past burning prior to excavation (Figure 23). Various repair campaigns have recycled these building blocks in non-original locations.

4.5.2. Deterioration Mechanisms

4.5.2.1. Lateral Load Pressure

Soil fill in Room 28 at a higher floor level exerts significant lateral pressure on the test wall. As a result, the wall experiences tensile stress on the opposing face. The force easily overcomes the tensile bond of the soil mortar as well as the interface between the stone and the mortar.

4.5.2.2. Salt Crystallization

Salts, both internal and external to building materials, are dissolved in water, transported and recrystallized within and on the masonry surfaces (Charola 2000: 328-330; Price 1996: 7-9). Salts crystallized under the surface of the stones exert volumetric pressure from inside resulting in spalling at a macroscale. Microscopically this may cause granular disintegration or blistering as well.

4.5.2.3. Hygroscopic Expansion

Clays in the sandstone and soil mortar expand when they absorb water (Torraca: 1988: 96). The sudden increase in volume by hygroscopic expansion of the mortar in

spring months may lead to dramatic mortar detachments. A rapid water absorption and desorption and resulting volume change puts extensive pressure on the bond strength between mortar and sandstone, and when unopposed by gravitational loads of the surrounding construction, mortar will detach itself from sandstone (ibid. 80). This is most pronounced with soil-cement mortar.

4.5.2.4. Thermal Expansion

Minerals and stone expand and contract at different rates given thermal energy. When a wall is a composite system of different materials it may develop differential volumetric change upon cyclical heating and cooling. This results in crack formation and detachment.

4.5.2.5. Salt Hydration

When salts become hydrated by water molecules, they expand. Salt hydration leads to similar symptoms as other deterioration mechanisms by differential volume change.

4.5.2.6. Frost Action

Water expands when freezes. Volumetric expansion from the water to the ice phase, the degree of water saturation, the pore size distribution and the pore connectivity determine the extent of frost action. Stones soaked continuously before freezing are more susceptible than stones which undergo repeated wetting and drying

(Winkler 1997: 253). In other words, the water saturation level of the stone determines the extent of frost damage. The pore size increases after cyclical freeze/thaw (ibid. 256)

4.5.3. Necessary and Sufficient Conditions

Based on the symptomatic conditions observed on the wall, possible deterioration mechanisms were listed along with conditions necessary for such mechanisms to occur. One of the striking features of this is how most deterioration mechanisms require moisture as a necessary pre-condition. Understanding the sources of moisture was deemed critical in formulating intervention strategies.

Table 4. Necessary and Sufficient Conditions

	Water Phase	Temperature Range	Drying	Material	Symptoms
Salt Crystallization	Liquid, Gas	Above Freezing	Yes	High Porosity	Efflorescence, Spalling of sandstone, Detachment of mortars
Differential Hygroscopic Expansion	Liquid	Above Freezing	Not required	Clay Matrix	Swelling
Differential Thermal Expansion	No Water	Not required	Not required	Not required	Microcracks
Salt Hydration	Liquid, Gas	Above Freezing	Yes	Salt	Swelling, Spalling, Detachment

Frost action	Liquid, Solid	Below and above Freezing	Not required	High Porosity	Granular disintegration, Microcracks, Soil heaving
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4.5.4. Moisture Sources

Based on the laboratory testing and in-situ monitoring, the sources of water to the test wall could be summarized as follows (Straube 2002):

- Water run-off from wall tops and faces as rain and melting snow
- Rising damp from ground moisture and fill soil
- Wet mortar during installation

4.5.4.1. Moisture Transport Process

The run-off water from wall tops and faces trickle down along the surfaces of the sandstone and mortar until eventual absorption. Sources may be diverse as rain, melting snow or even by human irrigation. The existing fissures or cracks provide pathways for water to travel. The slope of the wall also affects the direction of water movement. The lack of roofing and sagging of wall has expedited the water run-offs.

The standing snow cap constantly feeds water from the top as it melts. The melting ice trickles down through the porous snow and becomes absorbed. While melting snow may run off along the face of the wall, due to its controlled melting, most of the water is directly concentrated into the surface on which the snow sits. Only when there is a drastic increase in temperature and subsequent overwhelming heat absorption, can melting snow begin to run off the wall surfaces.

The ground soil feeds water into the wall through capillary action. The rate and amount of water entering the wall depends on material porosity, moisture and temperature gradients (Fitzner 1993; Massari 1993; Sereda 1981; Snethlage 1997). In addition, the differential soil fill covering significantly larger surface area than the wall bottom provides ample moisture from the side of the wall. Moisture can move laterally due to pressure, moisture, and temperature gradient.

Wet repair mortars can provide additional moisture into the wall system if it is incorporated into the wall construction without proper drying. Upon mortar hardening, the moisture inside the wall core can get trapped. The evaporating moisture from both wet soil and wet mortar diffuses through voids in porous soil and sandstone. It is adsorbed onto the surfaces of the building materials. It may also condense out as liquid droplets when it lands on a low permeability plane with temperatures below the dew point.

4.5.4.2. Summary

Moisture transport to and within the wall as well as cyclic high moisture content of the various wall materials influence wall conditions significantly. The presence of highly absorptive materials, the lack of protective cover over walls and room floors, the use of incompatible intervention materials that concentrates moistures into the core or sheds water to absorptive wall sides, the severe and fluctuating environmental conditions that provide a constant source of moisture, the disuse of the site, and finally the lack of proper and regular maintenance have all contributed to severe deterioration

of the site. The current building condition calls for an immediate intervention to repair the deformation and address moisture problems.

5. TEST WALL INTERVENTION

5.1. Justification

Compared to the more protected alcove sites at Mesa Verde National Park, the mesa top sites, including Far View House, exhibit serious deterioration from direct exposure to moisture as well as solar radiation and wind. Candidates for likely mechanisms of stone and mortar deterioration include hygric expansion, subsurface salt crystallization (cryptofluorescence), and freeze/thaw cycling. These mechanisms all require moisture. At the microscale these mechanisms cause stone and mortar erosion; at the macroscale, they can result in wall collapse.

Despite the high vulnerability to environmental weathering, there is no easy solution for proper protection at Far View House. With the collapse of the original roofs after an extended abandonment of the site, the pueblo would have been slowly buried with Aeolian deposition, construction debris, and vegetation. While the resultant mounds would have offered some protection to direct exposure, the ground moisture in an aerobic burial environment would have continued to deteriorate both organic and inorganic materials. Excavation in the early twentieth century exposed the remaining masonry and removed the lateral support of the walls provided by the soil fill. In addition, it introduced various mortar caps made of cement to protect the wall tops and

to allow visitors to walk on the walls for viewing. These impermeable caps readily shed water but inadvertently caused basal erosion from high water concentration and poor drainage and when cracked, allowed water to flow into the wall cores, leading to erosion, subsidence, and structural collapse. Although wall capping has been replaced over the years and cracks are repaired, the hard surfaces still shed large quantities of water to the base of the walls or into the core through breaches in the surface. The wall caps do not reduce the volume of water available to the walls through the top, bottom and sides; they merely divert it from the top to the wall faces and concentrate the unabsorbed volume in the soil at the base. Rather, one needs to look at the cyclic wetting and drying of the wall in its entirety to best address the deterioration of the wall by moisture. Soft cap partially addresses the problem by retaining some small amount of water for re-evaporation without entry to the wall system.

Given the environment's severe annual, seasonal and daily temperature fluctuation and water feed from standing snow in winter, it has been hypothesized that the past interventions have more than likely contributed to structural instability while at the same time have required high maintenance. Improvement in the preservation and display of the walls as well as reduction in long term maintenance cost and labor demands consideration of new intervention methods that would better manage water collection and disposal at the site. In order to measure the effectiveness of any new intervention, the performance must be quantitatively compared to that of the existing mortar capping system. Data from materials testing and environmental monitoring

were analyzed to confirm hypotheses on the sources and mechanisms of deterioration and to evaluate the effectiveness of the new intervention techniques.

The test wall allowed manageable diagnosis of the wall condition given the time, resources and access to the site. The plan for a more comprehensive conservation program could then follow based on this initial pilot study.

5.2. Methodology

In order to compare methods for the protection of the wall tops and the prevention of water penetration into the wall core, two types of caps were installed on top of the test wall: a hard mortar and stone cap based on current methods of stabilization, and a soft vegetative cap. Temperature and moisture probes were installed to monitor and evaluate the performance of each cap. In addition, crack monitors were installed to monitor any lateral movement from thermal or settlement sources.

5.2.1. Wall Preparation

Before installing the caps, the wall was stabilized to prevent collapse during work. Shoring was installed to brace the wall bulge before any mortar removal and stone disassembly at the wall top. Once the wall was supported by the shoring, the top four to five stone courses were removed to a level sufficient to install the new capping system. The core and bedding mortars were saved for further laboratory testing.

5.2.2. Cap Installation

Both caps were installed on top of the existing stabilized wall dating from the previous repair campaign. The wall was divided into two sections of roughly equal length, one for the hard cap on the north side of the wall and the other for a soft cap on the south side. The two caps were separated by a water impermeable geomembrane separator (Appendix A).

5.2.2.1. Hard Cap

The hard cap was installed using the same method that has traditionally been used by the Park's stabilization crew. 1 part Quickrete® type N masonry cement to 3 parts angular masonry sand was mixed with an added Colorant (Colortech® # 52) at a ratio of 1 part colorant to 24 parts mortar mix for the stone setting mortar. The wall faces were overpointed with soil mortar amended (all parts by volume) with Rohm and Haas Rhoplex™ E330 at a ratio of 1 part E330 to 2 parts water. The soil mortar is a fine sandy loam blended from local red silt loam (2 parts), yellow clay loam (1 part), and medium to fine masonry sand (1 part). Once the soil mortar foundation was prepared, a sandstone course was laid parallel along the edge of the wall top. Afterward, the gaps were pointed and the wall core was filled with the mortar. In the second course of the reconstructed wall top, an RH/Temperature probe was buried in the mortar and the rest of the courses were prepared using the same method.

5.2.2.2. Soft Cap

The soft cap foundation was prepared using the same soil mortar for overpointing the hard cap. The number of stone courses was the same as the hard cap but the fill materials were different. A 200 ml HDPE geonet layer by Poly-Flex, Inc was first laid to provide reversibility of the system for any future intervention (Figure 24).



Figure 24. Geonet Installation (Matero 2008)

Next the first stone course was laid with an interior buffer zone filled with 0.6 – 1.2 cm grade gravel of approximately 25 – 35 % void ratio to accommodate water drainage. An RH/Temp probe was placed in the gravel. Next, a drainage and separation layer was laid on top of the gravel and the sandstone course using a textured 60mil HDPE geomembrane from Poly-Flex, Inc (Figure 25).



Figure 25. Gravel Fill and HDPE Geomembrane Installation (Matero 2008)

Above this, a single sided 6 ounce per square foot geocomposite by the same supplier was installed consisting of a 200mil geonet facing down and geotextile facing up to prevent soil from accumulating within the net matrix (Figure 26). The layer also functioned as a capillary break. The edges of each geofabric layer were pointed with soil mortar. Additionally two stone courses were laid in soil mortar on the geocomposite layer and the second RH/Temperature probe was installed on top of the geocomposite layer. Weep holes were added using two plastic straws on each side roughly at one third interval at the same level in the soft cap section. The wall core was then filled with

turf consisting of growing medium and local western wheat grass burying the probe.

The cap was then manually watered to ensure the survival of the grass in dry weather.



Figure 26. Geocomposite Installation (Matero 2008)

5.2.2.3. Vegetation

5.2.2.3.1. Choice of Local Grass

Western Wheatgrass (*Pascopyrum smithii* (Rydb.)) was used for the capping after the recommendation by the Park's natural resources staff based on the following criteria:

- Low maintenance

- Drought tolerance
- Weed competitiveness
- Adaptability

Western Wheat grass is a native perennial grass with coarse blue-green leaves and prominent veins (United States Department of Agriculture Plants Database 2008).

Stems arise singly or in clusters of a few and reach heights of 1 to 3 feet or 30 to 90 cm.

The sheaths are hairy and the purplish auricles typically clasp the stem. It has extensive, strong, rhizomatous root systems.

It is known for its high adaptability to soils of varying pH level, relative drought tolerance and extensive, strong, and rhizomatous root systems combined with a few deep roots. Once established, it is very competitive with weedy species. It is very cold-hardy and can grow in partial shade. In addition, it tolerates saline and saline-sodic soils, poor drainage and moderately severe drought.

These factors make Western Wheatgrass ideal for reclamation in areas receiving 12 to 20 inches (300 to 500 mm) annual precipitation. It is also good for erosion control and ground cover due to its low growth form, vigorous sod, and low maintenance requirements. However, it shows slow germination resulting in poor initial establishment.

5.2.2.3.2. Plant Preparation

Since the weather conditions by October 2008 were not conducive to propagation from seeding, mature wheatgrass was removed from a grassy field nearby in Morefield campground and was directly transplanted to the top of the wall as sod

plugs (Figure 27-28). Smaller sized sandstone blocks were additionally laid to give erosion control at the edges of the wall top. Afterward, the soft cap was watered to help with vegetation relocation. Additional hand irrigation by park staff on October 18th, 23rd, 30th, and 31st of 2008 supplied water to the transplanted wheatgrass.



Figure 27. Western Wheatgrass Sod Transplantation (Matero 2008)



Figure 28. Completed Soft Cap (Matero 2008)

5.2.3. Monitoring

5.2.3.1. Moisture Content and Gravimetric Analysis of Mortars

A total of six samples were taken by drill from the repointing upward along the height of the wall, first at 2 inches (5.08 cm) depth and then 4 inches (10.16 cm) to retrieve the wall core soil. Each sample was placed in a metal container and tightly sealed with duct tape to avoid losing any moisture content. The moisture content for each sample was calculated by weighing the sample container before and after drying in an oven in the lab.

5.2.3.2. Temperature and RH Monitor

To record temperature and moisture level change, HOBO® Temperature/RH smart sensors (model number S-THA-M006) by Onset Computer were used. This device measures RH level between 0 to 100% and temperature between 0 and 50 deg C with an accuracy of plus or minus 3%, and plus or minus 4% in a condensing environment. It has a resolution of 0.5% RH at 25 deg C. The reading may drift plus or minus 1% per year and an additional reversible drift of 3% is expected when the average relative humidity is above 70%. The probe responds to change within 5 minutes. It has an operating range between -40 to 75 deg C although its reading loses accuracy at temperature below 0 and above 50 deg C. When the RH sensor becomes saturated, the sensor will read 100% and is hard to dry out the probe once wet. While short-term condensation/ water exposure does not affect at or below 25 deg C, at 30 deg C or above it will lead to permanent positive drift. The effects of condensation/water exposure vary with the length of exposure time, the number and frequency of exposures, and the operating temperature. When the RH sensor is subjected to cyclical exposure to water and air, its terminals will likely corrode, reducing its sensitivity and reduction in RH reading. In an environment with high humidity between 0 and 25 deg C for over 1000 hours, the drift of plus 3% RH will result. The THA sensor is also sensitive to insects, a possibility at least within the gravel matrix.

The data was then stored in HOBO® Micro Station Data logger model H21-002 encased in a Pelican™ Case. The data logger was programmed to record temperature and RH level change every hour. Wires were sheathed in plastic plumbing tubes to

protect them from possible damage by animals. At the same time, each end of the tubes was tightened with a rubber cork and then sealed with adhesive in order to prevent moisture entry from the exterior (Figure 29).



Figure 29. Completed Moisture/Temperature Monitoring System on Soft Cap (Matero 2008)

5.2.3.3. Soil Moisture Monitor

A dielectric aquameter probe, SMA Soil Moisture Smart Sensor model S-SMA-M005 was used for measuring soil moisture ranging from -0.29 to $1.4475 \text{ m}^3/\text{m}^3$ with an accuracy of plus or minus $0.041 \text{ m}^3/\text{m}^3$ or 4%. Its operating temperature is from 0 to 25 deg C. Although the sensor probe itself can operate below freezing temperatures and

above 75 deg C, the data collected at these extreme temperatures is outside the accuracy range. The resolution of the probe is $0.0004 \text{ m}^3/\text{m}^3$ or 0.04%. A value of 0 to $0.1 \text{ m}^3/\text{m}^3$ indicates over-dry to dry soil respectively. A value of $0.3 \text{ m}^3/\text{m}^3$ or higher normally indicates a wet to saturated soil.

For Room 13, the soil was dug about 10 cm deep and the sensor was placed length wise vertically in order to avoid any pressure damage (Figure 30). For Room 28, the probe was buried under a geomembrane found during digging which was approximately 15-20 cm deep. HOBO® Micro Station Data logger model H21-002 received and recorded data from moisture monitor every hour.



