A Comparative Study of Epoxide Resin and Cementitious Grouts for the Delamination of Sandstone at El Morro National Monument, New Mexico

Dawn Marie Melbourne
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A COMPARATIVE STUDY OF 
EPOXIDE RESIN AND CEMENTITIOUS GROUTS 
FOR THE DELAMINATION OF SANDSTONE 
AT 
EL MORRO NATIONAL MONUMENT, NEW MEXICO

Dawn Marie Melbourne

A THESIS

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1994

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ABSTRACT

Inscription Rock, part of El Morro National Monument in New Mexico, has experienced deterioration and loss of areas of inscribed sandstone through the detachment and subsequent delamination of layers of stone. While grouting is a frequently used and versatile technique for the concealed reattachment of delaminated layers of stone and related materials, the question remains as to the type of grout and method of application for reattaching exfoliating layers of stone of historic importance which are under a potentially wide range of mechanical stresses. In response, an experimental program was designed to investigate and compare the properties of epoxide resin and cementitious grouts applied as continuous films, epoxy "spot welds" and a combination of both epoxy "spot welds" and cementitious grout infill, and to assess the physical and mechanical properties of these various methods of application and their relative effects on the stone. The ultimate objective of the experimental program was to determine the minimum amount of adhesive required for readhesion, and to assess whether epoxy applied as spot welds was more or less effective than epoxies and cementitious grouts applied as continuous adhesives. The results of the experimental program revealed several significant differences between the mechanical properties of the epoxy and cementitious grouts and the effectiveness of the various application methods tested. On the basis of these results, only two materials and three systems of application were chosen for further testing in the second phase of the project. The purpose of this second phase was to develop a program to field test at Inscription Rock the grouting materials and systems of application recommended as a result of the research and testing carried out in the first phase of the project. A program of field testing, aided by means of nondestructive investigation, was thus carried out in order to provide the opportunity for in situ evaluation of the facility of grout application, verification of the success of grouting and assessment of the weathering of the systems.
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PREFACE

The Architectural Conservation Laboratory of the University of Pennsylvania and the Southwest Regional Office of the National Park Service undertook a joint research and training program in response to the ongoing deterioration of the petroglyphs and inscriptions carved into the surfaces of Inscription Rock, part of El Morro National Monument in New Mexico. The project was conducted under a cooperative agreement established in 1992 between the university and the National Park Service, and provided graduate thesis research and practical conservation training. The project was undertaken from September 1993 to July 1994. Team members included: Frank G. Matero (U/Penn), Jake Barrow (NPS/SWRO), and Mike Taylor (NPS/SWRO), project directors; Dawn Melbourne (U/Penn), project intern.

Early documentation at El Morro indicates that damage has occurred to areas of inscribed sandstone, displaying detachment and subsequent exfoliation of layers of stone. Although Inscription Rock suffers from a multitude of deterioration phenomena, the problem of detachment and subsequent exfoliation of layers of sandstone can be considered to be of considerable urgency, deserving immediate attention. Thus, the treatments selected and tested in this study were chosen and designed to address the problem of reattaching exfoliating layers of sandstone and re-establishing adhesion between the detached layers and the sound stone.

The choice of conservation treatments and materials tested was based upon a four fold approach:

• the characterization of the stone and its mechanical and physical properties

• the determination of the mechanisms of deterioration responsible for the primary weathering and detachment of the stone

• identification of environmental conditions on site

• the assessment of past treatments of the observed deterioration, including an extensive literature review
One standard solution to problems of detachment in both the conservation and engineering fields is injection grouting. Grouting may be defined as the injection of appropriate liquid materials under pressure into voids and cracks through the surface in order to fill and therefore seal voids, cracks, seams, fissures or other cavities in building materials, soils or rock strata. Recent conservation research has focused on developing appropriate in situ methods of readhering non-structural layers of detached materials such as paints, plasters and mosaics to their substrate. This technique of injection grouting, borrowed from civil engineering, requires modification to meet the needs of conservation. Both the materials and methods of application often require the substitution of high strength polymeric and cementitious grouts applied in large quantities through high pressure injection with lower strength materials, such as lime or hydraulic lime based grouts, applied using low pressure injection. These efforts have been based in large part on the use of materials and methods which conform to the primary chemical and mechanical the issues of compatibility of the grout and adherend including water vapor permeability of the system, low shrinkage and the presence of damaging soluble salts. While lime and hydraulic lime based grouts often used in masonry conservation may provide adequate structural support for some situations, they do not always demonstrate adequate mechanical properties for materials under substantial stress.

Because of their excellent mechanical properties, the use of high strength industrial adhesives (polymeric and cementitious grouts) have long been used in engineering for the structural consolidation and stabilization of masonry structures such as dams, bridges and rock faces. These materials are expected to behave as structural adhesives which fill cracks and act as water sealants. The success of such industrial grouting is generally equated with high strength and complete readhesion between the adherends, 100% being optimal. One of the problems with this approach, is that high strength polymeric and cementitious grouts can be deleterious to an already fragile material. Water vapor permeability, for example, can be significantly altered causing mechanical and chemical damage from salts and ice. High pressure injection may accelerate detachment and reactive grouts such as cements are known to cause efflorescence and further loss of material due to high
differences in strength, permeability and thermal expansions between the grout and the historic material.

While grouting appears to be the most appropriate and versatile technique for the concealed reattachment of delaminated layers of stone and related materials, the question remains as to the type of grout and method of application for reattaching exfoliating layers of stone of historic importance which are under a potentially wide range of mechanical stresses. In response, an experimental program was designed to investigate and compare the properties of epoxide resin and cementitious grouts applied as adhesives both as continuous films, epoxy "spot welds" and a combination of both epoxy "spot welds" and cementitious grout infill, and to assess the physical and mechanical properties of these various methods of application and their relative effects on the stone. The ultimate objective of the experimental program was to determine the minimum amount of adhesive required for readhesion, and to assess whether epoxy applied as spot welds was more or less effective as epoxies and cementitious grouts applied as continuous adhesives.

Compound assemblies of unweathered, commercial sandstone were fabricated to simulate the thickness of detachment measured at Inscription Rock. The detachment joints of these assemblies were grouted with pre-selected epoxies and cementitious grouts in a series of applications, cured and subjected to selected tests to measure their effectiveness as adhesives. Commercial stone was used in the experimental program in order to provide more measurable and statistically comparable results. While the quantitative results of this study may not be directly applicable to the Zuni Sandstone of Inscription Rock, qualitative comparisons between the various grouting materials and the selected means of application are relevant.

The results of the experimental program revealed several significant differences between mechanical properties of the epoxy and cementitious grouts and the effectiveness of the various application methods tested. On the basis of the results of the experimental program only two materials and three systems of application were chosen for further testing in the second phase of the project.
The purpose of this second phase was to develop a program to field test at Inscription Rock the grouting materials and systems of application recommended as a result of the research and testing carried out in the first phase of the project. A program of field testing, aided by means of nondestructive investigation, was thus carried out in order to provide the opportunity for *in situ* evaluation of the facility of grout application, verification of the success of grouting and assessment of the weathering of the systems.
1.1. SITE HISTORY

Part of El Morro National Monument, Inscription Rock is one of the many mesas that randomly cover the highlands of the northwest region of New Mexico. What sets Inscription Rock apart from the other sandstone outcrops, is a life-sustaining natural water basin nestled at its base. Undoubtedly water was the attraction, which prompted Inscription Rock to play host to a long and varied list of guests whose presence has been made known to us through a legacy of petroglyphs and inscriptions on the rock face.

The layered and varied history of this region is played out on the rock faces of El Morro. The foundations of this historical collage were first laid by the Anasazi, native Americans who occupied the four corners region of the southwest, and whose history dates back to at least 400 AD. The Anasazi largely constructed and inhabited villages of masonry structures which consisted of cellular, contiguous, flat-roofed rooms. (Lister and Lister 1983, 30) The ruins of one such village still exists on the top of Inscription Rock.

Aside from the archeological ruins of the village atop Inscription Rock, evidence of the Anasazi occupation can be seen at the base of the outcrop. Here, the Anasazi carved petroglyphs into the stone of different shapes and sizes, often representing animals and humans. The existence of these petroglyphs provides insight into a culture and people long gone from the region.

With the arrival of the Spanish colonialists in the late sixteenth century, begins a tradition, which existed into the present century, of using El Morro as a kind of monolithic writing tablet. In 1605 the first non-native American to make his mark on Inscription Rock was the Spanish conquistador Juan de Onate. In the years that followed, travelers, soldiers, clergymen, workers and pioneers inscribed bits of information about themselves and their travels past El Morro. Pieced together, the inscriptions of hundreds of people spanning several centuries, read like a narrative which tells the tale of military campaigns, exploratory expeditions, and emigration and expansion into the American west.
The impact of these petroglyphs and inscriptions, which provide us with an historical account of the development of the southwest region of the country, is compounded by the fact they have survived in their natural historical context. One experiences an incredible power of place standing at the foot of the enormous outcrop, looking out over the spotty terrain whose contours have remained virtually unchanged since the time the first inscriptions were carved into the stone. Unlike museum installations where fabricated context is necessary in order to create a sense of place for the historical artifacts which line the exhibit cases, Inscription Rock needs no ambiance or setting to be artificially contrived. The petroglyphs and inscriptions at El Morro have become an integral part of the site, therefore their preservation in situ is paramount in any conservation treatment proposed.

1.2. CHARACTERIZATION OF ZUNI SANDSTONE

In 1992, the National Park Service contracted George S. Austin, a geologist with the New Mexico Bureau of Mines & Mineral Resources, to conduct a geological and hydrological assessment of El Morro National Monument. (Austin 1992) His analysis and assessment of the site includes a mapping and evaluation of the outcrop, evaluation of micro-geology of the land form, laboratory analysis and characterization of the stone types existing in the outcrop and the effects of hydrology and differentiation in geology of the outcrop on the inscriptions. In order to provide insight into the weathering of the inscriptions, a summary of Austin's report follows in this section of the report.

The geological stratigraphy of El Morro consists of different layers of rock from various stages in the geological time line. The earliest layer consists of eolian, dunal, deposits of Zuni Sandstone existing from the Middle Jurassic period. For the most part this rock remained the same until the beginning of the late Cretaceous period, when sedimentation occurred due to lower coastal-plain, marginal-marine and marine deposition. These marine depositions are represented in the next layer of rock in El Morro's stratigraphy known as Dakota Sandstone.