Figure 30. Installation of Ground Soil Moisture Probe (Lim 2008)

5.2.3.4. Crack and Movement Monitors

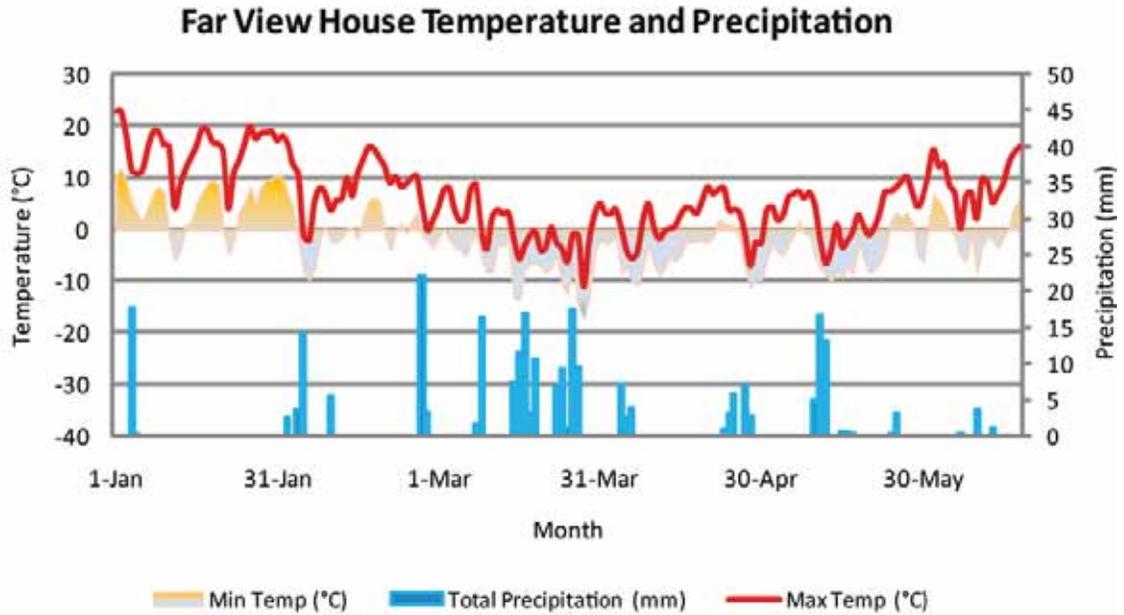
In addition to the moisture and temperature probes, Model 4420 Crackmeter by Geokon were installed on each end of the wall top and across the western face of the wall bulge to measure movement (Figure 31). It operates between -20 to 80 deg C with a resolution of plus or minus 0.1 % F.S. The ends of the sensor are attached to anchors with ball joints, bonded on opposite sides of the crack or target plane. Each anchor was screw fixed to a stone top on each side of the veneer. Model 8002 single channel datalogger by Geokon received and recorded the data from all monitors every hour.



Figure 31. The test wall at the time of data retrieval (Fisher 2009)

5.2.3.5. Weather Station

Since 2005, the weather condition at Far View House has been monitored by the site weather station (Graph 3). It records temperature, precipitation, wind speed and solar radiation. Precipitation is measured by capturing rain and snow inside a white metal container with a tapering top to a calibrated opening. The container holds oil that retards moisture evaporation and antifreeze that melts falling snow. Any weight change is recorded by the sensors. Since the sensors do not distinguish weight increase by trapped bugs or dust from actual precipitation, the contents need constant maintenance by park staff twice a year. Therefore, the reading is effective for measuring individual precipitation events but not good for cumulative precipitation.



Graph 3. Far View House Temperature and Precipitation Oct 08 - Mar 09 (NCDC 2009)

5.3. Observations



Figure 32. Room 13 Eat Wall in December 2008 (Lim 2008)

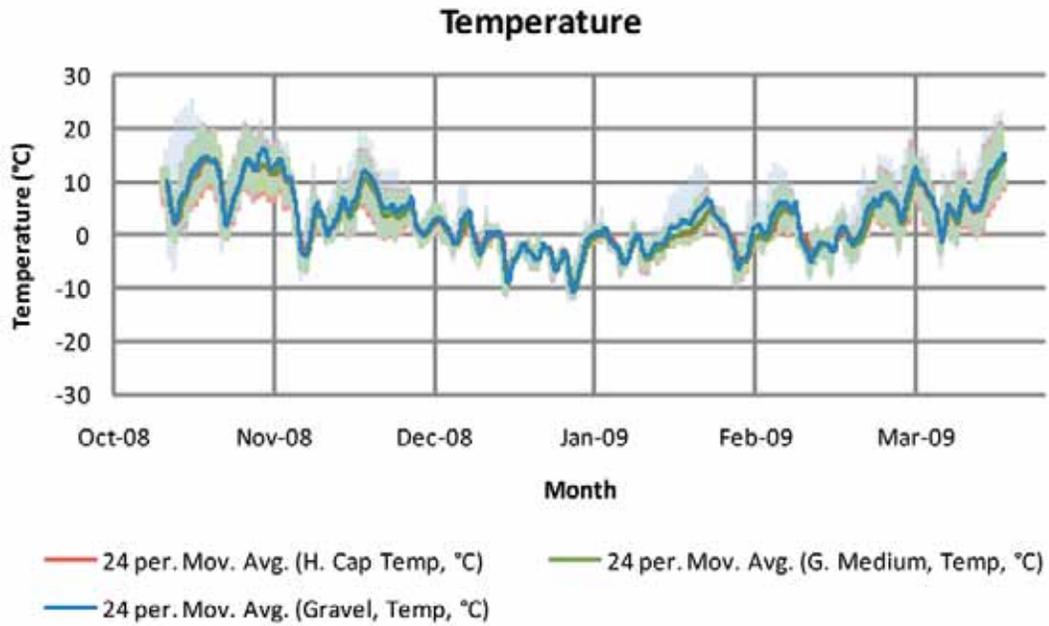
The probes were installed on October 9th, 2008 and the data was first retrieved on March 20th, 2009. These recordings were compared against the weather data from the weather station at Far View House. The lateral movement of the wall tops was also analyzed by installing two crack monitors on October 31st, 2008. The crack monitor installed on the wall face with epoxy fell due to the friability of the stone surface and was reinstalled with screws on November 6th, 2008 (Figures 32-33).



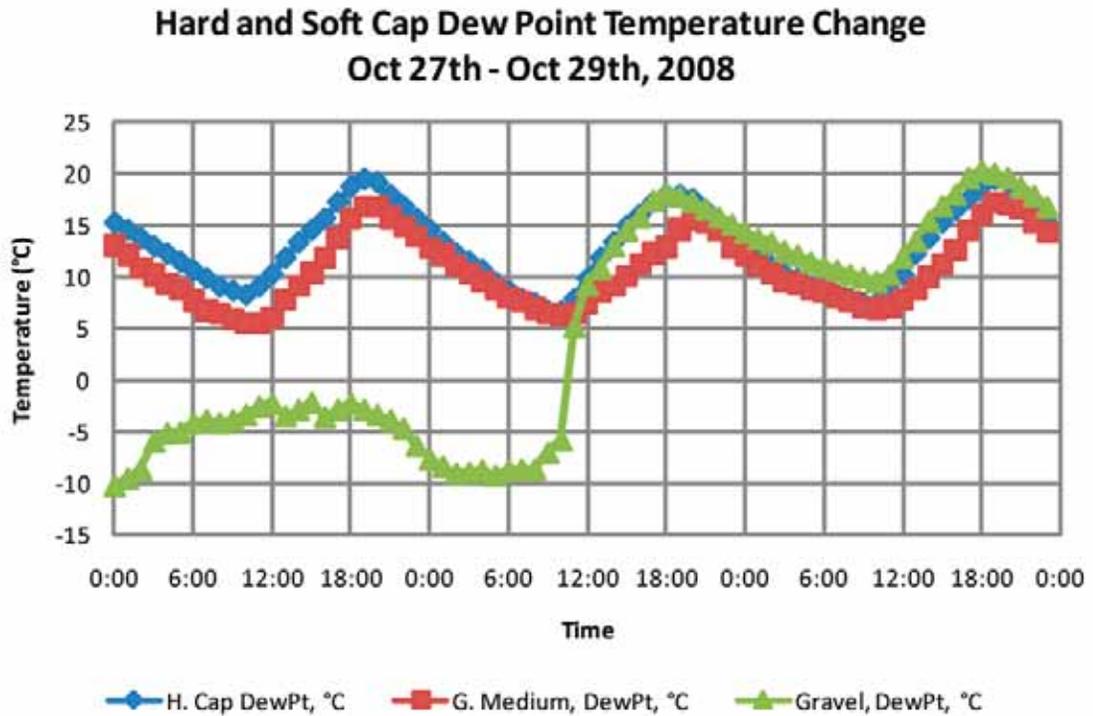
Figure 33. Room 28 West Wall in December 2008 (Lim 2008)

5.3.1. Temperature

The temperature recorded by all monitors show very similar patterns (Graph 4-6). The temperature data for the hard cap displays a broad U shape pattern with a range from mid 10 deg F to 70 deg F. The soft cap growing medium follows a similar pattern and range as the hard cap, but takes on a slightly more stretched U shape with less daily temperature fluctuation, especially in the fall and spring. The soft cap gravel fill yielded in general the greatest daily and seasonal temperature range, most pronounced in the fall and spring.

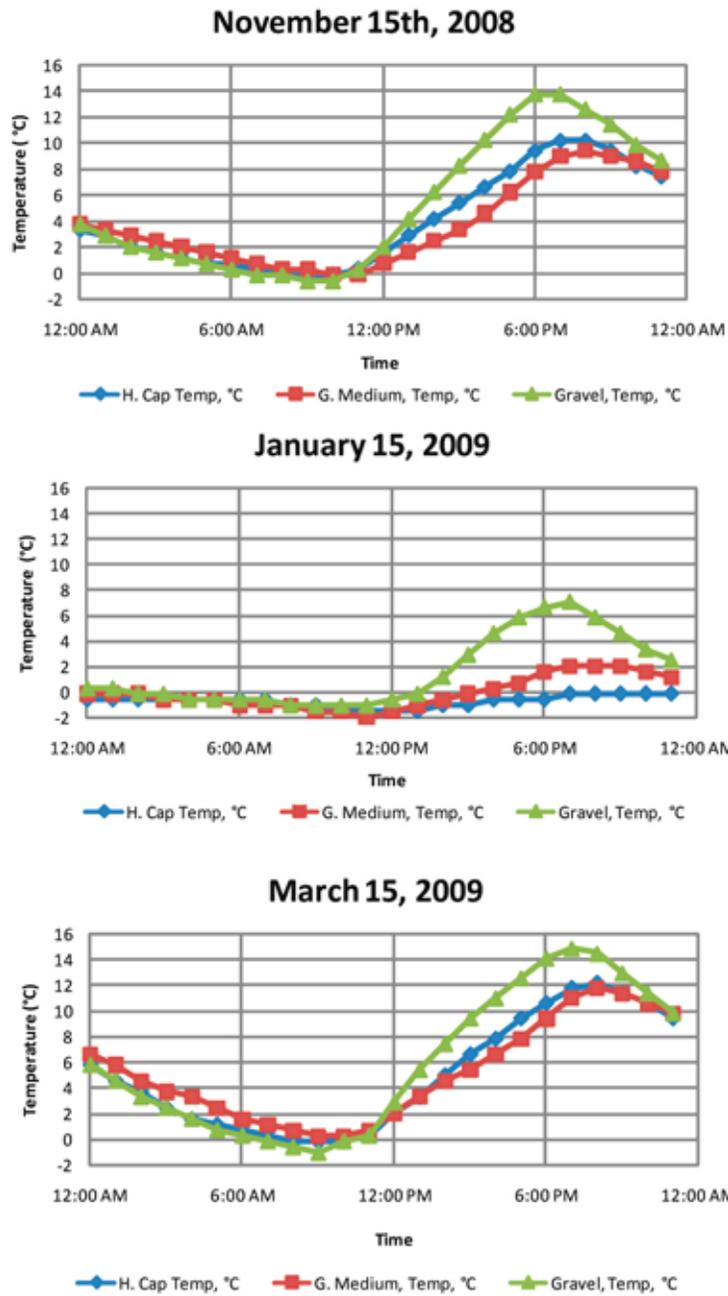


Graph 4. Hard Cap and Soft Cap Temperatures (Oct 2008 – Mar 2009)



Graph 5. Hard and Soft Cap Temperatures (Oct 27-29, 2008)

Daily Temperature Change of Hard and Soft Caps



Graph 6. Daily Temperature Change of Hard and Soft Caps

5.3.1.1. Hard Cap

In October, the wall temperature stabilized to the environmental equilibrium as shown by the great daily fluctuation. The temperature ranged from -5 deg C to mid 20's, covering about 35 deg C change in one month. There was a major temperature drop around October 22nd which soon recovered to mid 10's. The temperature fluctuation decreased by the end of October and remained around mid 10's.

In November, the temperature mostly read below 10 deg C. During the first ten days of November, the temperature dropped to near -10 deg C from upper 10's. The temperature gradually recovered to 10's by the mid November but the remaining week showed the gradual and permanent drop in temperature below freezing.

In December, the temperature mostly remained below 0's as it continued to drop to -10's. On few occasions the temperature reached below -10's. The change in temperature during the days did not fluctuate as much compared to the previous months.

In January, the temperature began to slowly ascend to freezing and reached slightly above freezing by the end of the third week. The daily temperature fluctuation began to increase again after the second week of January. The fourth week showed a drastic drop in temperature to -10's but it soon recovered to freezing. The gradual rise and drop in temperature took about two weeks.

In February, a similar pattern shown in the second half of January was repeated, covering the temperature range between -5 and 5 deg C. By the end of February, the daily temperature range showed greater fluctuation between 0 and 10 deg C.

In March, the temperature crossed the 10 deg C line for the first time since November. The temperature dived to freezing in the first week temporarily but it rose again gradually, nearing mid 10 deg C by the third week. The daily fluctuation of 10 deg C became more pronounced until the time of data retrieval.

5.3.1.2. Soft Cap

Overall, the temperature change inside the soft cap corresponded well with the data from the weather station. In the fall and spring, the daily fluctuation was more pronounced than in the winter when the temperature remained mostly below freezing.

5.3.1.2.1. Soft Cap Gravel

As with the hard cap, the temperature inside the gravel stabilized. The temperature ranged from -5 to 25 deg C, covering about 30 deg C change. There was a major temperature drop around October 22nd which soon recovered to mid 10's. The temperature fluctuation decreased by the end of October and remained around low 10's.

In November, the temperature remained below 15 deg C. In the first ten days of November, the temperature dropped to -5 deg C from 15 deg C. The temperature gradually recovered to low 10's by mid November. Afterwards, the temperature dropped gradually to freezing.

The temperature mostly remained below freezing in December as it continued to drop to -10's. On two occasions the temperature reached below -10 deg C. The

amplitude of the daily temperature fluctuation reduced during this month. By the end of the month, however, the temperature started to rise drastically.

In January, the temperature continued to rise and went past 4 deg C by the end of third week of the month. The daily temperature fluctuation returned after the second week of January. Temperature dropped drastically during the fourth week but it soon recovered to freezing.

In February, a similar pattern shown in the second half of January was repeated, covering temperature range between -5 to 10 deg C. By the end of February, the temperature range showed greater fluctuation between 0 and 10 deg C.

In March, the temperature crossed the 10 deg C line for the first time since November. Afterward, the temperature dived below freezing in the first week. It rose again gradually, passing 15 deg C mark by the third week. The daily fluctuation became more pronounced.

5.3.1.2.2. Soft Cap, Growing Medium

The pattern of temperature change was very similar to the hard cap gravel, except that in general there was an upward shift of a degree or two, a negligible amount given sensor accuracy variations due to wall shadings on the soft cap.

5.3.2. Moisture

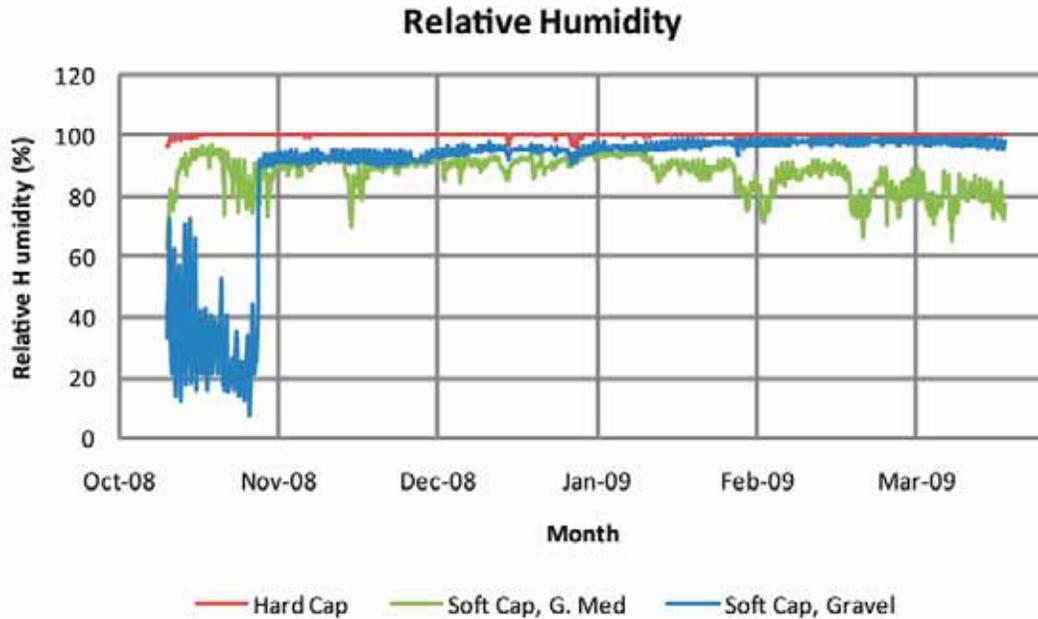
The wall received moisture from precipitation from rain and snow as well as from watering by park staffs. The site received various amounts of snow throughout the winter and on occasion received rainfall when the temperature was high enough.

5.3.2.1. Gravimetric Analysis

Gravimetric analysis of repointing moisture performed the day after the installation of caps showed that the surface of repointing was wetter than the inner core that stayed relatively dry (less than $2.0 \times 10^{-6} \text{ m}^3/\text{m}^3$). In addition, the southern portion of the wall showed a higher moisture content than the north side of the wall.

5.3.2.2. Relative Humidity

Relative humidity is dependent on temperature and atmospheric moisture content. Since the temperature changed constantly for a given void space inside which the probe was located, RH reading by itself does not reflect the amount of moisture available in the space. A sealed void containing liquid moisture will over time record 100 % RH as the vapor moisture level reaches equilibrium with the liquid moisture level, regardless of the volume of the sealed space (Pinchin 2009). The readings from the probes buried in the growing medium of the soft cap gravel as well as the hard cap approached 100 % within a month of installation and remained at a very high RH level for the rest of the testing period well above 70% RH level (Graph 7).

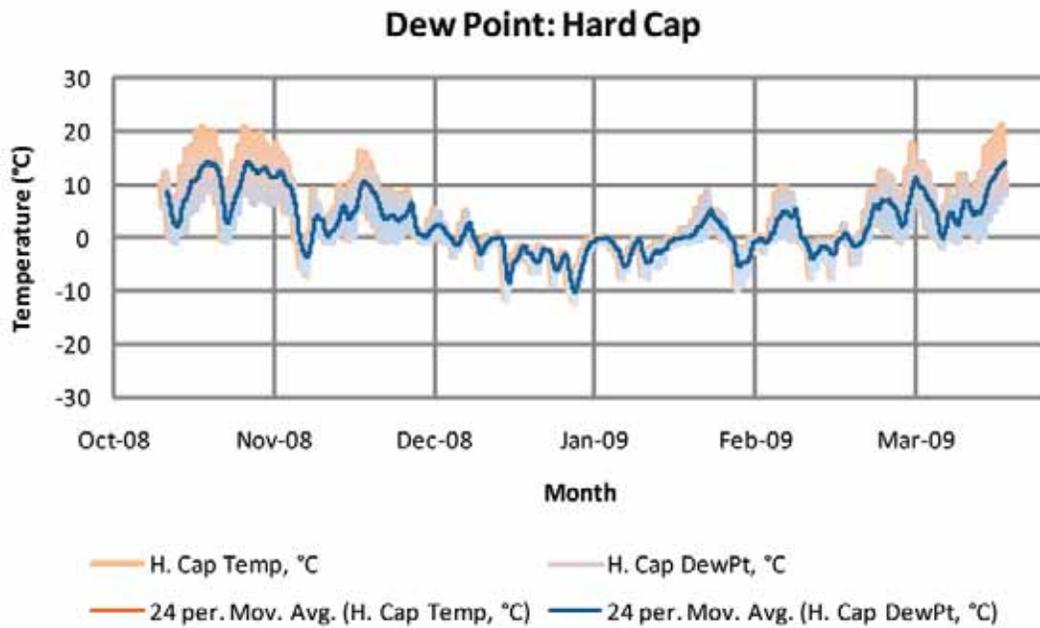


Graph 7. Hard Cap and Soft Cap Relative Humidity (Oct 2008 – Mar 2009)

In order to understand the change in the moisture content of the wall using RH readings, dew point temperatures for each cap were calculated by the HOBOWare™ software from Onset. An error in either temperature or RH reading from the sensors will result in an error in the calculated dew point. The data was then compared to the recorded temperatures to understand how the moisture content varied depending on the type of cap. In other words, the moisture content of an air space in the wall is expressed as dew point that denotes the transition temperature between liquid water and water vapor. Temperature readings higher than dew point indicate that the net phase transition of water favors the vapor form where the drying rate is faster than the condensing rate. The bigger the gap between the temperature and the dew point is, the less the moisture content. Conversely, the smaller the gap is, the slower the drying process than the condensing process. In this case, the moisture content increases.

5.3.2.2.1. Hard Cap

The probe in the hard cap almost immediately reached 100% RH and remained at that level. There were few very minor drops in RH level not more than a degree, but their impact on overall RH level was insignificant. These drops only occurred when the temperature dropped below freezing.



Graph 8. Hard Cap Dew Point (Oct 2008 – Mar 2009)

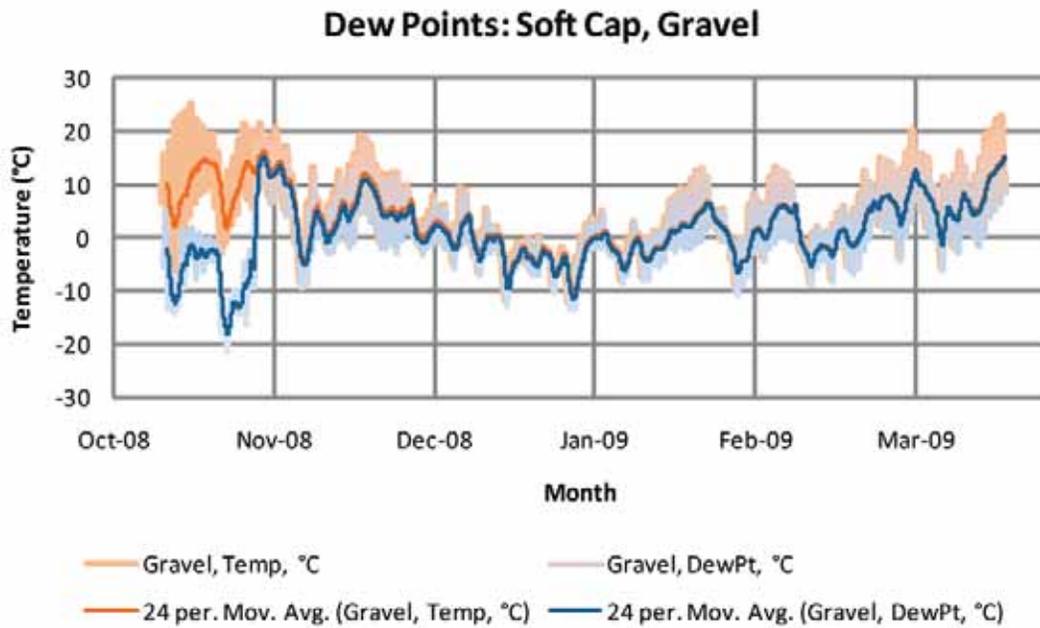
(Note: Overlap between two lines is such that they show up as one line)

The graph for dew point temperature very closely approximates the change in temperature level (Graph 8). The dew point graph slowly goes above the freezing point and reaches 70 F by mid March. The difference remains close to zero almost all the time, indicating the saturated environment inside the hard cap.

5.3.2.2.2. Soft Cap

5.3.2.2.2.1. Soft Cap Gravel

RH inside the soft cap gravel varied markedly before and after October 28th, 2008 at 11am, jumping from 38% to 71%. By the end of the day, the level reached 90%. The reading hovered around 90% for the rest of the monitoring period.



Graph 9. Soft Cap Gravel Layer Dew Point (Oct 2008 – Mar 2009)

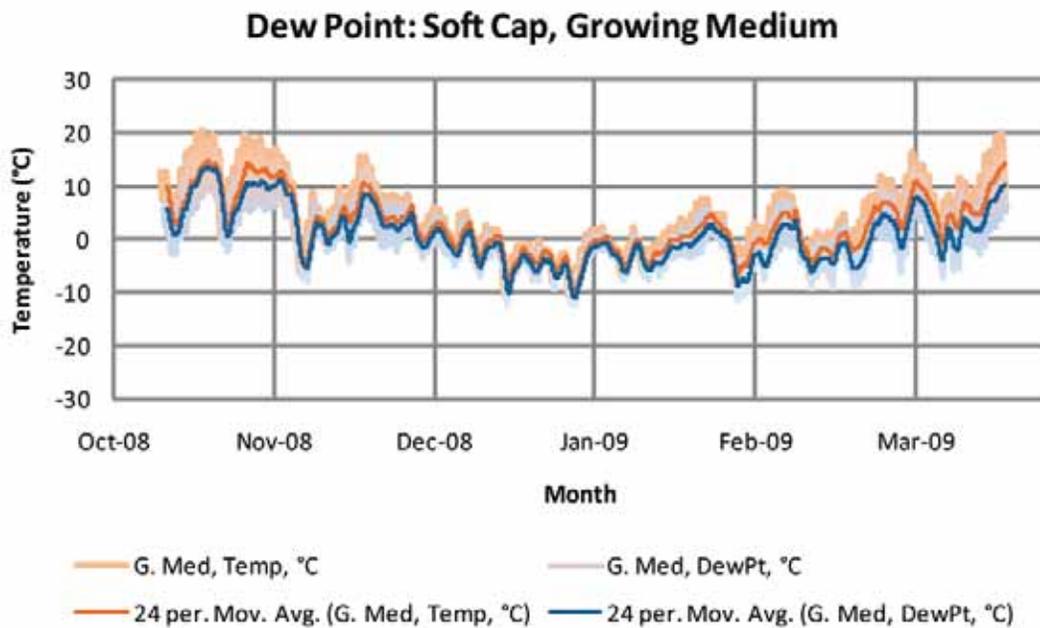
The difference between the recorded temperature and dew point temperature also reflects this change in moisture level (Graph 9). Before October 28th, the difference ranged from 10 to 70 deg F. However, after this date, the difference drastically dropped to below 3 deg F, and by the time the data were retrieved, the level was further down at below 1 deg F.

For most of the winter, the dew point stayed below freezing, indicating the water vapor had deposited on surfaces as frost, not as dew. After mid February, the

dew point went above the freezing point and gradually rose, reaching almost 60 deg F by mid March.

5.3.2.2.2. Soft Cap Growing Medium

The relative humidity level was high for the probe located in the growing medium. It stayed between 80 and 100 %. Unlike the constant readings from the hard cap, the reading from soft capping showed some variations. While the RH level showed a gradual drop since January, the level remained above 70% almost all the time.



Graph 10. Soft Cap Growing Medium Dew Point (Oct 2008 – Mar 2009)

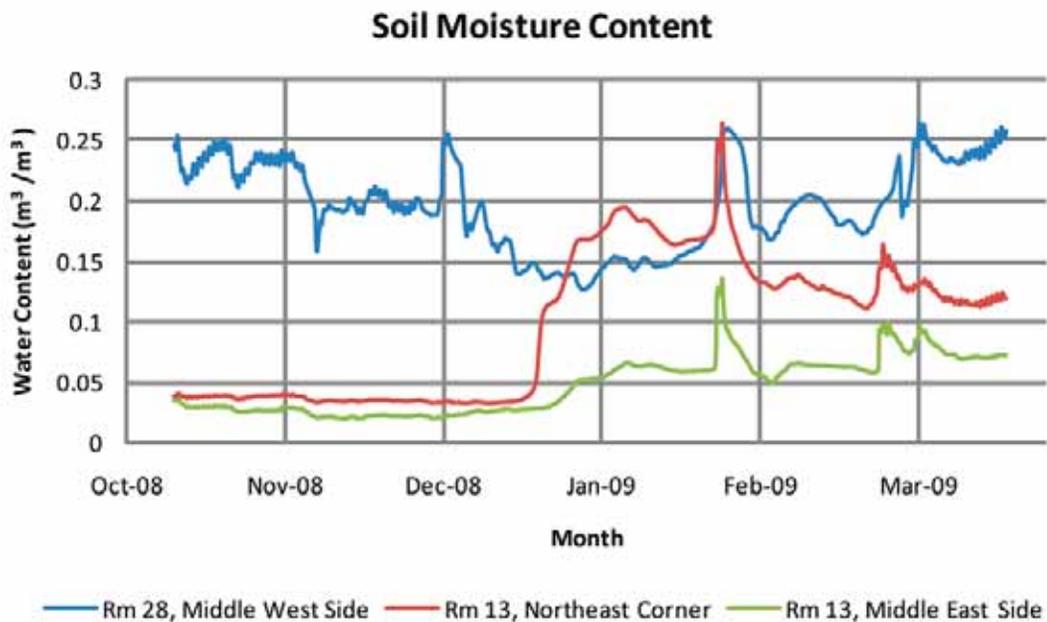
While the dew point temperature closely tracks the temperature reading, there is a noticeable temperature difference (Graph 10). The gap is small during winter but

wider in the fall and in the spring. In particular the gap in the spring continued to widen and corresponded to the lowering of RH level.

5.3.2.3. Soil Moisture Content

5.3.2.3.1. Room 13

The moisture content readings from two probes, one installed in the northeast corner of the wall and the other in the middle of the east end of the room, follow a similar pattern with differing amplitude (Graph 11).



Graph 11. Room 13 and Room 28 Soil Moisture Content (Oct 2008 – Mar 2009)

5.3.2.3.1.1. Northeast Corner

The wall maintained the moisture level at $0.04 \text{ m}^3/\text{m}^3$ throughout October and November and into mid December. Beginning in the third week of December, however,

the moisture content drastically changed. In increments of three until early January, the overall moisture content almost quadrupled to near $0.2 \text{ m}^3/\text{m}^3$. The level dropped a little through the third week of January but it rose up again reaching $0.25 \text{ m}^3/\text{m}^3$ almost five times the original amount at the time of the monitoring period. Afterward, the level almost halved by the beginning of February. By the end of the third week of January the level reached to lower $0.1 \text{ m}^3/\text{m}^3$. There is one sharp rise in moisture content above $0.15 \text{ m}^3/\text{m}^3$ near the end of February. Afterward, the moisture level dropped gradually with noticeable daily fluctuation and reached $0.12 \text{ m}^3/\text{m}^3$.

5.3.2.3.1.2. Middle East side

The probe located in the middle of the eastern end of the room 13 showed the exact same pattern but with a reduced amount of absolute change. From $0.3 \text{ m}^3/\text{m}^3$ it reached near $0.15 \text{ m}^3/\text{m}^3$ by the third week of January. Other noticeable peaks were observed during the week of March 1st.

5.3.2.3.2. Room 28, Middle West Side

Moisture levels from Room 28 showed a more complicated pattern than the readings in Room 13. The moisture level started high at $0.26 \text{ m}^3/\text{m}^3$ and gradually decreased to $0.12 \text{ m}^3/\text{m}^3$ by the end of the year 2008. It gradually recovered its original moisture amount by the time of data retrieval in March.

The series line shows a highly fluctuating pattern at four intervals: between the time it was installed and early November, between mid November until late November, during early March, and between March 10th until the data was received. During the remaining intervals, most notably between the beginning of December and early March, the series showed relatively flat patterns at a level below 0.2 m³/m³.

Two localized peaks stand out during the testing period. The first high peak was recorded in early December and the other in the latter part of January. In the latter third part of February the moisture again began to rise with one big dip on March 1st. Afterward, the moisture level never dropped below 0.22 m³/m³.

In October, the daily change in moisture level was quite noticeable on the graph as shown by the jagged lines. The moisture level varied between 0.21 and 0.25 m³/m³.

In the beginning of November, the level dropped drastically to 0.15 - 0.16 m³/m³ and the saw pattern of daily fluctuation temporarily ceased. The fluctuating pattern returned by the third week of the month but stopped before the turn of the month.

In the beginning of December, moisture content level reached 0.26 m³/m³ from 0.19 m³/m³. It soon dropped to 0.12 m³/m³ the lowest level during the whole monitoring period. After the drastic rise, the fall in moisture content occurred in steps, first a drop, and moderate rise, then a bigger drop.

In January, the moisture level again increased with a major jump during the last part of the month. By the last week of the month, the level jumped from 0.14 to 0.26 m³/m³, almost twice the amount. However, it dropped sharply again and the level reached 0.18 m³/m³ by the end of the month.