The majority of inscriptions at El Morro have been carved in the Zuni Sandstone, an evenly sorted, fine-to-medium grained quartzitic sandstone.
This sandstone is primarily composed of well rounded quartz grains. There are two types of chlorite present in the Zuni Sandstone; yellow-green, rounded, fine-grained particles that appear to be altered fecal pellets and smaller, brownish-green void-filling particles. The cementing agent or void filling masses of the sandstone are most-likely a mixture of clay-size particles of well-crystallized chlorite and kaolinite. Because the nature of its deposition was primarily eolian, Zuni Sandstone does not exhibit regular bedding strata, but crossbedding ranging from large to small from upper to lower regions of the outcrop. The color of the sandstone is pale yellowish gray with a greenish cast, the greenish color probably due to the inclusion of clay particles of chlorite and smectite.

There is a zone of bleached stone in the upper region of the Zuni Sandstone; a result of leaching in a strongly acidic environment during the Early Cretaceous period. There are locally cross cutting zones of red or greenish-gray staining and large, spheroidal, gray-brown nodules with calcitic cement and introduced organic material. The thickness of the Zuni Sandstone beds varies from 60m to 105m.

Within the outcrop, there are several large fractures known as geological joints. The age of the joints ranges from old to new, with some of the joints believed to be from the Early Cretaceous period. The faces of these joints have undergone alteration during their aging process due to mechanical abrasion and chemical reactions. The joints provided pathways for iron rich, acidic water to percolate down the rock. As a result of oxygenation, the joints were discolored and pores were filled with brown and yellow iron oxides. The chlorite was reduced to Fe₂ and Fe₃ and altered to limonite.

Limonite is a very chemically stable and hard material. Much of what is seen now as the outer rock faces of Inscription Rock was probably once joint faces, whose surfaces have been altered to a limonite crust, long since exposed. Most of the Anasazi petroglyphs appear on these harder limonite surfaces. Because the limonite crusts tend to be very hard and stable, the Anasazi petroglyphs carved on its surface have not suffered much granular erosion which may be caused by surface abrasion of clay washes from the top of the outcrop or rain water.
Calcium carbonate crusts have formed on more friable Zuni Sandstone. These crusts are caused by alkaline-rich water coming in contact with stone and evaporating, leaving behind deposits of calcium carbonate.\(^1\) The rain water in the region of El Morro is not alkaline, so the source of alkalinity water is probably from well water below the ground. This reaches the outcrop in the form of rising damp, having the greatest effect on the stone closest to the ground. The post 1605 inscriptions tend to be located on the calcium carbonate rich crusts of the Zuni Sandstone.

The source of kaolinite in the Zuni Sandstone is unclear. It may be a result of the alteration of feldspars into kaolinite. The downward migration of the kaolinite from the upper regions of the outcrop is believed to be the mechanism of kaolinite becoming part of Zuni Sandstone.

The Dakota Sandstone, deposited from a marginal-marine environment, consists of redepsoited Zuni Sandstone, as well as medium-coarse-grains of quartz, chert and rock fragments and kaolinite in the lower region. In the middle region, Dakota Sandstone is olive-gray to light to dark gray mudstone. The Dakota Sandstone has a more durable siliceous cementing material, protecting the underlying clay-cemented Zuni Sandstone. The lower part is 0 -15m thick, overall never exceeding 38m in thickness.

1.3. DETERIORATION AFFECTING THE INScriptions

Unfortunately Inscription Rock is suffering the weathering effects of nature and human intervention. As a result, many of the inscriptions and petroglyphs have diminished in clarity or completely disappeared from the rock face. The deterioration of the inscriptions is most likely not caused by isolated deterioration mechanisms, but rather is a function of a combination of several factors including the heterogeneous physico-chemical properties of the stone, environmental conditions such as temperature fluctuations from extreme highs to extreme lows, wind and moisture, biological growth and possibly past conservation treatments.

\(^{1}\)Per conversation with George Austin, June 1994.
A recent study and documentation of the inscriptions (Padgett 1992) outlines several observable deterioration mechanisms affecting the inscriptions at El Morro. After identifying the various deterioration mechanisms, a conditions assessment was made of each inscription in an attempt to distinguish the specific factors affecting the inscriptions. (Padgett 1993) The following are the major deterioration mechanisms identified in Padgett's report:2

1. A water/clay wash which appears to be a result of excess rain water washing down off the top of the outcrop as well as percolating out from within the stone from joints and cracks.
2. Insect activity, especially caterpillars (although it is still unclear whether the holes and burrows these insects inhabit are a result of the insects or natural dissolution of the stone)
3. Biological growth in the form of lichen, mosses and algae which appears on many areas of the rock in varying degrees of intensity.
4. Moisture in the form of runoff from the top of the outcrop, rise and damp, and vertical and horizontal percolation.
5. Human intervention in form of touching the stone, past conservation treatments, erasure of inscriptions and darkening of inscriptions with pencils.
6. Vegetation in close proximity to the stone.
7. Present water level of the water hole at the base of the outcrop.
8. Weak cementing agents in the Zuni Sandstone, composed primarily of clay minerals, in particular kaolinite and chlorite.
9. Climate.

Symptomatic conditions descriptions are still to be ascribed to the deterioration mechanisms. Because the extent of each deterioration mechanism and the direct and indirect effect on the inscriptions has not yet been quantified or monitored, it is difficult to interpret the severity of each reported mechanism and for that matter any possible interrelation. Hypotheses regarding the effects of the deterioration mechanisms are sound, yet for the most part they have not been verified with extensive testing or

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examination. Therefore, it would be premature to attempt to correlate the observed deterioration mechanisms with specific effects.³

The relative effects of deterioration are, however, identifiable to a certain extent, and should be addressed. The stone suffers in isolated areas from granular erosion, where grain to grain cohesion has been lost resulting in a subsequent loss of material and reduction of clarity of the inscriptions. This is particularly problematic in areas which are dressed in petroglyphs and inscriptions. Another problem facing the inscriptions is the coating of the stone with clay particles. This is probably due to the clay wash, however the degree of severity of the clay wash has yet to be determined, other than that it obscures the inscriptions below.

Perhaps the most serious effect of deterioration is the detachment of layers of stone of various thickness and area. Though the extent of the voids caused by detachment are not clearly discernible without the means of non-destructive testing, the effects are obvious: subsequent delamination of the weakened, detached layers and total loss of surface. The delamination of layers of stone can result in fragments of stone falling off the rock face, often shattering upon impact with the ground. These fragments range in size from very small to very large. The existence of this problem is observable when one refers to archival documentation and finds that many inscriptions have been lost by this mechanism. ⁴

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³Austin’s report discusses briefly the weathering of the inscriptions, noting the friable nature of the Zuni Sandstone. Austin states that water sources which appear to be detrimental are rain and surface water. The rain and surface water may, according to Austin, have caused degradation by mechanical, not chemical means, as water hits the surface of the stone often carrying with it small abrasive particles which can abrade the stone or clog its pores. Acid rain was not judged to be problematic.

⁴As per conversation with George Austin, the detachment and delamination of layers of stone can possibly be attributed to the differentiation of thermal and conductive properties of the calcium carbonate crust on which many of the inscriptions have been carved, and the softer weaker stone beneath.
2. GROUTING: CEMENTITIOUS AND SYNTHETIC RESIN GROUITS - CHARACTERIZATION AND USE FOR THE CONSERVATION OF STONE
2.1. OVERVIEW

One of the most common failures of many types of stone, whether it be building stone or natural rock formations, is the detachment and subsequent delamination of surface layers. Though the reasons for this deterioration phenomenon and the severity of the problem vary according to the type of stone and the particular environmental circumstances, the problem remains the same. How does one re-establish adhesion between the substrate and the detaching layers to restore structural integrity and avoid loss of material?

Historically, the repair of such problems involved pinning with metal anchors and pins, sometimes causing staining and often further loss of material due to incompatibility between the reattachment devices and the substrate material. An even more common practice was the removal of the weakened material, down to what was considered to be sound material and possibly resurfacing with patching material. The option of destructive repair becomes unacceptable however when such surfaces are irreplaceable.

The invention of grouting in the early 1800’s, introduced another option for readhering layers of detaching materials to a sounder substrate. Initially developed for use in the field of engineering, the method of grouting was borrowed for use in conservation in the later half of this century. The materials and methods of application were eventually altered by conservators in an attempt to meet the conservation needs of historic material, with particular attention given to injectability, water vapor permeability of the system, compatibility thermal coefficients of expansion, low shrinkage and the presence of damaging soluble salts.

The materials most often used for the stabilization and structural consolidation of materials under potentially high mechanical stress are epoxy and cementitious grouts. Although these materials are far from perfect, they have been submitted to rigorous testing in the engineering and conservation fields and have proven reliable and effective in many practical situations. With the addition of additives and fillers, many properties of both epoxies and cementitious grouts can be manipulated and altered to meet the needs of each specific situation, making them very attractive for a wide range of applications. While no grout exists that will fulfill all the requirements of an
ideal adhesive, epoxy and cementitious grouts were selected as the grouting materials of choice for testing potential reattachment treatments of the stone at Inscription Rock which is undergoing detachment and subsequent stone loss.

2.2. **HISTORY OF MATERIALS USED IN GROUTING**

Grouting may be defined as the injection of appropriate liquid materials under pressure into voids, through specially constructed holes in order to fill and therefore seal voids, cracks, seams, fissures or other cavities in soils, building materials or rock strata. (Bowen 1981, 1) There are perhaps as many different types of grouts available, custom designed or proprietary, as there are applications. Grouting is used in several fields that range from geotechnical engineering, construction to conservation on projects that vary in nature including stabilizing dam foundations, reinforcing masonry walls, slab jacking, soil consolidation, joints between precast concrete units, demolition, mosaic consolidation and reattachment of architectural surface finishes. Whether used to consolidate, seal off water flow or as an adhesive, grouting has become an indispensable tool in the maintenance of both the natural and man-made environment.

Grouting as a documented technique can be traced to 1802 when a Frenchman named Charles Berigny consolidated masonry walls using a suspension of clay and lime with a percussion pump which he invented. (Bowen 1981, 2) Portland Cement was used as the grouting material of choice, probably for its ability to set underwater and high mechanical strength, for the lengthy construction of the first Thames Tunnel at Wapping between 1825 and 1843. (Bowen 1981, 2) In the mid-to-late nineteenth century with the advent of the railway and the availability of Portland Cement, cement grouting became widely used in the reparation of cracks or as structural enhancers for bridges and older constructions which had to support heavier loads induced by greater traffic flow. (Bowen 1981, 2) With the invention of the grouting machine by James Greathead at the turn of the century, grouting was made easier and applications of the procedure grew. As dam construction produced bigger and higher dams, the necessity for deeper drilling holes produced lightweight diamond drills and positive displacement pumps capable of higher pressure injection. (Bowen 1981, 2) Sodium silicate based grouts were
developed early in this century as a means for soil consolidation and were the first "chemical" grouts used.

In the past fifty years, the development of new building materials and larger and more complex structures and infrastructures accompanied by the advances in the chemical industry, have been catalysts in the evolution of the grouting industry, spawning new grouting materials as well as methods for their application. Today materials for grouts include cement, cement and sand, clay-cement, slag-cement, resin gypsum-cement, clays, asphalt, pulverized fuel ash, bentonite, silt, asphalt emulsions, epoxies, polyesters calcium chloride, and several other colloidal and low viscosity chemical mixtures. Although materials vary for each situation, the assessment of success of grouting is constant, measured by the percentage of the void or crack which is filled, 100% being optimal.

Grouting in conservation takes on several functions from structural repair of masonry walls to stabilizing and reattaching non-structural surface layers of paints, plasters and stuccos. Initially grouting techniques for conservation were borrowed from civil engineering, utilized primarily for the consolidation of historic masonry, where walls were stabilized by filling the voids in their thickness. This method enabled stabilization without the disassembly of the structure.

Unfortunately the wholesale use of Portland Cement was also borrowed from civil engineering practice. Portland Cement and water mixes are relatively cheap and easy to use, which made them attractive and perpetuated their use in conservation. It has been widely documented that the use of Portland Cement in historic structures, especially those exhibiting failures due of weakened materials, is often the source of material failure. The partially soluble materials such as calcium and sodium hydroxide formed during the setting reaction of cement may induce staining, efflorescence and local surface failures due to crystallization cycles. Large differences in strength and thermal coefficient of expansion of the cement and the historic material can also cause failures.

It is only recently that the use of Portland Cement as a grouting material has been reconsidered. In the early 1980's a group of researchers and scientists
from ICCROM began researching alternative materials and methods of grouting which were sensitive to issues of conservation. (Ferrangi et al. 1984) What they developed was an indispensable model for a systematic approach to developing, testing and choosing appropriate grouts. Acknowledging that grouting in conservation deals often with a complex system of several materials, each with their own chemical and physical properties, the ICCROM group outlined the difficulties confronted in grouting and the ideal properties of grouting materials. These were then compared to grouting materials currently in use to systematically eliminate any inappropriate materials. The research also involved developing and customizing grouts, and evaluating through extensive laboratory testing the properties deemed important to the success of a grout.5

**Adhesion**

In order to understand and evaluate the adhesive properties of grouts, it is necessary to define adhesion, and review how adhesion between two surfaces may be achieved. The term adhesion has several meanings depending on the context in which it is used. Adhesion may be defined as "the state of being held together by means of an interlayer of adhesive between adherend interfaces; the attachment of two surfaces by interfacial forces consisting of molecular forces, chemical bonding forces, interlocking action or combination of these." (Shields 1985) In physical chemistry adhesion may be defined as the "attraction between a solid surface and a second phase." (Houwink, Salomon ed. 1965, 3) This second phase, which may be a liquid or solid, consists of particles, molecules or a continuous film which are adhered to a solid surface due to electrostatic attraction, Van Der Waals forces or chemical valence forces (ionic, covalent metallic.) In adhesion technology, only the interaction between a solid surface and a second liquid or solid phase is termed adhesion. (Houwink, Salomon edt 1965, 3) The technical process of producing adhesion between two solids is called adhesive bonding.

There are two ways in which to achieve the adhesive bonding of two surfaces, non-chemical and chemical. Non-Chemical adhesion involves the use of

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5The ICCROM method of evaluating and choosing appropriate grouts was used as a model for this thesis project.
mechanical devices such as clamps, pins or screws to achieve reattachment. Chemical adhesion utilizes a chemical adhesive which "fills the gaps between the pieces, adheres to both surfaces and achieves a sufficiently strong and rigid interface between both pieces." (Smith 1983, 14) Another definition terms adhesives as "liquids used to bond two surfaces in that they flow over the surface, penetrate irregularities and achieve intimate contact with the whole area." (Allen 1984, 6) It should be stressed that adhesion differs from consolidation in that it is not intended to reintroduce intergranular cohesion in the solid. Instead the polymer is used to form a bridge between the adherends. This type of adhesion is known as diffusion adhesion. (Allen 1984, 9)

In conservation, a good adhesive is one that will form a joint that is strong enough to sustain substantial stress. If failure occurs, the joint is considered sacrificial material as it is preferable that failure take place either within the adhesive of the joint or at the interface between the adhesive and the adherend. The strength of the adhesive joint must strike a delicate balance. If the joint is too strong, the adherend will break, whereas a joint that is too low in strength will not be adequate to sustain potential stresses. The joint should be stiffer than the adherend to ensure failure within the adhesive, not the substrate material. Proper application of the joint is essential as flaws within the joint can cause failure in the system.
2.3. CHARACTERISTICS OF AN EFFECTIVE ADHESIVE GROUT

In anticipation of reviewing the properties resinous and cementious grouts, it would be beneficial to consider the criteria which characterize an ideal adhesive for stone. An understanding of these criteria and the unique parameters which govern each particular situation, is essential for the appropriate selection and application of any adhesive grout.

**Ideal effects of an adhesive grout:**

- no production of deleterious hazardous waste compounds at time of application or with aging - decay products, if any, should not be detrimental to the adherend or environment
- no introduction of harmful amount of soluble salts
- should not cause or accelerate the deterioration of the stone
- no change of color in the stone
- no decrease in water vapor permeability
- increase shear and tensile strength between layers

**Ideal properites of an adhesive grout**

- viscosity should be such that it is low enough to inject, flow into the voids and crevices without diffusing into the pores
- good workability for ease of handling and application
- high glass transition temperature
- little or no shrinkage or expansion
- little or no bleeding
- modulous of elasticity and thermal coefficient of expansion should be compatible to that of stone
- water vapor transmission rate should be similar to that of the stone
- resistant to freeze thaw cycles
- resistant to biodeterioration and degradation from acid/alkaline conditions
- water insensitive
- lightweight
- set rapidly enough in both wet and dry environments or without contact with air
- retreatable
- affordable
- non-toxic to user and environment
2.4. VARIOUS TYPES OF GROUTS

For the purposes of this project, several types of grouting materials were researched and considered for use. Grouting materials were systematically eliminated according to the ideal properties of a grouting material and the specific conditions existing at El Morro. As a result, epoxy and cementitious grouts were selected as the materials of choice and are therefore the only grouting materials reviewed in the next section.

2.4.1. CEMENTITIOUS GROUTS

Cementitious grouts are "mixtures of hydraulic cement and water with or without aggregates and with or without admixtures. Depending on the application it is usually proportioned to produce a pourable consistency, like very wet mortar or soupy high-slump concrete, without segregation of the constituents." (Kosmatka 1990, 1) Cements should not be viewed as one material, but as a class of materials with properties varying with each type of cement used. Some of the cementitious binders used in grouts are Portland Cement, blended hydraulic cement, expansive hydraulic cement, ground slag and oil-well cements.

Normally, Type I Portland Cements are used in engineering practice unless there are special considerations involved such as necessity for sulfate resistance, high early strength or small particle size. The type of cement chosen will effect the properties of the grout, so the cement must be chosen to meet the particular needs of each application. Potable water is generally used in the grout mixtures, however if the water contains high levels of impurities, efflorescence, staining, or corrosion of the reinforcements may occur. If aggregates are used they essentially have the function of a filler, ranging in size from coarse to fine. Aggregates should be well graded, free of organics and non-staining.
Properties To Consider

By carefully choosing the materials, admixtures and their ratios, specific properties of grouts may be manipulated to achieve a desirable grout mix.

The consistency of a grout is defined as its ability to flow. The flowability of a grout can range from near water to a thick mortar-like paste. A grout intended to be injected to fill a void would be more successful if it were fluid rather than thick, however the size of the void or crack, the pore size of the material being injected, the percentage of fill desired and the consolidating effect of the grout would all effect the fluidity of the grout chosen. The consistency of low viscosity grouts is measured using a flow cone, where the influx time, the time it takes for a specific amount of grout to exit the cone, is monitored. Fluid grouts are ten to thirty seconds or less, water having influx time of eight seconds. (Kosmatka, 1990, 3) Viscous grouts are measures using a flow table where the spread of the grout is measured after the table has been dropped a specific number of times during a given time.

Workability can be considered as the ease with which a grout can be made, handled and placed without the segregation of the material. Working time should be calculated and adjusted to be comparable to the pot life of the grout being used.

Bleeding is a common problem with cement/water grout mixes where there is a separation of water caused by the settlement of the solid particles and the upward migration of water to the top of the grout solids. Bleeding may cause voids, reduction in volume and excessive shrinkage, all of which lead to poor durability and low strength. Studies show that high water-retentive grouts, such as those with thixotropic properties, show little or no bleeding. (Kosmatka, 1990, 4) Fumed silica, clays and fine cements and certain chemical admixtures can be used to reduce bleeding. It is essential that grouts which are intended, through intimate contact with the substrate, to act as void fillers, support systems or water sealers must have no or little bleeding in order to avoid debilitating water pockets between the grout surface and the item grouted. Bleeding may be measured using standard bleed test cylinders.
containing grout, where grouts are let to stand for specific time and setting is measured.

Setting and hardening in cementitious grouts occurs when their is a chemical reaction between the cement and water resulting in the formation of fiber like crystals of primarily calcium silicate hydrate. When water is not present, hydration ceases and in return there is a halt of strength gain. In order to ensure a full set it is often necessary to control the evaporation or migration of water from the grout mix once it has been placed. Setting time may be an issue if there is the necessity for a quick set. The Vicat needle is used to measure setting of grouts.