In February, the moisture content exhibited two localized peaks, less in height compared to that in January. The first occurred in the first half of the month, then another sharp rise at the end of the month. Both of these sharp rises are followed by a sharp drop to $0.19 \text{ m}^3/\text{m}^3$.

In March, the moisture level rose to above $0.26 \text{ m}^3/\text{m}^3$. The fluctuating pattern returned. Although moisture level gradually decreased during the second week, it rose again.

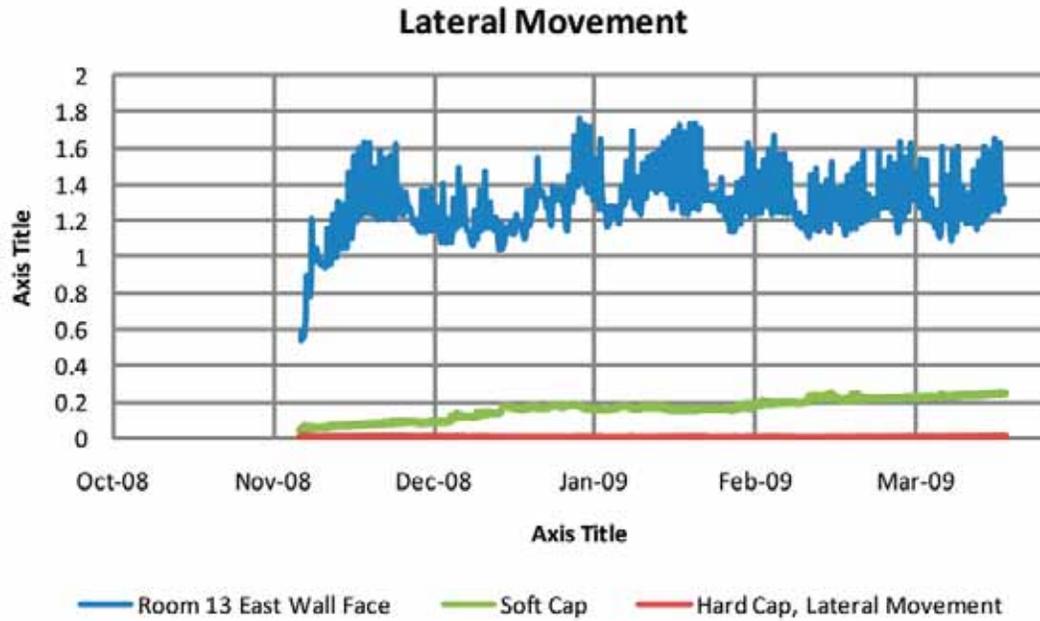
5.3.3. Lateral Movement

5.3.3.1. Hard Cap

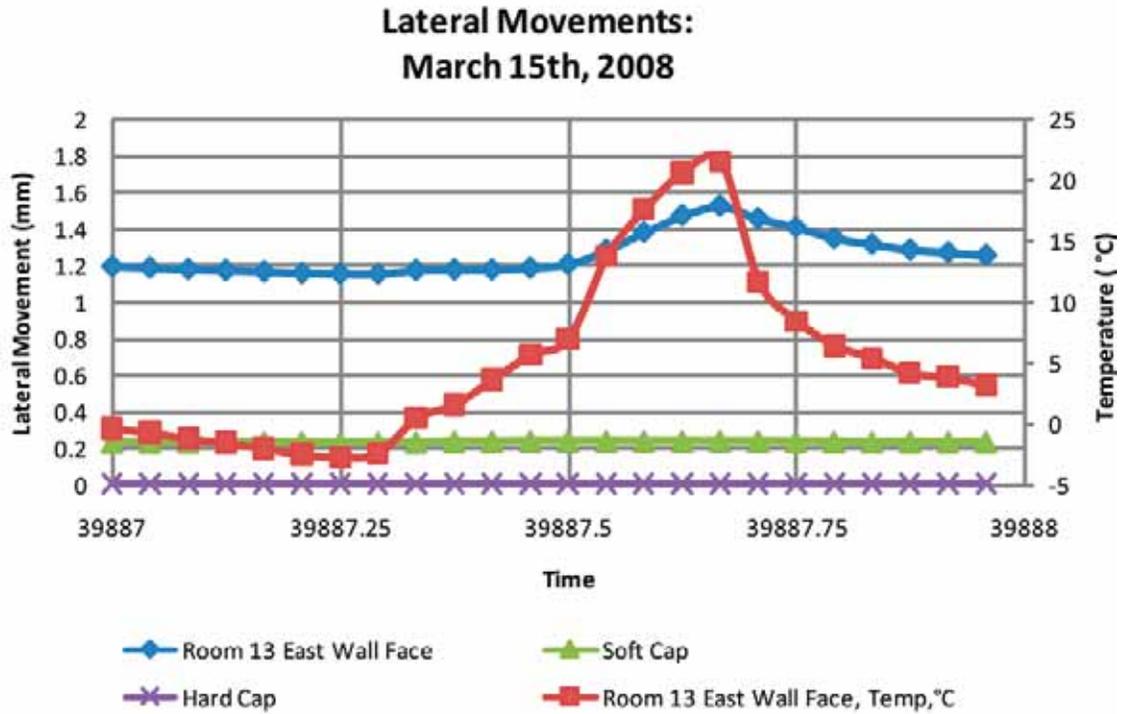
The lateral movement of the hard cap shows a very broad U shape pattern (Graph 12-13). The movement was recorded at around 0.01 mm in the beginning of the monitoring period in October. It gradually contracted to 0.002 mm around mid January then rose to 0.09 mm by the end of the monitoring period by mid-March.

5.3.3.2. Soft Cap

The lateral movement of the hard cap was almost linear from 0 to 0.25 mm spanning six months of the monitoring period. The rate of movement slightly increased in December but leveled off through January and early February. The graph rose again by the first week of February.



Graph 12. Lateral Movement of the Test Wall (Oct 2008 – Mar 2009)



Graph 13. Lateral Movement: March 15th, 2008

5.3.3.3. Room 13 East Wall Face

The western face of the wall recorded a change of approximately 1.3 mm within a month of the installation. Despite the daily changes spanning roughly 0.3 - 0.4 mm, the reading mostly stayed constant.

5.4. Data Analysis

5.4.1. Temperature

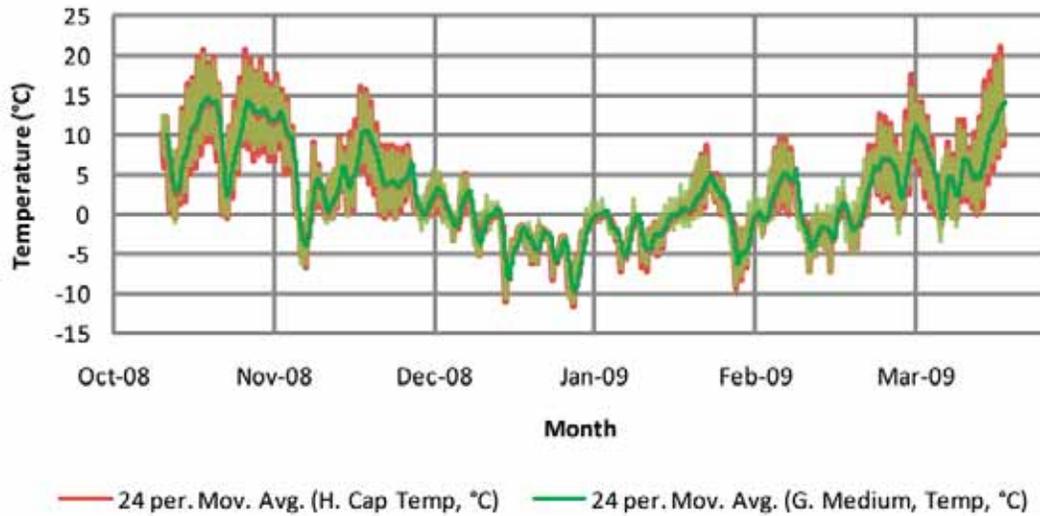
The different temperate regime is closely related to different ways of heat transfer into the test wall. Caps receive thermal energy in four ways: solar radiation, convective heat through air and water, conduction between contacting building materials and latent heat (Straub 2006).

5.4.1.1. Comparison between the Hard Cap and the Soft Cap

Overall, the soft cap retained heat and suppressed the daily temperature fluctuation. While the soft cap growing medium displayed relatively the same temperature pattern as the hard cap, its seasonal fluctuation was less than the hard cap.

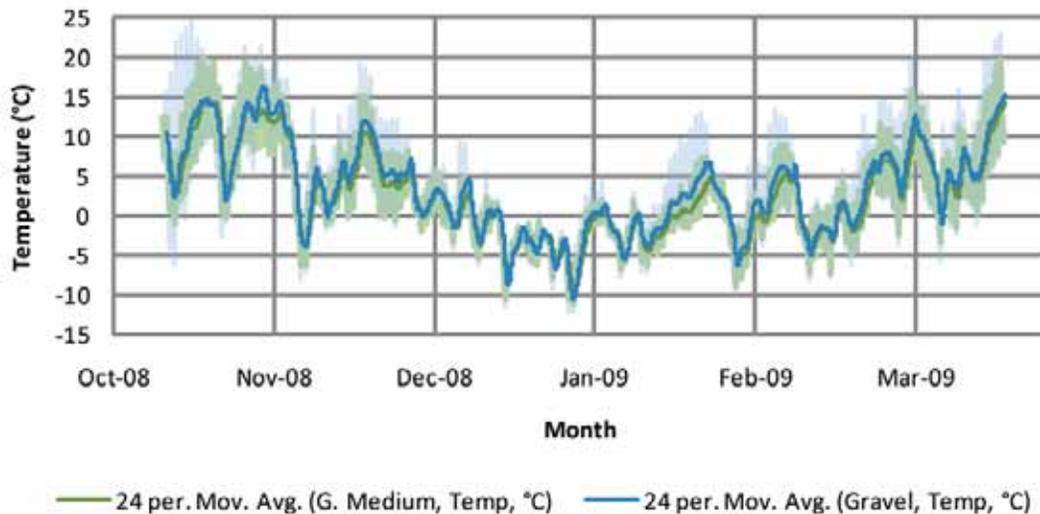
The overall effect of heat transfer through solar radiation, conduction, convection and latent heat indicates that the soft cap growing medium would show lower temperature rise compared to the soft cap gravel fill layer.

**Temperature:
Hard Cap vs. Soft Cap, Growing Medium**



Graph 14. Temperature Comparison between Hard Cap and Soft Cap Growing Medium (Oct 2008 – Mar 2009)

**Temperature:
Soft Cap, Gravel vs. Growing Medium**



Graph 15. Temperature Comparison between Soft Cap Gravel Layer and Growing Medium (Oct 2008 – Mar 2009)

Solar radiation on wall tops and wall faces is a major method of heat transfer. While the soft cap may have retained more heat due to its darker color, the shading effect on the east wall face seemed to have reduced the total net heat gain. The low thermal conductivity of the growing medium would have further reduced the net solar heat gain, resulting in relatively the same temperature regime as the hard cap. The daily temperature fluctuation of the soft cap was more severe, however, due to the re-radiation into sky at night.

The standing snow on the wall tops blanketed and insulated both caps from a more severe temperature fluctuation during the winter. The comparison to the weather data shows that the air temperature without standing snow was generally lower than the temperature registered by the installed probes inside the test wall.

Solar radiation on wall faces was affected by the shade from adjoining walls. Since the east face of the soft capped wall was shaded by the south wall of room 28, the total amount of heat that the soft cap received should be less than for the hard cap.

Another way of heat transfer is conductive heat rising from the foundation that concentrates toward the wall propelled by thermal gradient. Since the wall has more surface areas for cooling, the heat naturally rises upward until it reaches the caps. Both the cement repointing and the sandstone conduct heat well. The hard cap, made of both of these materials, conducts heat well and loses it relatively fast. The soft cap, on the other hand, relays it much more slowly due to its composite core made out of gravel, voids, and growing medium. Even though individual gravel may conduct heat well, the angular shape reduces the effective surface contact between grains and it fails

to meet its full conductive potential. In addition, the air in the void spaces between gravel and in the soil greatly retards conductive heat transfer. Therefore, the soft cap gravel layer retards the heat transfer and retains it, resulting in the increase in daily maximum temperature. The soft cap growing medium receives relatively no contribution from conductive heat from below due to the layers of geosynthetics that effectively disrupt the heat transfer.

Convective heat transfer through air and water during the cold season was considered negligible. However, frequent wind and cold air took heat away from the wall through convective cooling.

Latent heat results from the thermal energy transfer when water changes its phase (Lechner 2001: 39). The soft cap shows gradual drying as indicated by the increasing difference between the temperature and dew point. Such drying would cool the wall surface. Since the soft wall growing medium area is a soil that dries relatively fast, the result would be additional cooling of the wall top.

5.4.2. Moisture

5.4.2.1. Gravimetric Analysis

The moisture content is directly related to the equilibrium between the wetting and drying process. The wall below the soft cap was still wet from the hand irrigation the day before sampling and showed greater moisture content especially toward the top. The inner core at 4 inches depth was mostly dry indicating that the soft cap prevented the water from entering into the core and the moisture from the wall surface

was either not sufficient to penetrate to the core or the wall was experiencing faster evaporation than wetting.

5.4.2.2. Relative Humidity

There is no evident correlation between the spike in relative humidity level and precipitation. RH level change seemed to be more strongly determined by residual construction moisture than precipitation as rain or snow or even hand irrigation.

5.4.2.2.1. Sources of Error

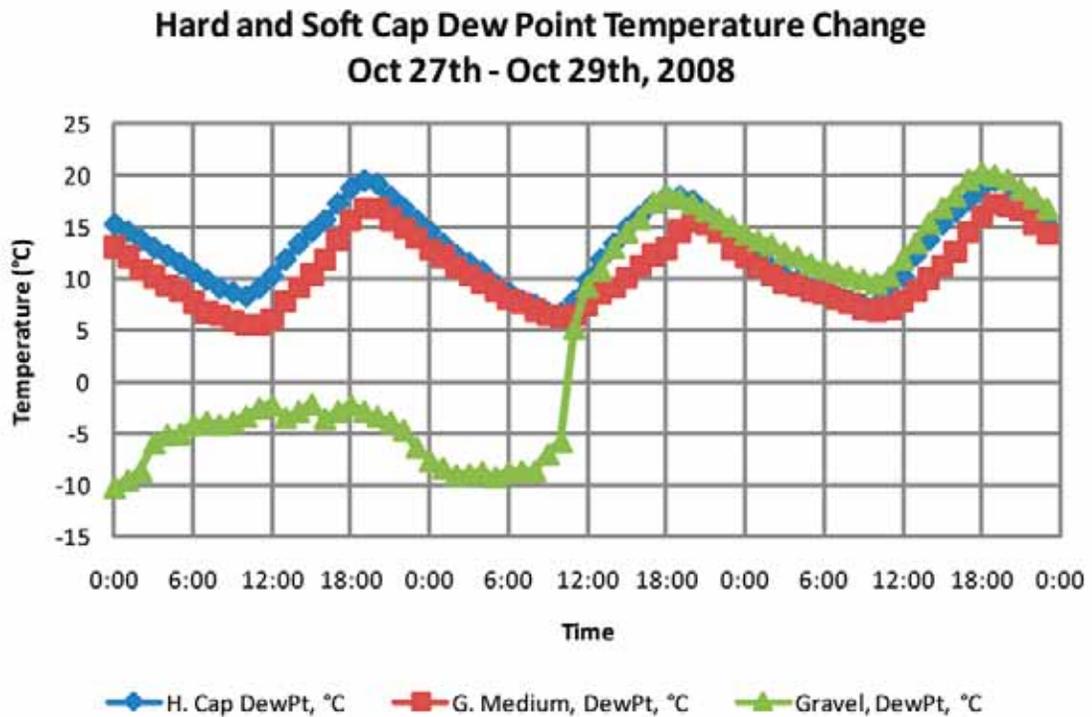
For all RH probes, constant exposure causing the RH level to rise above 70% would have most likely caused the probe reading to drift plus or minus 3%. In addition, the temperature below freezing point for more than two months would have also contributed to an additional drift of plus or minus 1%.

5.4.2.2.2. Hard Cap

Moisture evaporation from the mortar mix soon saturated the void space inside the cap where the probe was located. The absence of any weep holes and the low vapor permeability of the concrete cap effectively sealed the space. In this condition, the residual construction moisture in the cap would take several months to dry (Sereda 1981; Torraca 1982).

A very slight drop in RH level occurs when the temperature falls below freezing temperature. At a given volume with a pressure slightly less than 1 atm in high

elevation, water vapor changes to solid ice directly, reducing the amount of water molecules in gas form and thus RH level. However, this phenomenon did not significantly reduce the amount of water vapor in the void space and the probe continued to record saturated atmosphere.



Graph 16. Hard and Soft Cap Dew Point Temperature Change (Oct 27-29, 2008)

5.4.2.2.3. Soft Cap

5.4.2.2.3.1. Gravel

The big jump in RH level and Dew Point level at the end of October suggests that at around this time, water penetrated the gravel level but did not escape (Graph 16).

One possibility is the sensor contamination leading to a false offset in the readings. The

spike in moisture level comes after the repeated irrigation of the grass cap by the park staff. There is no recorded precipitation immediately before, on, or after October 28th, 2008, the day the probe recorded a sudden spike in RH level. Therefore, it is most likely that the accumulated watering had finally entered the gravel system from the wall faces through absorption by the wall face mortars and sandstone, as these building materials readily absorb water. However, due to the covering by the geocomposite that provides thermal blanketing, and relatively small surface area for the water to evaporate out, the saturated gravel area remains wet throughout winter. Some water vapor might have condensed on the bottom surface of geocomposite and recycled back into the gravel fill. Unlike RH levels in the hard cap, however, the RH level in the soft cap gravel level exhibits daily fluctuation that indicates that there is some level of ventilation. Overall, however, the weep holes on the sides seemed to have failed to provide adequate ventilation for the gravel.

5.4.2.2.3.2. Growing Medium

The RH in the growing medium reached a high RH value early on. For the rest of the testing period, the RH level gradually fell, reaching the lowest RH level out of all three probes. However, RH value was still higher than 70%, a critical point for the probe to avoid drift.

Unlike the gravel level, the growing medium level has more surface area for evaporation. The moisture in soil evaporates fast under dry conditions. In addition, the grass consumes a certain amount of moisture for its own evapotranspirative process.

The water drainage to a lower level also should have reduced the amount of moisture in the growing medium. However, these processes seemed to have been relatively insignificant to the overall reduction in moisture around the probe since the geocomposite encasing the probe must have acted to attract moisture and kept the immediate environment around the probe wet. While there are some daily fluctuations indicating changes in net evaporation and condensation, overall the drying rate is slower than the condensation rate.

5.4.2.3. Soil moisture

Air temperature directly affects soil moisture level. When the temperature falls below freezing, liquid water freezes to solid ice crystals, resulting in the reduction in the amount of liquid available for the monitor to register. As a result the moisture content drops. As temperature rises, frozen water melts and the monitor again registers increased moisture content. When the air temperature is high enough so that liquid water begins to evaporate, the soil moisture content again drops.

There are two types of moisture content rise, one a localized sharp rise followed by sharp drop and the other a more seasonal gradual rise and drop. The sharp rise generally coincides with the sudden air temperature drop below freezing. The sharp rise can also occur when rain precipitates above freezing temperature but there was no recorded rain event during the testing period. The gradual change in moisture content occurs step-wise diurnally. In this case, the air temperature is generally above freezing.

5.4.2.3.1. Room 13

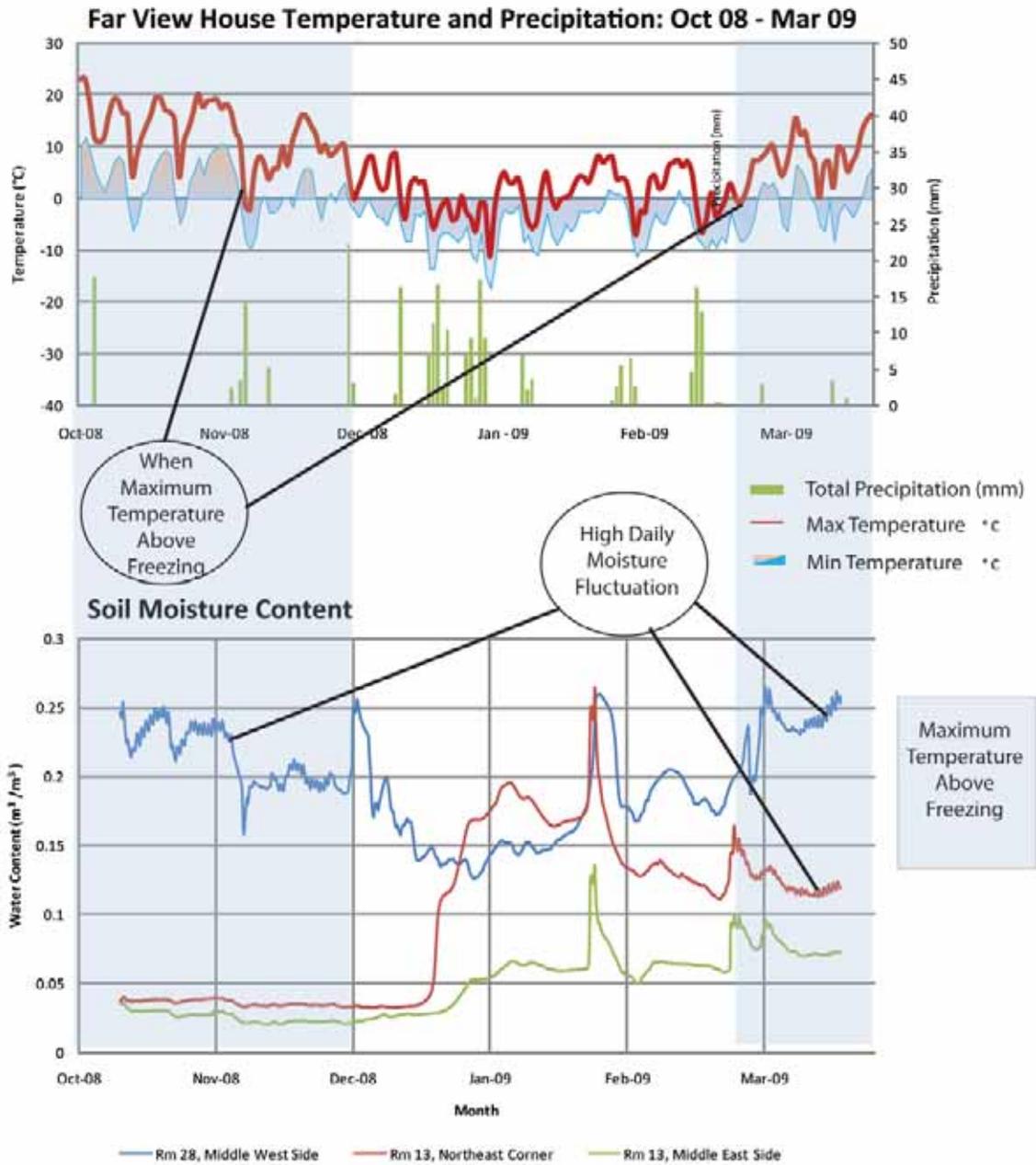
Despite the recorded snow precipitation in November and early December, the probe recorded no drastic changes in moisture level and maintained a dry condition. This seems to indicate that the moisture did not penetrate to the depth where the sensor was located.

5.4.2.3.2. Room 28

The graph for soil moisture content shows remarkable parallels to the temperature graph (Figure 17). When combined with the fact that most of the snow precipitation at Far View House remains in solid phase throughout the cold winter days below the freezing point, the graph strongly supports the idea that the snow cap on soil constantly feeds the soil with moisture diurnally when the temperature rises above freezing.

The minimum temperature remains below freezing starting around the beginning of December until the end of February, delaying the snowfall from melting immediately after the fall. All the accumulated snow melts in spring, leading to a massive increase in moisture content.

The precipitation during the testing period was recorded as both rain and snow in liquid form as weight. December saw the largest amount of precipitation with few other localized precipitation events in the early November, and two occasions in January, and one big event around February 10th. Afterward, the precipitation was low.



Graph 17. Maximum Daily Temperature and Soil Moisture Content

Based on environmental data, there seems to be no direct correlation between the soil moisture level and the precipitation level. The soil moisture probe measured the amount of water in liquid form only, whereas Far View House weather station included both snow and rain as precipitation. The drop in moisture level in December despite frequent precipitation events indicates that the snowfall remained frozen and did not contribute to the total amount of liquid water available in the soil. At the same time, the rise in soil moisture level occurs in spring when the precipitation level is low.

Soil moisture level series approximates the pattern of temperature rise and fall with slight time lag. In particular, the trend in the rise of moisture level beginning early February parallels the temperature trend. The drop in moisture level in the fall also followed the lead by temperature drop.

The change in pattern between a smooth and jagged line indicates that the soil was covered on and off by snow cap. In particular, in the absence of a snow cap, which works as a sun light reflector and heat insulator for the soil below, the soil experienced a high fluctuating pattern in temperature. As the heat from the sun evaporates liquid water during the day, the moisture pattern tends to follow diurnal cyclical patterns in temperature. In contrast, when the snow cap is present, the series is relatively smooth as the sun light is reflected off or the heat from the sun is used for phase transition from snow to liquid water, not affecting the temperature level of the soil.

5.4.2.3.3. Comparison between Room 13 and Room 28

One would expect the level of moisture below the geotextile in Room 28 to be low since the geotextile should block the water from the top from travelling down and prevent wetting of the gravel. The result, however, showed the opposite. Although the probe in Room 28 was installed under the geotextile, it recorded high moisture content from the very beginning. The reading seems to indicate that the previously installed geotextile in the soil is working as a vapor retarder, slowing the drying rate through the top of the fill and elevating moisture vapor content of the voids. When water vapor encounters the plane of condensation in the cool soil, it condenses, increasing the liquid moisture content. As the temperature drops, water freezes, leading to the drop in moisture content. With temperature rise in spring, the moisture level rises again.

The slower drying rate indicates high capillary rise to the wall top (Massari 1993: 10). While the height of capillary rise is determined by the pore structure of the wall material (Torraca 1982: 147), the faster the moisture evaporation, the lower the capillary rise. Cooler environment and low moisture gradient contribute to the capillary rise.

Instead of rising up, the moisture seems to travel laterally in the test wall. The wall surface facing west allows the water to dry, creating a lateral moisture gradient. As the wall receives moisture from the wet lateral fill, its strength is significantly reduced. The laboratory test has shown that the sandstone loses two third of its flexural strength parallel to its rift when saturated. The result is the vertical ruptures of the sandstone and deformation of soil mortar. The development of cracks on and eventual

detachment of less plastic repair mortar further reduce the structural stability and the strength of the compound wall system composed of soil mortar and sandstone. The original soil mortar contains highly plastic clays and exhibits a low plasticity index of 15. By discouraging water to rise to the top of the soil through vapor transmission, the geotextile buried in the soil is detrimental to the structure of the wall by increasing the amount of moisture in the soil.

To complicate the matter, the wall core with missing fill from water runoff through cracked hard caps is also detrimental to the strength of the wall, already devoid of any wooden beams that might have held the composite elements together while providing lateral support.

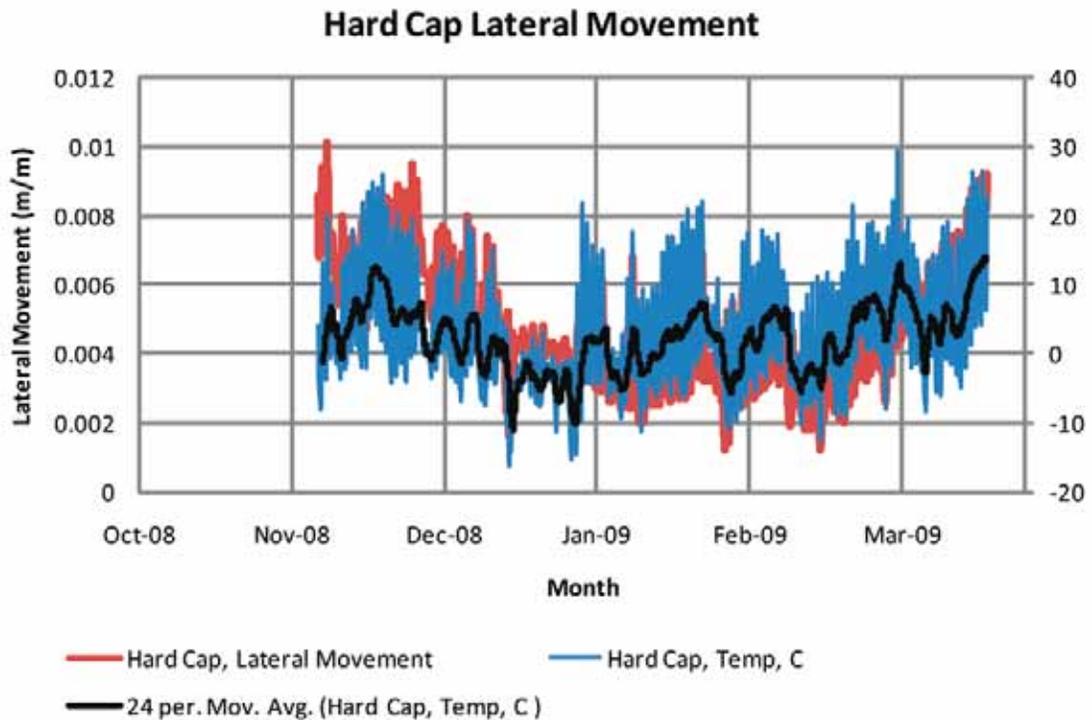
The data shows the importance of drying, as well as wetting, in maintaining moisture content. With the geotextile retarding effective moisture desorption, the soil remains wet and accepts even more water from snow melting. Since the geotextile is permeable to water, and especially since the cut was made in order to place the probe underneath it, the melting snow or any other forms of precipitation only increase the amount of moisture in the soil.

While the surface area does dry, the soil below a certain depth remains wet. This observation is in agreement with the results from the studies at Chaco Canyon where the wet soil boundary was located around 30 cm deep, below which the soil remained wet throughout the year (Maekawa 2004: 322). The result from another site in Chaco Canyon also confirms that the installation of geomembranes in soil results in the increase of moisture content.

When applied to the soft capping layer, the observation substantiates the idea that the geomembrane layer works as a vapor barrier and a condensation plane, resulting in the increase in moisture content. Since the layer cannot dry easily, the moisture level will either stay or go up, but will very unlikely go down.

5.4.3. Lateral Movement

The lateral movement of the hard cap, although very subtle, closely resembles the fluctuation patterns in temperature (Graph 18). It is likely that the wall movement is due to the thermal expansion and contraction of the probe material itself and not the lateral movement of the wall top.



Graph 18. Hard Cap Lateral Movement

The soft cap, on the other hand, exhibits much greater movement that increases in amplitude. The stones along the edges of the wall top that support the growing medium are not fixed with mortar. As snow accumulates in December, there is an increasing tendency for the stones to move away from each. The movement somewhat stabilizes after the heavy precipitation of snow fall ceases but picks up again as the temperature rises above freezing. Therefore, the weight of the snow cap and melting snow could have contributed to this gradual movement away from the wall core.

Another possibility is the frost heaving. The accumulation of moisture in the growing medium could have led to the increase in frost amount. This could have exerted pressure laterally to the unfixed stones. Since the interface between the top stones and the pointed stone course below is not fixed, the stones on top do not return to their original positions once displaced. Rather, they will continue to move as the growing medium collapses to fill any gap between it and the displaced stones.

The plant roots may have also pushed the stones away, but it is unlikely that plants grew much during the cold winter season. Therefore, such possibility is discarded.

If the movement was indeed caused by the thermal behavior of the monitor, the pattern will cycle throughout the year closely resembling the temperature pattern. This would require additional monitoring period.

5.5 Conclusions

Any conclusive evaluation of the capping techniques would have to wait until the data from at least one full year is gathered. Both soft cap and hard cap experienced humid conditions in the bottom layer. The lack of ventilation and the evaporation of water would increase the hydrostatic pressure on the wall top and invite unnecessary biological growth.

Equally important, until one of the capping methods fails, it would be challenging to see clearly how well the systems manage water. The newly installed hard cap has not shown any cracks nor has the soft cap shown any cataclysmic failure in holding back water from the top. In addition, it is yet to be determined whether the vegetation has successfully survived the weather and how its root system would affect the stone courses through possible root jacking. The most critical data would arrive in spring, from April to June, when all the accumulated snow melts, exposing the soil surface to direct drying.

The moisture introduced during the installation of both caps affected and determined the RH level of each cap and therefore compromised the effectiveness of the RH probes for evaluating the performance of the caps. The readings, however, provide important information for future design and implementation of the caps. Improvement in soft cap design will require an informed installation that blocks moisture retention and a more appropriate selection of moisture probes to effectively evaluate the performance of the capping intervention.

First, the penetration of moisture into the gravel fill showed that despite the installation of a horizontal geocomposite layer for drainage of water and for redirecting water horizontally, moisture still continues to penetrate from other areas – probably from the wall sides through suction – into the fill level below the geocomposite, an area expected to be dry. It prompts an improvement in the design of the drainage system for more effective moisture control.

The repointing mortar also introduced excess moisture into the system during drying. The probes from both gravel fill and hard cap showed a huge spike in RH soon after the installation of the caps, quite possibly due to evaporating moisture from the mortar mixture. This suggests that when mortar is applied in the wall construction, extra time should be allowed for drying the mortar first, before installing any additional layer on top, in order to minimize the moisture entrapment.