"Compressive, flexural and tensile strength required of a grout depends upon the grouting application, whereas the strength actually achieved by the grout is a direct result of the amount of cementitious materials and water in the grout as well as the degree of hydration."(Kosmatka, 1990, 5) In essence, strength is directly related to the water:cement ratio of the grout mix. However, less water is not always better. For example, good bond strength is achieved with a wetter grout than a drier grout.

Volume change can consist of both shrinkage and expansion. In fact, cementitious grout will experience first a slight expansion during set, followed by a small contraction as it hydrates and consumes water. After set, outside factors such as temperature can induce volume change. As a rule, cementitious grouts will expand as temperatures rise and contract as it falls. However, if there is any free water present it will result in expansion due to freezing. Moisture is another source of volume change. With moisture gain there is expansion, with moisture loss there is contraction. Here again, the water:cement ratio of initial grout mix will have an effect on the subsequent volume change of hardened grout; the less water in the mix, the less the shrinkage there will be. A grout that is classified as a non-shrink grout is one that will exhibit no drying shrinkage.

It is generally desirable in the engineering field for the porosity and permeability of cementitious grouts to be as low as possible. Low permeability and porosity can be accomplished through a high percentage of hydrated cementitious material, achieved by moist prolonged curing and low
water:cement ratios. There are instances, in particular in the field of conservation, when moderate to high permeability and porosity of grouts are desirable in order to ensure that the grout does not form a water vapor barrier.

2.4.2. RESIN ADHESIVE GROUTS

Polymers

Film forming materials, both natural and synthetic, are utilized as adhesives, consolidants and coatings. Most film-forming substances are comprised of polymers. (Horie 1987, 11) Polymers are large molecules which consist of hundreds, thousands, or even millions of atoms (Smith 1983, 25) and are based on many small identical units, called monomers. (Horie 1987, 11) The joining of monomers to make polymers is known as polymerization. Polymers may be made of more than one kind of monomer, and are called copolymers. Polymerization results in the formation of either long-chain molecules or network polymers. Most long-chain polymers are produced synthetically, while nature prefers network polymers.(Smith 1983, 31)

The term thermoplastic is used to refer to long chain polymers as they are composed of discrete chains which may be separated from one another because they are held together by relatively weak secondary bonds. Thermoplastic materials become soft when heated and can be molded into desired shape and they dissolve in solvents. (eg.: cellulose derivatives, vinyl polymers, acrylics, polystyrene)

Thermosetting is the term used to describe polymers whose molecules have crosslinked into an immobile, interlocking network in which sliding of the molecules will not occur. These network polymers can be formed either by the linking of long chains by atoms or small molecules or by an interaction between small molecules producing branched chains that join together. (Smith 1983, 35) Unlike thermoplastics, thermosets will not dissolve in solvents, but will swell, and will not melt when heat is applied, only soften. (Horie 1987,12) (eg.: epoxies, polyesters, aminoplast)
Properties Affecting Resins

Many physical properties of resins are influenced by their molecular weight. The increase in molecular weight of a polymer will vary the tensile strength, melting point and elasticity. (De Whitte, Florquin and Goessens-Landrie 1984, 32) The solubility of a polymer will decrease with higher molecular weight. The higher the molecular weight of a polymer, the higher the viscosity of the liquid, as larger molecules will create resistance to flow. (Horie 1987, 17)

The glass transition temperature of a material (Tg) is the temperature at which the material changes from a glassy state to a rubbery one. (Horie 1987, 18) This is an important property to consider when choosing an adhesive because many of the mechanical and chemical properties of adhesives may alter with temperature fluctuations. For example if the Tg is too low, the adhesive may become soft when undesirable and lose its capacity to bond. If the material softens it will also have the tendency to pick up dirt when it becomes tacky. Thermoplastics tend to have a much lower Tg than do thermosets. Because resins are composed of both long and short chains, which melt at different temperatures, the Tg and the melting point of resins is generally not sharp, but has an index of a small range of temperatures.

The mechanical properties of resins vary widely. Elasticity ranges from flexible to very brittle. These properties are influenced by molecular weight and glass transition temperature, and are generally measured by degree of elasticity under tensile stress. A resin with a high modulous of elasticity might be stronger than a resin of low modulous of elasticity, but it will also be more brittle. Hardness is measured by resistance to indentation, scratch resistance, damping of a pendulum and flexibility. (Horie 1987, 25)

The optical properties of a resin are important in choosing an appropriate adhesive or consolidant. The refractive index, color and gloss of resins vary greatly and can cause drastic changes in those same properties to the material to which it has been applied (eg.: darkening, yellowing, sheen.)
Setting

Although it is necessary for adhesives to be mobile, low viscosity liquids of low surface tension in order to obtain intimate contact with the surface of the solid, they must also function adequately under mechanical stresses. This generally requires the modification of the liquid to a solid phase after it has been placed. There are several methods of achieving this phase change, and many polymers can be prepared and applied in different forms. The method of application chosen should reflect the properties of the polymer and the circumstances of application:

- Melt-freeze Adhesives: These are solids which are introduced to heat and subsequently melted. They are applied in a molten form and then left to freeze into a solid form. The adhesion is not dependent on a chemical alteration of the material but on a physical alteration. An advantage of this system of setting is the elimination of the necessity of solvents. eg.: wax, soldering metals, some animal glues, vinyl polymers, acrylics, rosin

- Solution Adhesives: Many adhesive polymers are in solid form and must be dissolved in a liquid solvent in order to obtain the liquid form necessary for application. There are certain suitable solvents for each adhesive, these solvents may be organic or aqueous. Many solution adhesives set slowly, shrink, and are not very strong. Solution adhesives may also be made as dispersions of adhesive powders mixed with a liquid. This liquid will eventually evaporate leaving behind a solid. eg.: gum arabic, shellac, cellulose nitrate, polyvinyl acetate, rubber solutions, starch based glues

- Reaction Adhesives: These adhesives involve the chemical reaction of two or more liquid compounds to form a solid. Some liquids are self-setting with contact with humidity in the air. Many are exothermic - giving off heat during cure. eg.: epoxies, polyesters, urea formaldehyde, cyanoacrylate

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6Some adhesives remain as liquids such as those used in pressure sensitive tapes and labels. (Horie 1987, 5)
For the purposes of this project, several synthetic resins were reviewed and their suitability for the project was assessed by comparing their properties to the ideal properties of an adhesive. Natural resins were discounted at the beginning, as most are sensitive to biodeterioration and do not exhibit adequate structural properties. Although none of the resins available on the market fulfill all the requirements of an ideal adhesive, it was felt that the most appropriate to this project would be epoxy resins. Epoxy resins exhibit the necessary structural strength, without being water sensitive, they have excellent weatherability and several properties can be modified to meet application needs.

**Epoxy**

Epoxide resins ("epoxies") are organic resins which fall into the class of thermosetting resins. Epoxy resins were commercially available in the 1940's, but began being used in conservation in the 1950's as wood, metal and ceramic adhesives, and in the late 1960's for the consolidation of stone. (Horie 1987, 173) Epoxy resins are among the most widely used polymer resins as structural adhesives. There are a wide variety of epoxies on the market available as liquids, pastes or solids, which must pass through a liquid phase on curing.

Epoxy resins are either one or two component systems. The one part systems are solvent-free liquids, solutions in solvent, liquid resin pastes, fusible powders, sticks, pellets and pastes. The two component systems are formed by mixing components just prior to application which undergo an irreversible chemical and physical alteration upon curing. Basically there are two methods of manufacturing epoxies. One by mixing a substance already containing epoxide groups with a substance having replaceable hydrogen atoms or second by using a peracetic acid to cause epoxidation of an olefinic compound. (Rayneer 1964, 240) In the first case, one of the components contains the epoxide group and the other component, known as the hardener, reacts with the epoxides causing the molecules to cross link.

The most commonly used epoxide resin in the industry are the gycidal esters of bisphenol A, formed by the condensation of epichlorohydrin and the bisphenol in the presence of caustic. (Selwitz 1991, 182) The hardeners generally used are aliphatic amines and amides. (Horie 1987, 170) The correct
proportion of resin to hardener, the temperature, and humidity are all critical components to the successful cure of an epoxy. Depending on the combination of the resins and hardeners, epoxies are available in a wide range of viscosities. Various solvents are often added to decrease the viscosity of epoxies. This is especially true when epoxies are intended for use as consolidants and their viscosity must be equal to or less than that of water.

Aromatic epoxies were first used in conservation both as consolidants and as adhesives. The problem with aromatic epoxies is that they have low ultraviolet stability and thus tend to yellow, have low resistance to chemical attack by oxygen and sulfuric acid, lack hydrophilic properties making impregnation and adhesion to humid substrates difficult, and they often suffer loss of mechanical properties due the detachment of the adhesive from the substrate. More recently aliphatic epoxy resins have been used more frequently in conservation. They have low viscosity, good ultraviolet stability, strong hydrophilic properties, compatibility with many substrate materials and excellent mechanical properties.

2.5. ADDITIVES AND FILLERS

Many properties of grouts can be modified easily with the addition of additives such as fillers, colorants, plasticers, and fluidifiers. Though the terminology for these materials becomes confused in the literature, for the purposes of this paper additives are to be defined as materials added to base materials in order to enhance the base material or achieve a desired property. The choice of additives used in grouting depends on the particular grout material and the properties being altered. Both cementitious and epoxy grouts are commonly altered with additives prior to application in order to obtain a grout mix most compatible with the substrate material and specific environmental conditions of the application. Additives can be used to alter properties either in the cured or uncured state of the composite or both. Although it is known that properties of the final product depend on the combination of various additives and base materials and the environment in which they are used, the following generalities regarding the effects of additives are useful when trying to find one which is appropriate.
Fillers are generally selected by particle size distribution, particle shape and the way in which they group together. (Katz, Milewski 1978, 12) The basic unit of the filler is the individual particle which comes in a variety of shapes and surface areas and may be classified as sphere, cubes, blocks, flakes and fibers. (Katz, Milewski 1978, 12) Fillers are rarely homogeneous in size and shape, except man made fillers such as glass spheres. Many effects of a filler are dependent on their surface area especially surficants and dispersants. Fillers can be reactive or inert, inorganic, organic, natural or synthetic.

Cost reduction is among the most common reason for the addition of fillers. Fillers are generally less expensive inert materials which provide bulk to the more expensive base mixture, reducing the percentage of unfilled mixture necessary thus lowering the cost. These fillers are known as "extending" fillers.