Water can also enter into the gravel fill through an incomplete seal between the barrier and mortars. This also requires attention during the installation process, since the mere presence of liquid water barrier does not ensure the complete seal-off of water.

At the same time, in order to better evaluate the moisture level inside the caps, a soil moisture reader that records the absolute amount of liquid water should replace the RH/temperature probe that measures only the relative amount of water vapor inside the wall. While an RH/temperature probe has an advantage of measuring two variables using one probe, it introduces many sources of error, particularly when it is installed in an enclosed system that does not allow ventilation. For an environment

with ample sources of moisture, in this case a snow cap, in addition to watering of the vegetation layer during the initial phase of cap installation, the RH probe does not provide effective readings. More robust RH/Temperature probe and a soil moisture probe should resist better against salt and insect damage. Furthermore, the soil core of the wall dries out slowly when the temperature is low and the surface area for evaporation is greatly reduced by surrounding stone masonry. Therefore, more effective measurement could be achieved using separate temperature and soil moisture sensors that could monitor environmental variables in absolute terms.

Finally, the results from the study also help understand the results from the study done in England with greater implication for the soft capping design. The moisture content graph taken in July 2005 at Byland Abbey shows that while hard cap provides initial protection against precipitation by reducing the overall water absorbed, it dries slowly, resulting in greater overall moisture content for an extended period of time. Soft cap absorbs more water but dries faster. Therefore, although there is greater water intake by soft cap during rain events, it will give up moisture faster than hard cap. As long as there is enough recovery period for soft cap to dry, it will be a better choice over hard cap in managing moisture and temperature fluctuation. This means that soft cap is a better choice in dry weather than in wet weather.

Moreover, the analysis points to the need for designing soil layer with appropriate soil particle size ratios customized for local climate. The use of soil mortar at Mesa Verde was effective, since not only does it provide shear and tensile strength to the masonry walls, it is also more compatible with dry climate by giving up moisture

easily. The fibrous organic additives in mortar and cap act as wicks to accelerate drying just as straw functions in adobe. They also impart tensile strength as well as protecting soil mortar from washing away by rain. The cap design would need to address this either through the use of appropriate plant type or geosynthetics.

6. CONCLUSIONS

6.1. Summary

The effects of a hard cap and a soft cap on a masonry wall top were qualitatively and quantitatively evaluated from late fall to early spring. From October 2008 to March 2009, temperature, moisture and wall movement, as well as weather conditions were monitored. The data did not provide conclusive results for determining the preferred system. It would require more time, at least one full year, to make a meaningful analysis. However, as a prototypical installation, valuable information was gathered on environmental conditions, materials properties, deterioration mechanisms, moisture balance and monitoring methodologies. The sources of moisture and thermal energy were evaluated in order to understand the enabling factors for deterioration mechanisms. From the documentation on the past intervention and the observations made in laboratory and in the field, possible deterioration mechanisms were analyzed. In addition, the research showed the difficulties in installing a monitoring that predictably records what is desired. These findings will be incorporated into designing a new soft cap system and monitoring system in the future.

One of the most significant findings from the study is the need to understand how water balances itself through the interaction with the wall and the environment. Moisture uptake by the wall from the soil occurs for an extended period of time and is probably more damaging to the wall than moisture entering the wall from the top through occasional precipitation events. This has a huge implication on choosing correct and effective intervention methods.

6.2. Recommendation

Based on this initial pilot study, the following recommendations are drawn:

6.2.1. Implement regular maintenance on site

Moisture continues to damage the site despite nearly a century-long effort to manage it. The installation of cappings on wall tops is only one component of maintenance. A regular check-up on walls is fundamental in order to understand the rate of deterioration at the site, to provide timely intervention and eventually to implement a preventive intervention. Far View House represents one of the key mesa top ruins with links to other sites in the Southwest. The mesa top ruins do not receive protection against precipitation, solar radiation, and wind unlike alcove sites that are relatively well protected. Given the site's archaeological importance, this study urgently asks that the site be monitored regularly and properly documented for any deterioration until proper funding and access by trained personnel can allow a more systematic architectural study and stabilization work.

6.2.2. Select compatible intervention materials

The various cementitious hard caps have shown clear defects since their initial application in 1916. They pose visual, physical, and chemical threats to the walls and therefore undermine the site's material, historical and aesthetic integrity. The development of cracks, the retardation of water evaporation and the supply of soluble salts into the vulnerable original building materials are only some of the inherent

material characteristics of hard caps that activate deterioration mechanisms. These conditions have been observed and noted at various other archaeological sites resulting in severe consequences to the masonry structures. Updating information on the performance of soil-cement based mortar mixes and research into other formulations could help develop intervention materials more compatible with the original building fabric and systems.

6.2.3. Control water movement both from wall tops and from grade and room soil

Even if a properly installed cap system blocks water entry from wall tops, water can still enter the walls through other sources. The volume of the water available to the wall is not necessarily reduced by mere diversion of the water from the top of the wall. The water penetration from the wall faces needs to be controlled as well as moisture from the soil below. The geosynthetic drainage system in Room 28 installed in 1983 needs an evaluation of its efficacy in controlling moisture content in the room soil. Based on observations, the geosynthetics seem to have attracted moisture underneath them, the opposite result of intended use. This observation has a direct consequence on the soft cap design as well since it also utilizes the same layering to control water movement. The performance of the geosynthetic layer, therefore, needs critical assessment to determine whether it increases the uptake of moisture by the wall from the lateral fill. This is especially important for walls between differential fills, since moisture from the wet soil will be forced to exit through the walls, seriously

undermining the wall stability by reducing the stone and mortar strength and introducing soluble salts that accelerate weathering.

6.3. Limitations

The extent of fully understanding the test wall was limited due to the inability to visualize the inner core of the wall. While the documentation of past interventions and observations from other parts of the site provided valuable information, an improvement in visualization methods could improve the efficacy of the treatment design.

6.4. Future Research

Future research should be focused on four areas. First, it should improve the design and installation of the soft cap. The data showed that the soft cap system requires further modification during the design and installation phase. Reducing moisture levels during the installation phase, fully taking advantage of evapotranspirative mechanisms to obviate the need for relying on drainage systems, and maximizing the plant's ability to reduce moisture penetration from the wall top would become critical in order for this system to be effective. The dissemination of information, as well as getting inputs from other industry leaders would make this system more predictable and reliable in terms of its performance by making it easier for installation and retrieval as well as more cost efficient. The construction of wall mock-ups would help assess the cap performance.

In addition, the research needs to address effective monitoring methodology. For example, a non-contact monitoring system could offer helpful information. Available methods need to be explored to map out void spaces and cracks as well as heat and moisture transfer in the wall within the confines of site access. Drawing on resources from other industry leaders would benefit this aspect. For a contact based monitoring system, the design should allow easy replacement of the probes in case of any monitor failure. Running a simulation model based on the data would also help visualize the system.

The research should also incorporate investigating the mechanisms of water entry into the wall from the soil below. Parallel efforts to reduce the amount of liquid water in the soil and to prevent water shedding from the wall tops by evapotranspirative process could circumvent potential structural and material failures resulting from water absorption.

Finally, the Investigation of original construction technology would also benefit the long term maintenance of the site. Analyzing the original soil based mortar mixes would be critical in understanding the technology of construction that could be applied as an intervention method. By investigating the original technology, one may avoid introducing novel materials to the system that had never existed before. In addition, by observing how the materials on site behave under the local environmental condition, one can provide a sustainable and long term intervention method. Reliance on new materials not only increases cost and labor demands but also reduces the sustainability of the site.

Integrated research into both modern and original technology would bring about measurable benefits to the site as a mean to sustainable management of an archaeological site.

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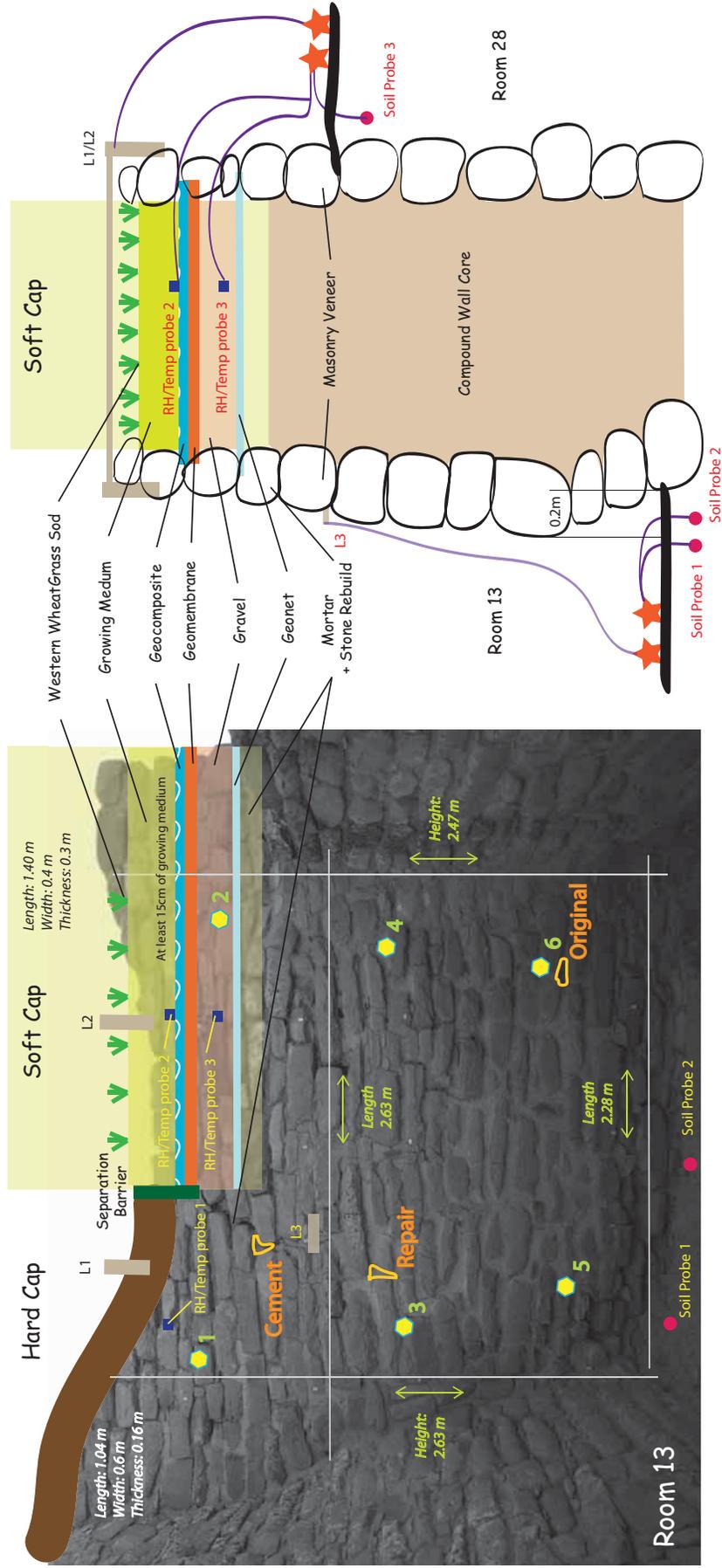
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Appendix A: Soft Cap Design Diagram

* Not In Scale

- RH/Temperature Probe
- Soil Moisture Probe
- 1 Moisture Sample (2 & 4 inches in depth)
- 2 Mortar Sample
- L1 L1
- L2 L2
- L3 L3
- ★ Data Logger



APPENDIX B: Test Data

1. Wall Surface Ratio Calculation

Geographic Information System (GIS) was used to estimate the total surface area of the materials component. A photograph of the east wall of Room 28 was inserted into AutoCAD and the individual masonry blocks as well as the whole wall boundary were traced. The file created was then imported into GIS software which then calculated the total areas for masonry and the total wall surface area. The difference between the two was used as the surface area of the mortar surface.

Table 5. Room 13 East Wall Surface Ratio

	Total Sandstone Surface (Masonry + Chinking Stones)	Total Mortar Surface (Soil + Repair mortar)	Total Wall Surface
Calculated Square Inches	7301.27	3329.39	10630.66
Percentage of Total Wall Surface	69%	31%	100%

2. Gravimetric Analysis of Mortars

A: 2 inch depth, B: 4 inch depth (Refer to Appendix A for location)

Sample (Depth - Location)	Wet Sample (g)	Dry Sample (g)	Water Content (g)	% Moisture
A-1	18.49	17.75	0.74	4.17
A-2	18.55	18.56	-0.01	-0.05
A-3	18.17	18.17	0	0.00
A-4	24.13	24.1	0.03	0.12
A-5	25.12	25.09	0.03	0.12
A-6	19.67	19.65	0.02	0.10
B-1	18.93	18.92	0.01	0.05
B-2	15.03	15.03	0	0.00
B-3	16.72	16.71	0.01	0.06
B-4	32.82	32.78	0.04	0.12
B-5	19.73	19.71	0.02	0.10
B-6	19.19	19.2	-0.01	-0.05
Rm28 middle west side	35.22	35.2	0.02	0.06
Rm13 northeast corner	30.63	30.61	0.02	0.07
Rm13 middle east side	42.35	42.31	0.04	0.09

3. Material Characterization

3.1. Sandstone

For all the tests, sample prisms were 4 inches long x 1 inch high x 1 inch wide. The samples were cut using a diamond saw blade with lubricating water. Afterward, they were oven dried until the weights were stabilized.



Figure 34. Sandstone Prisms (Lim 2009)

3.1.1. Density

ASTM C97-96: Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone

3.1.1.1. Density Data

Table 6. Far View House Sandstone Density

Sample	Width (in)	Height (in)	Length (in)	Volume (in ³)	Volume (mm ³)	Weight (g)	Density (g/cm ³)
1	0.951	0.989	4.113	3.87	63.4	112.61	1.78
2	0.985	0.999	4.115	4.05	66.4	117.96	1.78
3	1.008	1.012	4.106	4.19	68.6	123.72	1.80
4	1.018	0.985	4.099	4.11	67.4	120.71	1.79

Average Density = 1.79 g/cm³

3.1.2. Porosity

3.1.2.1. Procedure

NORMAL 7/81: Water Absorption by Total Immersion – Imbibition Capacity

The apparent and open porosities were determined by using the sample prisms. The sample weight was measured and then remeasured after it was totally immersed in water for at least 24 hours. The difference in weight is the amount of water that has entered the sample and it is represented as the percentage of the dry sample weight.

$$\text{Apparent Porosity} = \Delta W/W \times 100$$

$$\text{Open Porosity} = (\text{Volume of water}) / (\text{Volume of sample}) \times 100$$

3.1.2.2. Possible Sources of Error

Slight variations in surface finish and the angle of cut may have affected the final volume of the sample prisms. Water on surfaces of the samples not completely absorbed by paper towel prior to the sample weighing could have rendered the calculated porosity value higher.

3.1.2.3. Porosity Data

Table 7. Apparent and Open Porosity

Sample	Sample Weight (g)	Sample Volume (mm ³)	Water Weight (g)	Apparent Porosity (g)	Open Porosity (g)
1	112.61	63.39	14.31	12.71	22.57
2	117.96	66.35	14.29	12.11	21.54
3	123.72	68.64	15.08	12.19	21.97
4	120.71	67.35	14.70	12.18	21.83

Percentage Apparent Porosity (Water Absorption Capacity)

=12.30% (Weight)

Percentage Open Porosity

= 21.98% (Volume)

3.1.3. Water Absorption and Drying Behavior

3.1.3.1. Procedure

NORMAL 11/85: Water absorption by Capillary action – Capillary Absorption Coefficient

NORMAL 29/88: Measurement of the Drying Index

To test absorptivity, four sandstone sample prisms were prepared 1 inch wide x 1 inch high x 4 inches long. They were all placed vertically with the 1 x 1 inch square face down on top of a layer of 5mm glass beads in a container filled with water to the top of the beads. Filter paper was laid between the stone and glass beads to provide buffering and to ensure constant water contact. The sample was weighed before the test and then was measured at three minutes interval to record the change in weight to calculate the amount of water absorbed by the samples. This was done until the change in weight was constant within 0.1% after three consecutive weighing.

After the test was completed, the samples were fully immersed in water for 24 hours to test porosity. Afterward, they were left to dry and weighed again. The samples were weighed at 5 minutes intervals for forty five minutes, then 15 min for the next hour, followed by 30 min for the next hour, and one hour until the sample weights remained relatively constant for three consecutive readings. The recorded room temperature was 21 deg C at 40 % RH.

3.1.3.2. Possible Sources of Error

The high porosity and permeability of the sandstone led to absorption of water at a very fast rate. As a result, during the absorption test the water prepared in the bath needed to be constantly refilled. Controlling the amount of water was difficult, since the water level needed to be kept at just below the bottom of the contacting surface area and not touch the sides of the sandstone prisms. When water was not supplied on time, a sample had no contact with water and began to dry.

3.1.3.3. Water Absorption Data

Table 8. Water Absorption

Time		Sample 1		Sample 2		Sample 3		Sample 4	
Time (min)	square root of time (sec ²)	Total Weight (g)	Water Content (g)						
0	0.00	112.61	0	117.96	0	123.72	0	120.71	0
3	13.42	118.74	6.13	122.87	4.91	130.01	6.29	126.78	6.07
6	18.97	121.23	8.62	125.28	7.32	132.49	8.77	129.17	8.46
9	23.24	123.11	10.50	127.14	9.18	134.31	10.59	130.89	10.18
12	26.83	124.64	12.03	128.75	10.79	135.85	12.13	132.24	11.53
15	30.00	125.85	13.24	130.03	12.07	137.17	13.45	133.36	12.65
18	32.86	126.19	13.58	131.17	13.21	138.08	14.36	134.48	13.77
21	35.50	126.21	13.6	131.61	13.65	138.19	14.47	134.69	13.98
24	37.95	126.25	13.64	131.62	13.66	138.21	14.49	134.72	14.01
27	40.25	126.26	13.65	131.66	13.70	138.22	14.50	134.54	13.83
210	112.25	126.31	13.70	131.76	13.80	138.34	14.62	134.82	14.11
415	157.80	126.35	13.74	131.79	13.83	138.37	14.65	134.89	14.18
800	219.09	126.47	13.86	131.89	13.93	138.48	14.76	134.99	14.28
1520	301.99	126.92	14.31	132.25	14.29	138.80	15.08	135.41	14.70
2960	421.43	127.32	14.71	132.61	14.65	139.16	15.44	135.80	15.09

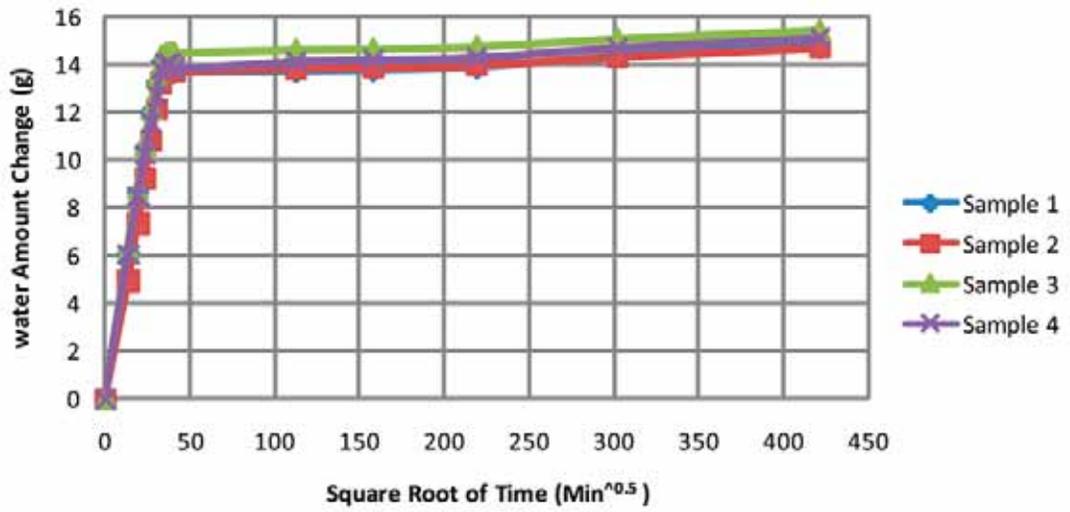
Table 9. Capillary Absorption Coefficient

Sample	Capillary Absorption Coefficient (g/cm ² sec ^{0.5})	Correlation Factor
1	0.0641	0.997
2	0.0623	0.999
3	0.0677	0.999
4	0.0649	0.999

Average Capillary Absorption Coefficient = 0.0648 g/ (cm² sec^{0.5})

$$= 38.85 \text{ kg/ (m}^2\text{hr}^{0.5}\text{)}$$

Water Absorption: Far View House Sandstone



Graph 19. Water Absorption

3.1.3.4. Water Drying Data

Table 10. Water Drying

Time	Sample 1		Sample 2		Sample 3		Sample 4	
Hour	Total weight (g)	Water weight (g)						
0.00	127.32	0.23	132.61	0.22	139.16	0.22	135.80	0.22
0.08	127.11	0.23	132.43	0.22	138.98	0.22	135.60	0.22
0.17	126.96	0.23	132.27	0.22	138.80	0.22	135.44	0.22
0.25	126.77	0.22	132.11	0.21	138.66	0.22	135.26	0.22
0.33	126.63	0.22	131.96	0.21	138.47	0.21	135.08	0.21
0.42	126.47	0.22	131.79	0.21	138.33	0.21	134.94	0.21
0.50	126.31	0.22	131.66	0.21	138.20	0.21	134.80	0.21
0.58	126.16	0.21	131.49	0.20	138.02	0.21	134.63	0.21
0.67	126.03	0.21	131.38	0.20	137.90	0.21	134.50	0.20
0.75	125.87	0.21	131.23	0.20	137.78	0.20	134.38	0.20
1.00	125.50	0.20	130.86	0.19	137.39	0.20	134.00	0.20
1.25	125.17	0.20	130.52	0.19	137.07	0.19	133.66	0.19
1.50	124.80	0.19	130.17	0.18	136.71	0.19	133.26	0.19
1.75	124.38	0.19	129.75	0.18	136.31	0.18	132.88	0.18
2.25	123.64	0.17	129.02	0.17	135.59	0.17	132.12	0.17
2.75	122.88	0.16	128.24	0.15	134.80	0.16	131.31	0.16
3.75	121.25	0.14	126.73	0.13	133.33	0.14	129.77	0.13
4.75	119.90	0.12	125.35	0.11	131.94	0.12	128.40	0.11
5.25	119.26	0.10	124.71	0.10	131.32	0.11	127.76	0.10
6.25	117.93	0.08	123.39	0.08	130.01	0.09	126.49	0.09
7.25	116.77	0.07	122.22	0.06	128.87	0.08	125.41	0.07
14.42	113.06	0.01	118.57	0.01	124.81	0.02	121.65	0.01
19.42	112.65	0.00	117.97	0.00	123.94	0.00	120.91	0.00
24.42	112.62	0.00	117.91	0.00	123.80	0.00	120.79	0.00
48.00	112.63	0.00	117.92	0.00	123.81	0.00	120.80	0.00
72.00	112.62	0.00	117.91	0.00	123.78	0.00	120.80	0.00

3.1.3.4. Water Drying Data, continued

Table 11. Water Drying Rate

Sample	Initial Drying Rate g/(cm ³ hr)	Correlation factor
1	0.023	0.999
2	0.022	0.999
3	0.021	0.999
4	0.022	0.999

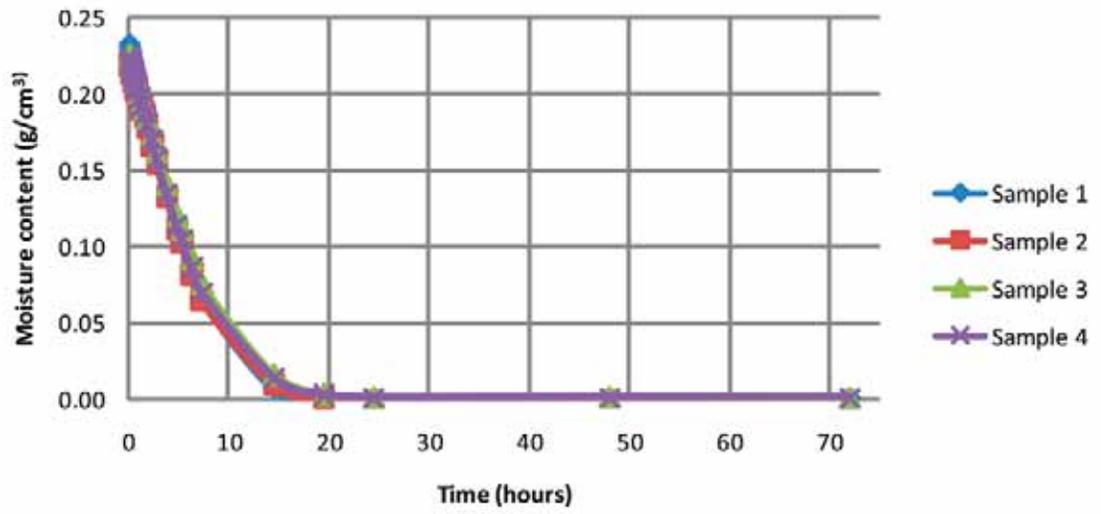
Average Initial Drying Rate

$$= 0.022 \text{ g/ (cm}^3 \text{ hr)}$$

Critical Moisture Content

$$= 0.069 \text{ g/cm}^3$$

Water Drying: Far View House Sandstone



Graph 20. Water Drying

3.1.4. Frost Resistance

3.1.4.1. Procedure

RILEM Test V3

In order to observe the durability of sandstone to cyclical freezing and thawing action, the stone samples were subjected to frost resistance test using RILEM V3. There were two variations in the testing that deviated from the procedure. Instead of the recommended size, 4 inches long x 1 inch high x 1 inch wide sandstone prisms were used to reduce the amount of sample needed. In addition, 16 hour cycles with alternating 8 hours of freezing and thawing were used, instead of 12 hour cycles with alternating 6 hours of freezing and thawing.

Five samples were placed along their lengths on a grided gardening box with holes in the bottom. The sandstone prisms were then immersed in cold water of 5 deg C for 8 hours. Afterward, they were moved out of the water bath and into the freezer at -15 deg C for another 8 hours. The cycle was repeated for 30 cycles for 20 days. In order to record change in bulk volume the samples were hydrostatically weighed during the first immersion, and every third cycle until completion. When the samples were taken out of the water, moisture on the samples was briefly wiped with a paper towel. They were also photographed for visual comparisons at every weighing.

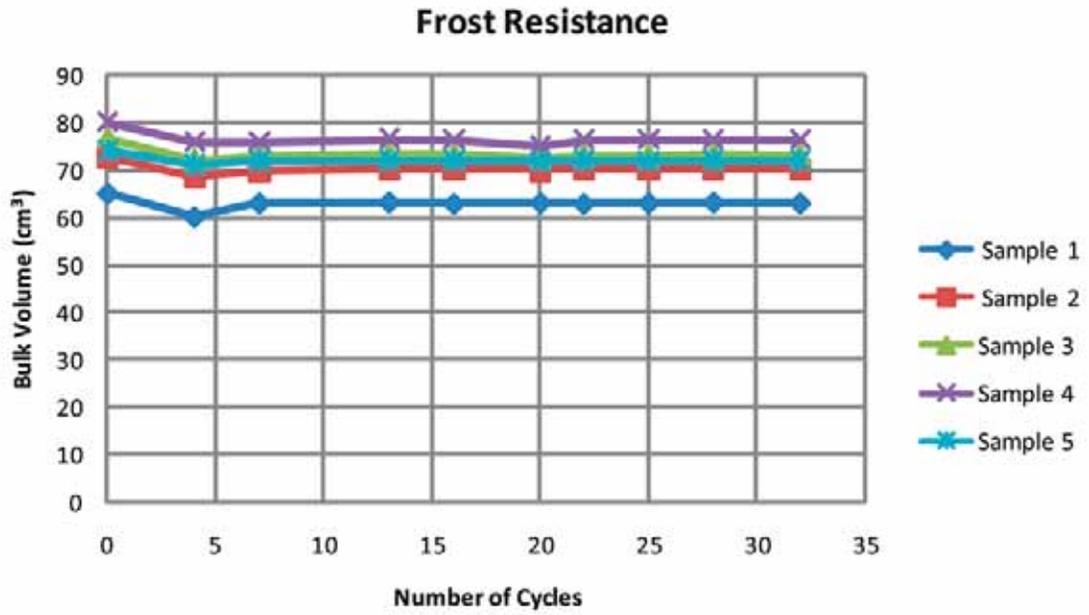
3.1.4.2. Possible Sources of Error

While the cycling regime adhered to the 8 hour alternation, there were variations of plus or minus ten minutes due to time needed for performing hydrostatic weighing and the photo-documentation of samples.

3.1.4.3. Frost Resistance Data

Table 12. Bulk Volume of Sandstone Prisms during Frost Resistance Test

Number of Cycle	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
0	65.23	72.69	76.76	80.19	74.12
4	60.15	68.7	72.20	76.03	71.19
7	63.13	70.05	73.19	76.10	71.97
13	63.32	70.35	73.33	76.60	71.97
16	62.97	70.34	73.25	76.23	71.96
20	63.20	70.10	72.79	75.15	71.85
22	62.98	70.27	73.07	76.53	71.97
25	63.16	70.41	73.03	76.46	71.85
28	63.30	70.46	73.25	76.53	71.95
32	63.10	70.39	73.14	76.56	71.92
% Volume Change after 32 cycles	-3.27	-3.16	-4.72	-4.53	-2.97



Graph 21. Frost Resistance

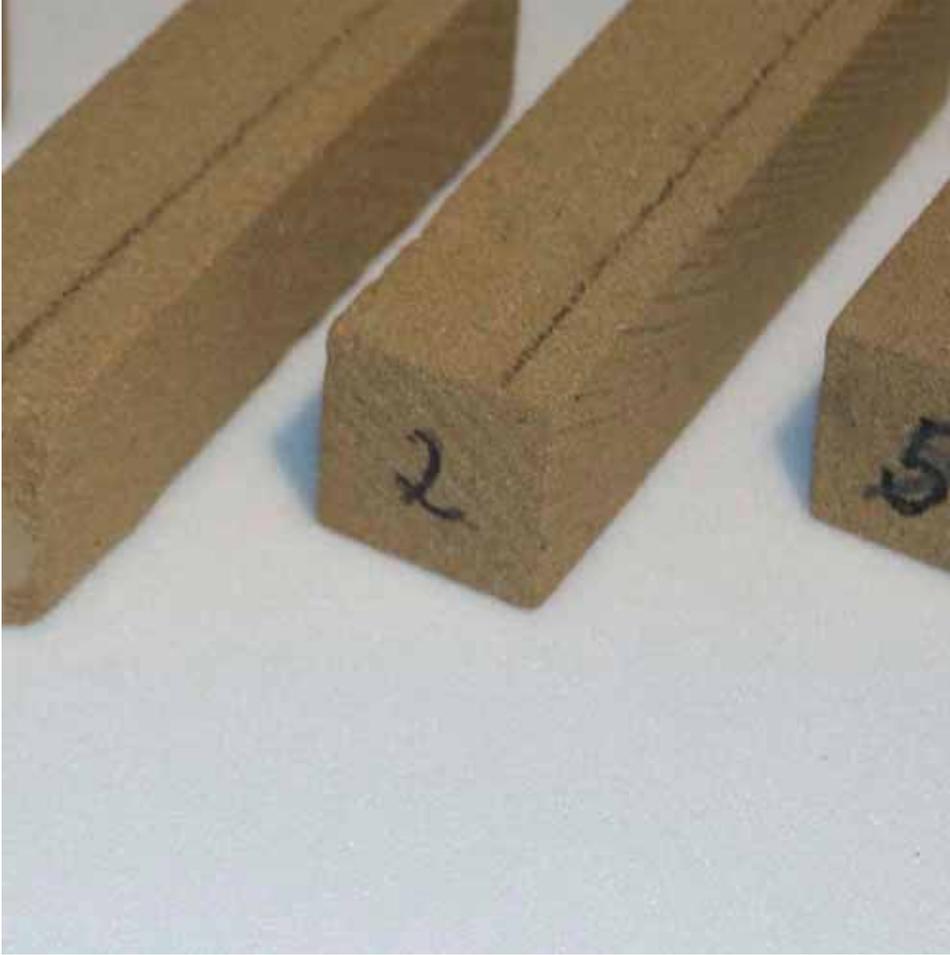


Figure 35. Samples before Freeze/thaw (Lim 2009) (Note: Dark line is a pencil mark)



Figure 36. Sample after 32 cycles of Freeze/thaw (Lim 2009)

3.1.5. Mechanical Properties

Two types of strength tests, flexural and compressive, were performed following ASTM standards. An Instron Testing Machine Model 4206 at the Laboratory for Research on the Structure of Matter (LRSM) at the University of Pennsylvania was used for the test.

3.1.5.1. Flexural Strength

3.1.5.1.1. Procedure

ASTM Standard C99 – 87: Standard Test Method for Modulus of Rupture of Dimension Stone

In order to calculate the dry-to-wet strength ratio, sandstone prisms, one group dry and the other wet of 4 inches long x 1 inch high x 1 inch wide were prepared to determine the modulus of rupture.