Fillers can be added to reduce shrinkage upon curing, such as adding aggregate to a lime mortar. They can also be used as "reinforcing" fillers when their function is to increase strength of a material. Usually the addition of fillers will result in a decrease of tensile and flexural strength. The effects of fillers on compressive strength vary, resulting in either an increase or decrease in compressive strength depending on base material and fillers used. Some fillers can behave both as extending and reinforcing agents. The porosity and permeability may be reduced or increased by addition of fillers.

The modulus of a base material is generally increased with addition of filler material, and will proportionally increase as the percentage of filler added increases. (Katz, Milewski 1978, 29) This effects workability of the material, as it will become stiffer. This is generally because fillers are more rigid than their matrix. The hardness of the cured base material will generally increase with fillers.

The rheology of the base material can often be controlled with the addition of fillers. Fillers tend to increase the viscosity of base materials, provided the filler is well dispersed in the matrix. This will help decrease bleeding and sagging of the base material. Some fillers, such as microspheres, can be added to increase flow potential while adding bulk to the mix. In certain systems
fillers can be added to confer thixotropy to the base material, meaning it will tend to gel at rest but will flow under pressure or agitation.

The thermal expansion of polymers may be reduced significantly by fillers. Because fillers in polymers are under substantial stress when cured, the formation of microfractures generally results. These microfractures create slippage planes which help reduce the coefficient of thermal expansion. If the filler has a direction, the material will expand in a perpendicular direction to the filler to relieve stress. Thermal conductivity is a combination of both the filler and the matrix, thus the higher the conductivity of the filler, the higher the conductivity of the composite.

Fillers also have an effect on the optical properties of the composite. They can be used to impart color, change color, intensity of color, or reduce intensity of color. Fillers which do not have the same refractive index as the matrix will change the refractive index. The greater the difference in the refractive index between the filler and the matrix, the greater the opacity of the composite. The aging of fillers must be considered if alteration in color with aging is desirable or problematic.

In addition to fillers there are other additives which may be used to modify base materials. One of the major problems with polymers is their susceptibility to deterioration with age caused by either thermal or photo degradation. Stabilizers and anti-oxidants are used to control or prevent these types of deterioration. Tackifiers are a group of additives which induce stickiness, often important in application. Plasticizers reduce brittleness by increasing flexibility in the polymer chains and raise impact strength. Emulsifiers and dispersants are used to create suspensions and reduce bleeding. Dilutents, both reactive and non-reactive, are employed to reduce viscosity of polymers. Superplasticizers decrease the necessity for large amounts of water in cement grouts while making the grouts much more fluid.
2.5.1. FUMED SILICA

One of the major problems confronted in this project was the controlled application of the epoxy adhesives as discrete spot welds. This involved finding an epoxy that was of a low enough viscosity to be injected under low pressure yet would stay in place after injection. As the viscosity of epoxies tested increased, the sag potential after application decreased. Consequently, the injectability drastically decreased. It was decided that an additive would be necessary to impart thixotropic properties to the epoxy. Research indicated that the best solution would be the use of condensed fumed silica.

Condensed fumed silica is a by-product of fabrication of silicon or ferrosilicon alloys. It is produced by "the vapor phase hydrolysis of silicon tetrachloride in a hydrogen oxygen flame. The combustion process created silicon dioxide molecules which condense to form particle. The result of these processes is a three-dimensional branched chain aggregate with a length of approximately 0.2 to 0.3 microns. Once the aggregates cool below the fusion point of silica (1710° C), further collisions result in mechanical entanglement of the chains, termed agglomeration."(Cab-O-Sil Untreated Fumed Silica Properties and Functions) Fumed silica has an amorphous structure and extremely small particle size with large surface area. The large surface area is a major factor in its ability to be used as a thickening agent.

Historically fumed silicas were termed pyrogenic silica. Its function as a thickening agent, optical clarifier, and suspender of solids has application in a wide variety of fields from the cosmetic industry to medicine, to conservation and engineering on diverse materials such as adhesives, coatings, inks, and plastics. It is often used in cementitious grouts to increase the compressive strength and reduce the permeability of the cured grouts and reduce the bleeding and sedimentation of uncured grouts.(Parizeau 1984, 1) Because the fumed silica has an even finer particle size than the finest cements, it has the ability to move between the cement particles aided by its round shape. Fumed silica is a very reactive pozzolan. The fumed silica reacts with the lime liberated during hydration forming a secondary CSH thus reducing the risk of chemical degradation by alkali aggregate reaction. (Parizeau 1984, 1) Often the use of fumed silicas in grouts to impart thixotropic properties is
accompanied by an initial increase of viscosity (Parizeau 1984), but this can be eliminated by the use of superplastisicers which increase the fluidity without negating the thixotropicity of the uncured grout. (Parizeau 1984)

The use of fumed silica is also common in controlling the rheology of epoxies. It is recommended that the fumed silica be added as a percentage of the weight of the epoxy. Because the fumed silica is so light weight, the amount by volume needed for only 5% weight of the epoxy is surprisingly high. Depending on the percentage of fumed silica added to the epoxy the viscosity, plasticity and thixotropy can be manipulated. Fumed silica will form a three-dimensional lattice which will break up under stress and reform as stress is removed, enabling it to modify the flow property of base materials. The addition of the correct amount of fumed silica to an epoxy of low viscosity imparts thixotropic characteristics so that the epoxy will stay in place, without sacrificing injectability. Thus fumed silica can be an important aid in the handling and correct placement of epoxies by eliminating sagging, running and dripping. This is an especially desirable property in the case of blind application, as there would be a greater sense of success in application knowing that the adhesive remains where intended. It is essential that the fumed silica be mixed thoroughly into the epoxy, or any other base material, in order to assure full coverage of the particles.

Fumed silica is available in a variety of grades, in untreated and treated forms. Grading is generally based on surface area, pH, bulk density and thickening efficiency. Untreated fumed silica is hydrophilic due to the hydroxyl groups on the silicon atoms which are capable of hydrogen bonding with water in vapor, liquid or solid form. Treated fumed silica has a surface chemistry which differs from untreated. The surface of the silica is coated with a silicone fluid treating agent, which reacts with the surface hydroxyl groups making the product hydrophobic. (Cabot Technical Data, Cab-O-Sil TS 720) Unlike untreated systems of fumed silica which thicken liquid systems by hydrogen bonding, treated fumed silica depends on the interaction of the surface chemistry with the liquid system. (Cabot Technical Data, Cab-O-Sil TS 720) The use of treated fumed silica is recommended for use with epoxy resins for the following: superior water resistance, stable sag resistant
properties in high temperature cure systems, excellent anti-settling properties, and insignificant change in cure rate or lap shear tensile strengths.

2.6. APPLICATION METHODS

There are several methods of application of grout into masonry including gravity feed, pumps, vacuum and manual injection systems. The appropriate means of application will depend on the properties of the grout being used, the nature and condition of the substrate material and the desired depth of penetration of the grout.

2.6.1. GRAVITY-FEED

The gravity system of grout application involves the use of gravity in order to achieve pressure for impregnation of the grout. Generally the grouting apparatus in this type of system includes large containers with an opening at the bottom to which is fitted a flexible tube or pipe, which is in turn fitted with flexible rubber hose and terminates in a nozzle with a stopcock. (Ashurst 1988, 30)

Prior to grouting several holes should be drilled in the masonry where voids have been located. Holes should be cleaned and flushed with water prior to grouting, starting with the top hole until the clean water runs out of the bottom holes. (Ashurst 1988, 32) Generally to ensure that voids have been filled, grouting would commence at the bottom of a wall and continue until no more grout is accepted or until the grout emerges from upper holes. The grouting procedure would move systematically up the wall until voids are completely filled.

The operation of gravity grouting involves the placement of the large containers at an upper level so that the grout flows down the tube to the nozzle by force of gravity. The flow of grout can be manipulated by opening and closing the aperture known as the stopcock.
2.6.2. PUMPED

Pumping systems come in a variety of shapes and sizes, but the basic equipment is generally the same, including a mixer diaphragm pump, suction and delivery hoses, and metal nozzles fitted with control devices. Pumping systems can be either hand-operated or power-operated. The pressure obtained depends on the pumping apparatus, but as a rule much lower pressures can be obtained using hand-operated pumps. (Ashurst 1988, 33)

In the case of resininous grouts consisting of a two part system which are mixed immediately prior to application, namely epoxies, there are pump systems known as plural pumps. Plural pumps have two separate chambers, one for each component. The plural pump mixes the two components in appropriate ratios within the system at the nozzle. This eliminates potential error in mixing the components and provides ease in handling hazardous materials. The pressure used depends on the viscosity of the resinous components. The higher the viscosity, the more pressure is needed for injection. The pressures on these machines can be adjusted between 15-700 psi depending on the application requirements. The flow of the grout can be regulated with a flow monitor, allowing exact amount of grout to be injected.

2.6.3. VACUUM

This means of application would not be useful in most building or large structures as it involves enclosing the entire area to be grouted in an airtight, flexible shroud. (Ashurst 1988, 33) A vacuum pump is used to remove the air from the covered area allowing the grout to be sucked in. This type of grouting would be useful on small objects in situations where microfissures were involved.

2.6.4. MANUAL INJECTION

Generally, manual injection is carried out using hypodermic syringes or grout guns varying in size depending on the grouting material. This method of application is tedious and time consuming and is generally used on small scale projects in the conservation field.
Voids and fissures are determined and holes are then drilled in those areas if none already exist. The holes are usually flushed and cleaned with water. The grout is then injected into the holes using the syringes or grout guns with cotton held against the hole as backpressure. Again as in gravity feed systems, it is generally recommended that injection of the grout work proceed from the bottom up when filling all the voids is desirable.
3. LABORATORY TESTING PROGRAM
3.1. OVERVIEW

The mineralogy and petrology of the stone of Inscription Rock and the deterioration mechanisms affecting the inscriptions have been addressed in recent studies, and documented in reports for the National Park Service. (Padgett 1992 and Austin 1993) The information gleaned from these reports together with a site visit by the author, determined that one of the most immediate problems which needed to be addressed was the detachment and subsequent delamination of stone. Review of the conservation and engineering literature, the geo-chemical and geo-physical analysis of Zuni Sandstone, and consideration of specific deterioration mechanisms and environmental conditions at El Morro guided the selection of materials chosen for the conservation of the stone and the nature of their application.

The use of both epoxy resin and cementitious grouts are well documented in the literature as structural adhesives used for the stabilization of natural and man-made structures. Generally optimal performance of these grouts has been based on maximizing the strength of the system through adhesive selection and application of the grout as a continuous film which completely fills the void. Only recently, however have the physico-chemical effects of this type of application been reconsidered on non-traditional porous materials, such as deteriorating stone, plasters or mosaics. Substantial differences in a variety of mechanical properties between grouts and the substrate material can be damaging both to the adhesive joint and the adherends. This damage can be exacerbated when contact area between adhesive and substrate is increased, as in complete coverage of a void or a crack, altering the capacity of the grout to perform its adhesive function.

Although full cavity injection with a grout may be desirable for optimal adhesion between the grout and the adherends, it may not be desirable from the standpoint of compatibility of mechanical properties of the components of the system. (i.e. modulus of elasticity, thermal coefficient of expansion, water vapor transmission and strength) If differences in mechanical properties between grouts and the adherend are unavoidable, perhaps minimizing the amount of grout necessary to sustain forces exerted on the adhesive, would eliminate some of the problems encountered with full cavity injection.
Although there are many documented studies of epoxies and cementitious grouts intended to be applied as void-filling continuous films, the limited application of epoxies as discrete spot welds used alone and in combination with cementitious grout infill has not been tested. An experimental program was designed to compare the mechanical and physical properties of high strength commercial cementitious grouts versus injectable epoxy resin adhesives, and evaluate their performance in a variety of application systems.

For the initial testing of the conservation treatments, commercial sandstone similar in mineralogical composition to El Morro's Zuni Sandstone was obtained from a local stone dealer. The use of commercial stone was deemed necessary to eliminate unknown variables which might be encountered using naturally weathered stone from the site, thus ensuring that the test results would represent the performance of the grouts themselves and their application methods, not natural inconsistencies in the stone. The quantitative results of these tests are intended to be used as a means of qualitative treatment comparison, not only for the purposes of the treatment of stone at El Morro, but for conservation problems of a similar nature.

The commercial stone obtained for the project was cut using a circular water saw, into blocks measuring 4"x4"x1.5". Holes were drilled into the stone, the number of which depended on grout application intended. These blocks were then made into "sandwich assemblies," each consisting of two blocks of stone separated by wooden spacers of varying widths representing the range of detachment widths measured at the site (1, 3.5 & 7mm).

Low modulus epoxies and high strength cementitious grouts were chosen with consideration given to mechanical and physical properties of stone and grouts, review of literature and site conditions. The intention was, with the assemblies in a vertical position, to inject the grouts into the assemblies through the drill holes in a series of applications: continuous epoxy only, epoxy spot welds only, continuous grouts only, and combination of epoxy spot welds with grout infill.

The low viscosity of the epoxies needed for injection under low pressure into joints of 1-7mm in thickness presented a problem in the application of the epoxy as discrete spot welds. Epoxies were therefore modified with fumed
silica to increase viscosity and to impart thixotropic properties, ensuring the spot welds would remain where injected without subsequent sagging. The assemblies were then grouted and cured. After curing, tests were performed to measure the mechanical and physical properties of the adhesive joints: shear strength, water vapor transmission, freeze thaw, and bulk specific gravity of stone. (See Section 3.5) Standardized tests were followed whenever possible, and modified when necessary.

3.2. SELECTION OF TREATMENTS

The treatments selected were designed to address the problem of reattachment of delaminating layers of sandstone and reintroduction of adhesion between the detached layer and the sound stone. Preliminary measurements of the detachment at Inscription Rock were taken in random areas of previously delaminated stone by a National Park Service staff member. The detachment was found to vary from 1mm to 7mm in depth. These measurements set the parameters for the detachments to be simulated in the assemblies to be tested in the laboratory at 1mm, 3.5mm and 7mm. The thickness of the detached stone was measured to range from 2cm to 4cm, therefore the thickness of the stone blocks used in fabricating the assemblies satisfied te worse case scenario at a thickness of 4cm. (These measurements are a rough estimation of the degree of detachment that exists at El Morro; more accurate measurements will need to be taken before the next phase of treatment begins). Standardized tests were run to comparatively study the behavior of epoxy and cementitious grouts in various applications, not to infer that the quantitative results would correlate to the situation at El Morro. In the interest of the tests being relevant to the existing situation at El Morro, the preliminary measurements of detachments taken at El Morro were replicated in the experimentation assemblies.

Epoxy and cementitious grouts were selected as the materials of choice to be comparatively tested for the treatment of the detached stone. Factors considered in their selection were: adhesive strength, modulus of elasticity, width of detachment, environmental site conditions (water, and drastic temperature fluctuations), commercial availability of product, ease of application, previous product performance and toxicity. In the end, two epoxies and two grouts were selected for the testing program.
3.2.1. GROUTING MATERIALS

Epoxies

Because of the great fluctuation in temperatures experienced at El Morro, epoxies with a low modulus of elasticity were chosen. A low modulus of elasticity indicates a less brittle, more elastic material than an epoxy with a high modulus of elasticity. In theory an epoxy with a low modulus of elasticity would be able to withstand the flexural stresses induced by the potential expansion and contraction that the stone, and by association the adhesive joint, would experience under these conditions. It was also necessary to consider the viscosity of the epoxy. A resin of too high a viscosity would not be injectable under low pressure, while a viscosity that was too low would infiltrate the pores by capillarity, leaving the void without adhesive. Therefore two lo-mod epoxies with varying viscosities manufactured by Sika Corporation (Lyndhurst, NJ) were selected for testing:

1. Sikadur 21, Lo-Mod LV with viscosity of 1400 cps. for cracks of 1 - 3.5mm in thickness. Sikadur 21, Lo-Mod LV is a two component, solvent-free, moisture insensitive aliphatic epoxy which meets ASTM C-881, Type III, Grade 1, Class C, epoxy resin binder.

2. Sikadur 22 Lo-Mod with viscosity of 3500 cps. for cracks of 7mm in thickness. Sikadur 22, Lo-Mod is a two component, solvent-free, moisture insensitive aliphatic epoxy which meets ASTM C-881, Type III, Grade 2, Class B and C, epoxy resin binder.

Cementitious Grouts

The cementitious grouts selected for testing were required to be high strength, in order to be comparable, although not equal, to the epoxy resins. Commercial cementitious grouts that displayed in addition to high strength, frost and salt resistance, low shrinkage and easy preparation and application were highly favored. Two cementitious grouts developed for conservation manufactured by Heinz Jahn of the Netherlands and marketed in the US by Cathedral Stone Products, Inc. (Jessup, MD) were chosen:
1. *Jahn M30 Injection Grout*, recommended for hairline and microscopic cracks of 0.2 - 5.0 mm, is a cement-bound grout containing no chlorides, bromides or fluorides. It is a two component system with a small amount of synthetic additive to promote fluidity (additive is unknown). M30 is salt and frost resistant and displays minimal shrinkage.

2. *Jahn M40 Injection Grout*, recommended for cracks 5.0 - 10.0 mm, is a cement-based grout containing no chlorides, metal compounds or synthetic additives. M40 is salt and frost resistant and displays minimal shrinkage. (See Appendix A)

3.2.2. APPLICATION METHOD

Recommended use of most high strength adhesives, including epoxies and cementitious grouts, requires the maximum contact possible between the adhesive and the adherends for optimal bonding strength. For porous materials such as stone, the introduction of a continuous adhesive film could affect the overall behavior of the system due to the differences in mechanical properties of the materials. Therefore, the impact of the adhesive grout and altered performance of the whole system must be considered in selecting materials and designing their installation.

When applied, grouts will be subjected to forces or loads such as the weight of the detaching stone and expansion and contraction from thermal fluctuations and moisture penetration. Simultaneously the stone will undergo similar stresses. It is important to understand the properties of both the grouts and the stone in order to ensure that the design of the system will not result in excessive deformation or fracture. Ideally the grouting system should be comprised of materials which under stress will exhibit compatibility of deformation. Three important properties to consider in a grouting system are modulus of elasticity, thermal coefficient of expansion and water vapor transmission.

The linear relationship between stress (force) and strain (deformation) is explained in Young's Modulus or the Modulus of Elasticity. The modulus of elasticity is equal to the stress divided by the rate of strain. While the elasticity of a material is defined as a material's ability to return to its original
shape after a load is released, Young's Modulus measures the stiffness of a material, i.e. its ability to resist deformation. The greater the modulus, the stiffer the material. The modulus of elasticity of epoxy resins is approximately 4500 MNm$^{-2}$ (Crafts Council 1983), while stone ranges from 10,000 - 80,000 MNm$^{-2}$ (Crafts Council 1983). The lower modulus of elasticity of the grout would have the desirable effect of a joint more flexible than the adherend.

Most materials undergo expansion upon heating and contraction upon cooling. (Callister 1991) The extent to which a material expands upon heating is measured by the linear coefficient of thermal expansion. Sources indicate that the thermal coefficient of expansion of epoxies ranges from 3 - 5 x 10$^{-6}$ per °C and while sandstones range from 3.7 - 12 x 10$^{-6}$ per °C. (Doran 1992, Shackelford and Alexander 1992, Stulz and Kiran 1988, and Addelson 1976). Depending on the specific makeup of the epoxy and the sandstone, the coefficients of thermal expansion could vary, however there is potential for a large difference in expansion of these materials.

The suitability of the traditional application technique of polymeric grouts as continuous void-filling films came under question. If differences in mechanical properties between grouts and the substrate material are unavoidable due to strength requirements, perhaps minimizing the amount of grout injected to the least possible amount necessary to sustain the forces exerted on the adhesive, would eliminate some of the problems already discerned with complete coverage of voids with grout.

The application of epoxy as a series of discrete spot welds, rather than as a continuous film, was an idea developed in response to the problems and failures of epoxies when applied to completely fill a crack or void. When an epoxy cures, it releases heat in what is known as an exothermic reaction. This release of heat may not be disruptive if the amount of epoxy used is small, such as a discrete spot weld; however application of the resin as a continuous film often results in severe cracking of the stone and subsequent failure of the joint. Differences in thermal expansion and conduction between stone and epoxy are also potentially high and often result in stone deterioration. Again the spot weld would probably not introduce a large enough quantity of epoxy to result in deleterious effects. Thirdly, large masses of epoxies behave as
water vapor barriers. The epoxy spot welds would in theory provide adhesive strength in a concentrated yet distributed area, allowing the escape of moisture through more permeable surrounding material.