Ten recordings were made from each dry and wet sample set. Each sandstone prism was subjected to the testing twice at 2 inches span (or Gauge Length). The depth and width of each test sample was measured near the quarter and the third quarter length, where the samples made contacts with knife edges. All knife edges were parallel to the rift of the stone.

The samples were loaded on two parallel supporting knife edges at 2 inch spans and were subjected to a load from a loading knife edge with a speed of 0.01 inch per

minute. The initial load of 10N established complete surface contact. The load was applied until failure. All knife edges were parallel to the rift of the stone.

Modulus of Rupture

$$R = 3Wl/2bd^2$$

Where:

R = modulus of rupture, psi

W = breaking load, lbf

L = length of span, in

B = width of specimen, in, and

D = thickness of specimen, in

3.1.5.2. Compressive Strength

3.1.5.2.1. Procedure

ASTM Standard C170 – 90: Standard Test Method for Compressive Strength of Dimension Stone

In order to calculate the dry-to-wet strength ratio, sandstone cubes were cut and repolished from the fragments from the 3-point bending test. One group dry and the other wet of 1 inch long x 1 inch high x 1 inch wide were prepared to determine the modulus of rupture.

Load was applied both perpendicular and parallel to the stone rift. For each rift direction, seven wet samples and nine dry samples were prepared.

An Instron Testing Machine Model 4206 at the Laboratory for Research on the Structure of Matter at the University of Pennsylvania was used for the test. The sample

was subjected to initial loading of 10N to ensure complete surface contact. The load was applied at 0.01 inch per minute until failure.

Compressive Strength

$$C = \frac{W}{A}$$

Where:

C = compressive strength of the sample, psi

W = total load, lbf, on the sample at failure, and

A = calculated area of the bearing surface in in²

3.1.5.3. Sources of Error

3.1.5.3.1. Surface finish

Depending on how the sample surface was prepared, the behavior under compressive forces may show differences. In particular, the saw mark left visible striations on the surface that created wavy contours. When the thick steel coupon was applied on the surface, the load was focused along the edges of these contours, resulting in line loading. This explains why the cracks that developed tend to follow the micro grooves formed by the saw mark. The error affected both dry and wet samples.

3.1.5.3.2. Air Drying during Testing

Approximately 3 to 10 minutes of drying in air during wet sample testing could have slightly affected the water saturation level of the samples. Great care was taken to minimize the drying time by keeping the samples immersed throughout the testing except for one under study.

3.1.5.3.3. Modulus of Rupture Data

Table 13. Modulus of Rupture, Perpendicular to Rift

Sample	Type	Direction to Rift	Cross Section (in ²)	Cross Section (mm ²)	Modulus of Rupture (psi)	Modulus of Rupture (MPa)
D1	Dry	L	0.97	622.75	379.78	2.62
D2	Dry	L	0.94	607.48	421.63	2.91
D3	Dry	L	0.99	639.10	473.02	3.26
D4	Dry	L	0.99	635.82	445.10	3.07
D5	Dry	L	0.98	634.81	444.56	3.07
D6	Dry	L	0.98	635.02	383.08	2.64
D7	Dry	L	1.08	693.59	437.37	3.02
D8	Dry	L	1.10	711.01	406.44	2.80
D9	Dry	L	1.20	774.54	390.30	2.69
D10	Dry	L	1.18	758.29	359.92	2.48
W1	Wet	L	1.02	659.79	142.47	0.98
W2	Wet	L	1.02	656.45	174.90	1.21
W3	Wet	L	1.00	647.71	192.33	1.33
W4	Wet	L	1.01	650.33	195.73	1.35
W5	Wet	L	1.07	691.02	163.22	1.13
W6	Wet	L	1.09	706.13	160.00	1.10
W7	Wet	L	1.02	654.86	199.65	1.38
W8	Wet	L	1.03	667.19	202.35	1.40
W9	Wet	L	1.02	660.45	184.23	1.27
W10	Wet	L	1.01	650.15	196.83	1.36
F1	Frost	L	1.12	721.77	193.44	1.33
F2	Frost	L	1.13	732.06	197.79	1.36
F3	Frost	L	1.20	775.69	215.52	1.49
F4	Frost	L	1.20	773.05	178.83	1.23
F5	Frost	L	1.10	709.00	144.70	1.00
F6	Frost	L	1.09	702.64	192.54	1.33

(W: wet, D: dry, F: freeze/thaw)

3.1.5.3.4. Compressive Strength Data

Table 14. Compressive Strength, Perpendicular to Rift

Sample	Type	Direction to Rift	Cross Section (in ²)	Cross Section (mm ²)	Compressive Strength (psi)	Compressive Strength (MPa)
D1	Dry	L	1.01	649.46	2806.02	19.35
D2	Dry	L	1.04	667.93	2825.08	19.48
D3	Dry	L	1.10	707.71	2374.75	16.37
D4	Dry	L	1.02	659.33	3877.24	26.73
D5	Dry	L	1.02	655.12	2849.10	19.64
D6	Dry	L	0.97	624.74	2518.68	17.37
D7	Dry	L	1.04	669.16	2011.58	13.87
D8	Dry	L	1.02	658.75	1817.18	12.53
D9	Dry	L	0.94	603.97	2782.66	19.19
W1	Wet	L	0.99	636.16	2119.42	14.61
W2	Wet	L	1.05	677.99	1589.05	10.96
W3	Wet	L	1.07	689.80	1657.75	11.43
W4	Wet	L	1.06	681.51	2052.33	14.15
W5	Wet	L	1.06	684.11	2373.78	16.37
W6	Wet	L	1.05	678.74	2353.10	16.22
W7	Wet	L	1.03	667.72	1490.84	10.28

3.1.5.3.4. Compressive Strength Data, continued

Table 15. Compressive Strength, Parallel to Rift

Sample	Type	Direction to Rift	Cross Section (in ²)	Cross Section (mm ²)	Compressive Strength (psi)	Compressive Strength (MPa)
D1	Dry	//	1.08	699.18	1696.35	11.70
D2	Dry	//	1.13	728.28	1741.03	12.00
D3	Dry	//	1.08	694.30	3223.70	22.23
D4	Dry	//	1.11	716.00	2884.00	19.88
D5	Dry	//	1.12	723.46	2590.85	17.86
D6	Dry	//	1.12	722.82	1817.38	12.53
D7	Dry	//	1.07	689.99	2819.23	19.44
D8	Dry	//	1.05	678.37	1576.57	10.87
D9	Dry	//	1.00	647.58	1656.39	11.42
W1	Wet	//	1.09	705.69	691.92	4.77
W2	Wet	//	1.16	747.87	665.53	4.59
W3	Wet	//	1.16	746.83	1360.33	9.38
W4	Wet	//	1.15	743.71	1486.77	10.25
W5	Wet	//	1.09	700.78	1638.53	11.30
W6	Wet	//	1.06	681.79	1517.82	10.46
W7	Wet	//	1.09	705.88	1138.01	7.85

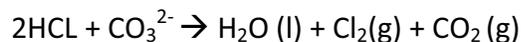
3.1.6. Salt Testing

3.1.6.1. Procedure

The salt test was performed on stone and mortars (original + repointing) and ground soil using semi-quantitative ion indicator strips. Chloride, sulfate and nitrate ions were identified by ion strip tests while carbonate ions were tested qualitatively by spot testing.

The sample mortars and soils were ground and dissolved in deionized water. The solution was then filtered and the final volume was measured to roughly calculate the concentration of the dissolved salts.

The presence of carbonate was determined by the solution's reaction with hydrochloric acid. A vigorous bubble formation indicates the presence of carbonate.



3.1.6.2. Sources of Error

While these strips allow semi-quantitative analysis, since the strips had expired their due date, the color readings were deemed less accurate.

The soil sample taken from Room 13 middle east side also contains high level of nitrate ions (0.20 %). This is in contrast to the soil sample from the northeast corner of the same room, where nitrate ions concentration is low (0.02 %). The contrast may stem from sampling itself, where the sample taken may not be representative of the area. Another possibility may have resulted from the high amount of moisture content

available in the northeast corner due to the surface runoff water facilitated by the sloped wall. The higher level of moisture in this corner indicates that when water evaporates, it will carry the soluble salts to the perimeters of the wet soil area following the moisture gradient. As a result more salts will be present away from the northeast corner. Still another possibility for difference in soluble salts content is simply the proximity to bio-organism. The mid east section of Room 13 is closer to the area in the southeast corner of the room where weeds grow. Water from surface runoffs easily saturate this area as indicated by lichens on the wall surfaces.

3.1.6.3. Salt Testing Data

Table 16. Salt Testing

Salt Concentration (g/g %)	Total	Chloride	Sulfate	Nitrate	Carbonate
Test		Merckoquant® Chloride Test	Merckoquant® Sulfate Test	Merckoquant® Nitrate Test	Reaction with HCL
Original Soil Mortar	2.23	Negligible	Negligible	.28	No
Repair Soil Mortar	1.45	Negligible	Negligible	.02	Yes
Cement Mortar	1.34	Negligible	0.932	Negligible	Yes
Soil #1, Rm 13 Northeast Corner	3.62	Negligible	Negligible	0.02	Yes
Soil #2, Rm 13 Middle East Side	2.00	Negligible	Negligible	0.20	Yes
Soil #3, Rm 28 Middle West Side	2.87	Negligible	Negligible	0.01	Yes

3.1.6.4. Salt Testing Data, Continued

Table 17. Mortars and soil samples except cement mortar

	Molar Weight (g/mol)	% salt concentration (g/g)				
		Original Mortar	Repair Mortar	Soil, #1	Soil, #2	Soil, #3
NO_3^-	62	0.28	0.02	0.02	0.20	0.01
NaNO_3	85	0.38	0.02	0.02	0.27	0.01
$\text{Ca}(\text{NO}_3)_2$	164	0.74	0.042	0.045	0.516	0.026

Table 18. Cement mortar

	Molar Weight (g/mol)	% salt concentration (g/g)
SO_4^{2-}	96	0.93
NaKSO_4	158	1.58
CaSO_4	136	1.36
Na_2SO_4	142	1.42

3.2. Mortar

3.2.1. Atterberg Limits Test

3.2.1.1. Procedure

Atterberg Limits test was performed on original mortars ground and passed through a 425 μm sieve (# 200). The Plastic limit and Liquid limit were identified.

3.2.1.2. Sources of Error

The samples could have dried while measuring weights.

3.2.1.3. Atterberg Limits Test Data

Table 19. Plastic Limit

Plastic Limit, Original Mortar	Sample 1	Sample 2	Sample 3
Container Weight (g)	23.52	23.49	24.05
Wet Sample with Container (g)	29.72	29.2	32.1
Dry Sample with Container (g)	28.67	28.25	30.74
Moisture (g)	1.05	0.95	1.36
Dry Sample weight (g)	5.15	4.76	6.69
% Plastic Limit	20.4	20.0	20.3

Table 20. Liquid Limit

Liquid Limit, Original Mortar	Sample 1	Sample 2	Sample 3
Container Weight (g)	23.52	23.49	24.01
Wet Sample with Container (g)	26	25.44	25.98
Dry Sample with Container (g)	25.38	24.94	25.47
Moisture (g)	0.62	0.5	0.51
Dry Sample weight (g)	1.86	1.45	1.46
% Liquid Limit	33.3	34.5	34.9

Average Plastic Limit = 20.2

Average Liquid Limit = 34.2

Plasticity Index = Average Liquid Limit - Average Plastic Limit = 14

3.2.2. Mortar Analysis

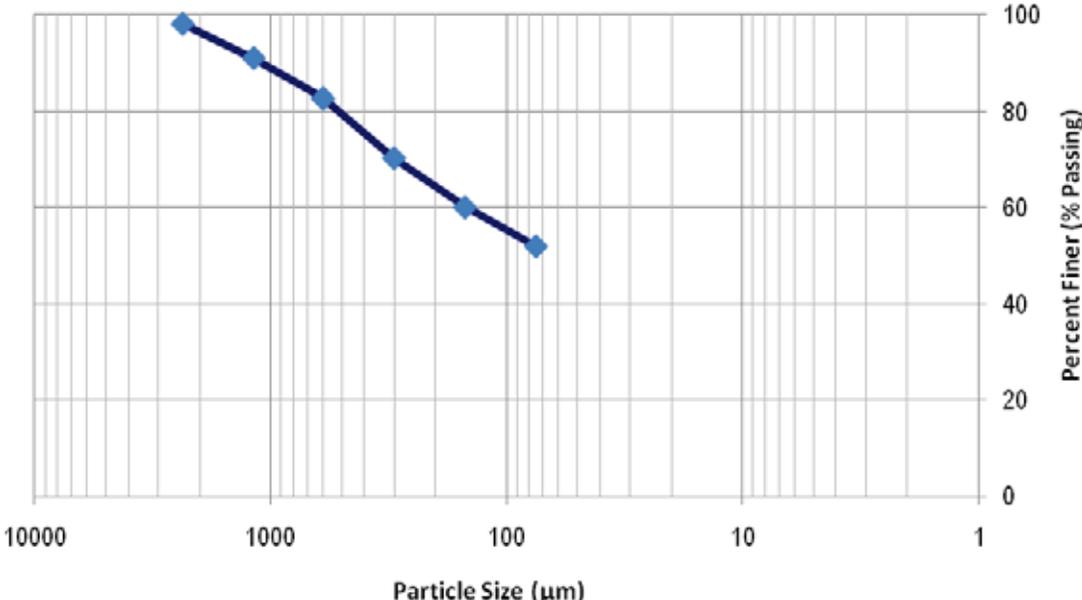
3.2.2.1. Procedure

Bulk mortar samples were ground and oven dried. They were then dissolved in 14% (w/v) hydrochloric acid to dissolve binding materials. The remaining samples were then separated by filtering and dry sieving.

3.2.2.2. Sources of Error

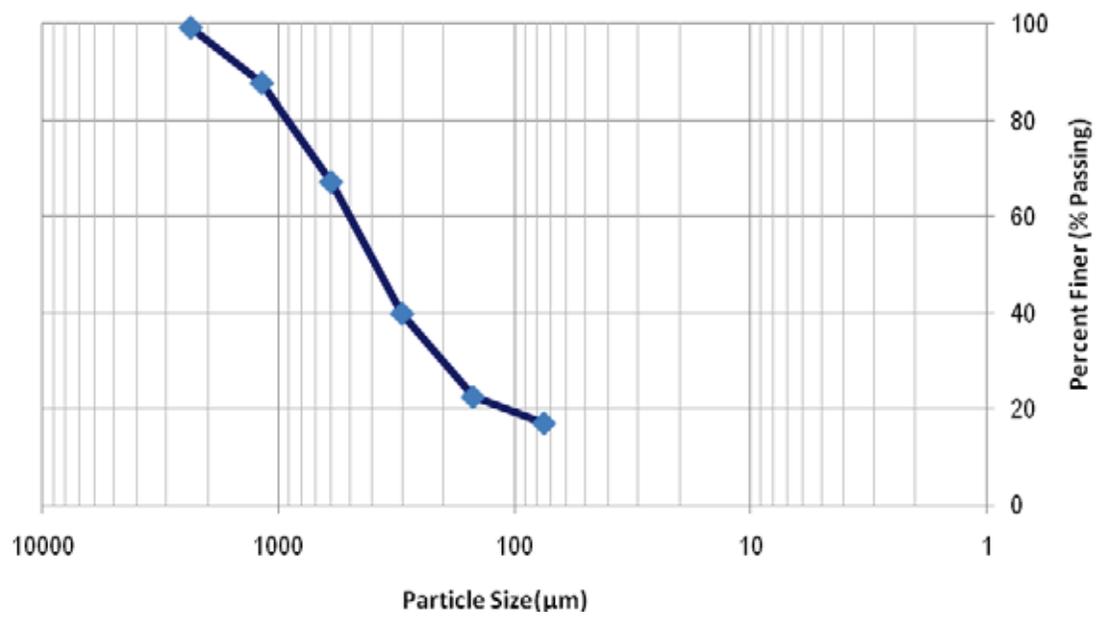
HCL dissolves calcareous aggregates and some silicates regardless of whether they are binder materials or not. Therefore, the result may represent inaccurate binder/aggregation proportions.

Particle Size Distribution Repair Mortar, Dry Sieving



Graph 22. Repair Mortar Particle Size Distribution

Particle Size Distribution Cement Mortar, Dry Sieving



Graph 23. Cement Mortar Particle Size Distribution

APPENDIX C: Supplier List

GSE Lining Technologies, Inc.

19103 Gundle Road
Houston, TX 77073
281.230.6747

<http://www.gseworld.com>

McMaster-Carr Supply Company

6100 Futon Industrial Blvd. SW
Atlanta, GA 30336
404.346.7000

<http://www.mcmaster.com>

Pelican™ Products, Inc.

23215 Early Avenue
Torrance, CA 90505
310.326.4700

<http://www.pelican.com>

Poly-Flex, Inc.

2000 W. Marshall Drive
Grand Prairie, TX 75051
888.765.9359

<http://www.poly-flex.com>

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