The size of the spot welds would have to strike a balance between being large enough to provide adequate strength, while being small enough to reduce or eliminate the problems mentioned above. In order to determine the minimum diameter of each spot weld of epoxy necessary to provide adequate shear strength to support the weight of detached stone, the following calculations are provided as a model. The model assumes that the total shear of the adhesive and the number of spot welds has been predetermined. The variables in the equation are the density of stone, thickness of detachment, area of detachment, number of spot welds and shear strength of the adhesive being used. In theory, this model may be used in any application involving detachment, by changing the variables to represent the parameters of the case being studied. It should be noted that there are some assumptions made when using this model such as uniform thickness of the detached layer, and uniform total shear over entire area of contact, these

SYMBOLS:

W= weight of detached stone
D=density of stone
V=volume of stone
t =thickness of detached stone
a = surface area of detached stone
T = thickness of detachment = thickness of spot weld (should not exceed 1/4")
S= total shear strength of adhesive
s = shear stress (psi)
F= shear force exerted by weight
A = surface area of single weld of epoxy
n= number of epoxy welds
v=volume of epoxy
An = total surface area of contact between the epoxy and the stone
CALCULATION METHODOLOGY:

<table>
<thead>
<tr>
<th>Equations</th>
<th>Explanation</th>
</tr>
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<tbody>
<tr>
<td>1) $W = DV = Dta$</td>
<td>1) Weight of detached stone equals density of stone times volume which equals the density of stone times thickness and area of detached stone.</td>
</tr>
<tr>
<td>2) $F = W = Dta$</td>
<td>2) If force equals the weight of the detached stone then force also equals the density of stone times the thickness and area of detached stone.</td>
</tr>
<tr>
<td>3) $s = \frac{F}{An}$</td>
<td>3) Shear stress equals the force divided by the total surface area of spot welds.</td>
</tr>
<tr>
<td>4) $s = \frac{Dta}{An}$</td>
<td>4) If total shear stress equals the force divided by the total surface area of spot welds then it also equals the density of stone times the thickness and area of detached stone divided by the total surface area of spot welds.</td>
</tr>
<tr>
<td>5) $An = \frac{Dta}{s}$</td>
<td>5) Thus the total surface area of spot welds is equal to the density of stone times the thickness and area of detached stone divided by shear stress or</td>
</tr>
<tr>
<td>6) $A = \frac{Dta}{sn}$</td>
<td>6) The surface area of a single spot weld is equal to the density of stone times the thickness and area of detached stone divided by shear stress times the number of spot welds.</td>
</tr>
<tr>
<td>7) $A = \pi r^2 = \frac{Dta}{sn}$</td>
<td>7) If the area of a single spot welds is equal to $\pi$ times the radius of the spot weld squared then it is also equal to the density of stone times the thickness and area of detached stone divided by shear stress times the number of spot welds.</td>
</tr>
<tr>
<td>8) $r^2 = \frac{Dta}{sn \pi}$</td>
<td>8) Thus the radius of a spot weld squared is equal to the density of stone times the thickness and area of detached stone divided by shear stress times the number of spot welds times $\pi$.</td>
</tr>
<tr>
<td>9) $r = \sqrt{\frac{Dta}{sn \pi}}$</td>
<td>9) or the radius divided by the root of the density of stone times the thickness and area of detached stone divided by shear stress times the number of spot welds times $\pi$.</td>
</tr>
<tr>
<td>10) $d = 2r = 2\sqrt{\frac{Dta}{sn \pi}}$</td>
<td>10) If the diameter of a circle equals the radius times two, then the diameter of a spot weld equals two times the root of the density of stone times the thickness and area of detached stone divided by shear stress times the number of spot welds times $\pi$.</td>
</tr>
<tr>
<td>11) $v = AnT$</td>
<td>11) Volume equals total surface area contact between stone and epoxy times the thickness of detachment.</td>
</tr>
<tr>
<td>12) $v = \frac{DtaT}{s}$</td>
<td>12) Thus the total volume of epoxy is equal to the density of stone times the thickness and area of detached stone times thickness of detachment divided by shear stress.</td>
</tr>
</tbody>
</table>
Example Calculation:

This example represents one of the fabricated assemblies with 3.5mm detachment used in the experimentation program.

\[ D = 2.17 \text{g/cm}^3 = 0.08(\pm 0.0036) \text{ p/in}^3 \]

\[ t = 1.5 \text{ in} \]

\[ a = 16 \text{ in}^2 \]

\[ T = 3.5 \text{ mm.} = 0.137795 \text{ in} \]

\[ s = 430.6 (\pm 170.9) \text{ psi} \] (note: this figure represents the mean shear resistance between Sikadur 21, Lo-Mod LV and the Delaware Valley Sandstone of an assembly of 3.5mm detachment as determined by this experimental program)

\[ n = 5 \]

\[ d = 2 \sqrt[4]{\frac{Dta}{s\pi}} \]

\[ d = 2 \sqrt[4]{\frac{0.08(\pm 0.0036) \times 1.5 \times 16}{430.6(\pm 170.9) \times 5 \times 3.14}} = 0.1113(\pm 0.0194)\text{in} \]

This equation demonstrates that theoretically an assembly made of the 4x4x1.5" Delaware Valley Sandstone blocks with 3.5mm detachment requires that the minimum diameter of each of the five spot welds of Sikadur 21, Lo-Mod LV to be 0.1113". In theory, epoxy spot welds of this diameter would yield the same shear resistance as the same adhesive applied in continuous coverage. Assuming that this calculation is accurate, it would appear advantageous to apply the epoxy in small discrete spot welds for the reasons discussed above, rather than applying the epoxy to completely fill the void. In addition, the use spot welds would lower the cost of application, reduce the amount of hazardous waste, and introduce less foreign material into the system.
Modification of Epoxies

Because epoxy intended as an adhesive is generally recommended for application of 100% coverage of the joint, the viscosities are such that they have great flowing properties. In the case where the assemblies for the experimental program were intended to be completely filled with the epoxy, their viscosities were optimal. Although flowability was desirable in the application of the epoxy as discrete spot welds, it was not desirable once in place. Initial testing of the epoxies for sag resistance was done empirically by injecting 1cc of epoxy onto a 10cm high piece of stone. The epoxies were observed for both infiltrating into the pores of the stone and sag resistance. In both cases, though epoxies did not appear to infiltrate the pores, they flowed down the entire stone, exhibiting no anti-sagging properties.

Fumed silica was then tested as an additive to impart thixotropic properties to the epoxy resins, meaning that with the addition of fumed silica the epoxies would flow under low pressure and set when pressure was released. The fumed silica chosen was Cab-O-Sil TS720 Treated Fumed Silica manufactured by Cabot Corporation, Tuscola, IL. (See Appendix A) The manufacturer recommends adding between 1-10% of fumed silica by weight depending on the desired effect - the higher the percentage of fumed silica, the more thixotropic the mixture. Epoxies with varying amounts of fumed silica were tested empirically by observing the flow of epoxy down a 10cm long piece of wood, beginning with 0% and increasing amounts of fumed silica to 6% in increments of 1%. The results for both types of epoxy indicated that the addition of 5% by weight of fumed silica was adequate to achieve an epoxy grout that was fluid enough to be injected by low pressure, yet would stay in place once applied.

Standard safety precaution would require multiplying the necessary amount of epoxy times four. For the purposes of this testing program the epoxy spot welds had to be larger than the injection port holes drilled in the stone in order to adhere to both sides of the assembly. As the size of the drill holes measured 1/4" in diameter, a spot weld of 3/4" diameter was considered an appropriate size, far exceeding the required safety factor.
To determine that amount of epoxy necessary to create a spot weld of 3/4" diameter, models of the assembly were fabricated using as one side the 4x4x1.5" stone blocks with drill holes and the other side a 4x4" clear Plexiglas sheet. The models were made using bass wood spacers simulating the three widths of detachment (1mm, 3.5mm & 7mm). The Plexiglas was marked for spot welds measuring 3/4" in diameter. The fumed silica modified epoxy was injected into the model assemblies using a 12cc disposable syringe, and the amount of epoxies necessary to make 3/4" spot weld was visually determined and recorded for each width of detachment. The amount of epoxy needed per spot weld was determined to be as follows: 1 mm = 1 cc, 3.5 mm = 2 cc, 7 mm = 3 cc. In each case (1 mm, 3.5 mm & 7 mm detachments) the amount of epoxy necessary to achieve a spot weld of 3/4" determined by visual means, differed from the amounts determined by mathematically calculating the volume required. The mathematical calculations determined volumes much lower than by visual means. Perhaps this was a function of some of the epoxy remaining in the injection hole, requiring more epoxy to make the spot weld. The models proved to be very useful in allowing for visual confirmation of the both the amount of epoxy required to make spot welds of uniform size, and the degree of sag of injected material. This would not have been possible in blind application.

3.3. FABRICATION OF ASSEMBLIES

For the initial testing of the conservation treatments, sandstone similar in mineralogical composition to El Morro's Zuni Sandstone was purchased from Delaware Quarries, Lumberville, Pa. According to the quarry dealer, the stone is called "Delaware Valley Sandstone" and the physical and chemical properties of the stone as specified by the dealer are as follows:

- Specific Gravity, 60\(^\circ\) / 60\(^\circ\) F - 2.531\%
- Compressive strength perpendicular to Rift - 11,120 psi
- Compressive strength parallel to Rift - 7,680 psi
- Water Absorption - 1.72\%
- Moisture content - 0.26\%
- Silicon dioxide as SiO\(_2\) - 72.98\%
- Iron Oxide as Fe\(_2\)O\(_3\) - 3.12\%
Aluminum Oxide as Al₂O₃ - 10.60%
Calcium Oxide as CaO - 2.52%
Magnesium Oxide as MgO - 1.57%
Sodium Oxide as Na₂O - 4.99%

Justification for the use of stone obtained from a dealer was the necessity for large amounts of stone with which to make the assemblies, removal of which from an historic site is problematic. Another advantage of using commercial stone is that variables in testing are reduced as the stone has not undergone severe and differential weathering or alteration prior to treatment and a more uniform composition of purchased stone was more probable than random sampling of stone from the site. This further ensured that the test results would represent failure or success of the grouts themselves and their application methods, rather than unknown inconsistencies in the stone itself. The results gleaned from the experimentation process are intended to be used as a means of qualitative comparison, not only for the purposes of treatment of stone at El Morro, but for conservation problems of a similar nature.

The assemblies designed for testing were modifications of those recommended in ASTM D3931-90 "Standard Test Method for Determining Strength of Gap-Filling Adhesive Bonds in Shear by Compression Loads." The Delaware Valley Sandstone was cut by the dealer using a circular water saw, into blocks measuring 4"x4"x1.5". The stone blocks were scrubbed with a soft nylon bristle brush to remove any excess dirt or debris. The blocks were then placed in plastic tubs and submerged in deionized water for a period of 24 hours to ensure the pores were clear and surface dirt could be flushed clean. The stones were then set to air dry for 48 hours at room temperature.

Various injection holes were drilled into the stone blocks according to the grouting method to be tested. For assemblies intended for injections of 100% coverage of joint, one hole was drilled in the center of one stone block of each assembly, using a 1/4" masonry drill bit and hydraulic drill press. Another set of stones, intended for the epoxy spot welds and combination of spot welds and cementitious grout, had five holes drilled, one at each corner and one in the center, with a 1/4" masonry drill bit using hydraulic drill press. In a few isolated cases there was minor loss of stone at the corners of the blocks due to the pressure of the drill. These blocks were again soaked overnight and
scrubbed with a nylon brush to remove surface debris, and set on racks to air dry. It should be noted here that a majority of the stone blocks were not accurately sawn, resulting in minor differentiation in the size of the blocks, and often unparallel edges. These slight differences in size made it impossible to use a template for the drilling of the holes, instead each block was marked for drilling individually.

These blocks were then made into two part "sandwich assemblies," each consisting of two blocks of stone separated by bass wood spacers of variable thickness representing the range of detachments widths measured at the site (1mm, 3.5mm and 7mm). There was a 1/4" vertical displacement between the stone blocks as cited in ASTM D3931-90. The wood spacers were glued to one side of the assembly with Sobo glue around three sides of the assembly, leaving the top of the assembly open. After twenty four hours of drying, the assemblies were sealed with modeling clay to prevent the adhesive grout from flowing out, and tightly taped in both directions with duck tape. The duck tape served as a means of temporarily clamping the assemblies together during grouting and curing while assemblies remained in a vertical position. The vertical position of the assemblies was intended to simulate as closely as possible the detachment of the stone at El Morro which occurs parallel to the vertical rock face. Assemblies were then marked with code to designate type of joint and treatment they were intended to undergo.
TABLE 1: SAMPLE SCHEDULE

I. ASSEMBLIES FOR SHEAR AND FREEZE THAW TESTS

Designated Testing:
S= Shear
F= Freeze thaw

<table>
<thead>
<tr>
<th>Designated Treatment</th>
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</thead>
<tbody>
<tr>
<td>100% epoxy = 1.00</td>
</tr>
<tr>
<td>Epoxy spot welds = 2.00</td>
</tr>
<tr>
<td>100% cementitious grout = 3.00</td>
</tr>
<tr>
<td>Epoxy spot welds &amp; cementitious grout = 4.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1mm DETACHMENT</th>
<th>3.5mm DETACHMENT</th>
<th>7mm DETACHMENT</th>
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</thead>
<tbody>
<tr>
<td>S1.01</td>
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<td>S1.09</td>
</tr>
<tr>
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</table>

II. DISKS FOR WATER VAPOR TRANSMISSION TEST

**Designated Testing:**
W = Water vapor transmission

**Designated Treatment**
Sikadur 21 = 1.00  
Sikadur 22 = 2.00  
Jahn M30 = 3.00  
Jahn M40 = 4.00  
Untreated Control = 5.00

<table>
<thead>
<tr>
<th>SIKADUR 21</th>
<th>SIKADUR 22</th>
<th>JAHN M30</th>
<th>JAHN M40</th>
<th>CONTROL</th>
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<td>W2.01</td>
<td>W3.01</td>
<td>W4.01</td>
<td>W5.01</td>
</tr>
<tr>
<td>W1.02</td>
<td>W2.02</td>
<td>W3.02</td>
<td>W4.02</td>
<td></td>
</tr>
<tr>
<td>W1.03</td>
<td>W2.03</td>
<td>W3.03</td>
<td>W4.03</td>
<td></td>
</tr>
</tbody>
</table>
3.4. GROUTING OF ASSEMBLIES

There are ten different types of assemblies representing different application techniques, different grout materials and different widths of detachment. Within each type there are four assemblies of each for shear and three of each for freeze thaw, with the exception of those simulating 1mm detachment. The categories are as follows:

TYPE 1: Continuous Adhesive Film - Sikadur 21, Lo-Mod LV, 1mm detachment

TYPE 2: Continuous Adhesive Film - Sikadur 21, Lo-Mod LV, 3.5mm detachment

TYPE 3: Continuous Adhesive Film - Sikadur 22 Lo-Mod, 7mm detachment

TYPE 4: Adhesive Spot Welds - Sikadur 21, Lo-Mod LV, 1mm detachment

TYPE 5: Adhesive Spot Welds - Sikadur 21, Lo-Mod LV, 3.5mm detachment

TYPE 6: Adhesive Spot Welds - Sikadur 22 Lo-Mod, 7mm detachment

TYPE 7: Continuous Adhesive Film - Jahn M30, 3.5 mm detachment

TYPE 8: Continuous Adhesive Film - Jahn M40, 7 mm detachment

TYPE 9: Combination of Adhesive Spot Weld and Adhesive Infill - Sikadur 21, Lo-Mod LV and Jahn M30, 3.5mm detachment

TYPE 10: Combination of Adhesive Spot Weld and Adhesive Infill - Sikadur 22 Lo-Mod and Jahn M40, 7mm detachment

(See Appendix B.1 and B.2)

After the assemblies had been drilled, cleaned, spaced and taped they were ready for injection. Standard procedure for handling epoxies involved mixing under the fume hood, using solvent protective gloves, goggles and respirator. The following procedures were used in the fabrication of the various assembly types: (Note: For information on exact amounts of grout in each assembly see Appendix B.3.)
Type 1 & 2:

The two part epoxy system was mixed 1:1 by volume of A:B using a paddle mixer on medium speed for three minutes. Using a 12cc disposable syringe and cotton for back pressure, grout was injected through the injection port of the assembly until it reached the top. The hole was then sealed with clay. As the grout began to settle the joint was filled with additional grout from the top of the assembly. Assemblies were then set in a vertical orientation on shims to level out displacement and left to cure.

Type 3:

The two part epoxy system was mixed 1:1 by volume of A:B using a paddle mixer on medium speed for three minutes. Using a 12cc disposable syringe and cotton for back pressure, grout was injected through the injection port of the assembly until it reached the top. The hole was then sealed with clay. As the grout began to settle the joint was filled with additional grout from the top of the assembly. Assemblies were then set in a vertical orientation on shims to level out displacement and left to cure.

Type 4, 5 & 6:

The two part epoxy system was mixed 1:1 by volume of A:B and 5% by weight of Cab-o-Sil TS720 fumed silica using a paddle mixer on high speed for ten minutes. Using a 12cc disposable syringe and cotton for back pressure, calculated amount of grout was injected through the five injection ports of the assembly to make spot welds measuring 3/4" in diameter. Assemblies were then set in a vertical orientation on shims to level out displacement and left to cure.

Type 7:

Assemblies were flushed and prewet with water. Grout was mixed according to product literature, 1:1.5 by volume of B:A (liquid: dry) in a high speed mixer for 10 minutes. Using a 12cc disposable syringe and cotton for back pressure, grout was injected through the injection port of the assembly until it reached the top. The hole was then sealed with clay. As the grout began to settle the joint was filled with additional grout from the top of the assembly.
This grout exhibited extensive settling and bleeding where the grout needed to be injected over a period of over an hour until it was filled. Assemblies were then set in a vertical orientation on shims to level out displacement and left to cure.

**Type 8:**

Assemblies were flushed and prewet with water. Grout mixed according to product literature, 2:1 by volume of cement: water, in a high speed mixer for 5 minutes. Using a 12cc disposable syringe and cotton to provide back pressure, the grout was injected through the injection port hole of the assembly until it reached the top. The hole was then sealed with clay. As the grout began to settle the joint was filled with additional grout from the top of the assembly. Assemblies were then set in a vertical orientation on shims to level out displacement and left to cure.

**Type 9 & 10:**

After five or more days of curing, the assemblies with spot welds intended to be filled with Jahn grout were prewet and flushed with water. Grout was mixed as above, and injected through the top of the assembly, as injection ports had been filled with epoxy spot welds. As the grout settled, more was added until the joint was completely filled.

### 3.5. TREATMENT ASSESSMENT

A testing program was designed to determine the mechanical and physical properties of the four different grouts in a series of application techniques, and evaluate their relative effects on the stone substrate. The testing program was designed to address some of the most important properties of an ideal adhesive grout: injectability, water vapor transmission, shear strength, and resistance to freeze thaw. In addition, the density of stone was measured in order to calculate the theoretical minimum amount of adhesive material necessary to provide adequate shear strength to a variable area of exfoliating stone. The following standardized tests were applied where possible, and modifications were made as necessary. Replicate sets of three to seven assemblies were made of each type of grout and application depending on the tests for which they were intended.
3.5.1. APPARENT POROSITY, WATER ABSORPTION, APPARENT SPECIFIC GRAVITY AND BULK DENSITY

**Standardized Test Used**


**Purpose**

To measure the apparent porosity, water absorption, apparent specific gravity and bulk density of the stone used to make assemblies.

**Significance**

In order to determine the minimum amount of adhesive grout necessary to sustain the stress of the detached stone in shear, the bulk density of the stone must be obtained. This would allow the calculation of appropriate size of epoxy spot welds, limiting the introduction of conservation materials of differential mechanical land physical properties than the substrate material to the lowest level possible. The porosity and water absorption are also key in choosing a grout with appropriate viscosity.

**Methodology**

Four blocks of stone used to make the assemblies were tested in accordance with the ASTM guidelines. Dimensions of blocks were approximately 4x4x1.5"

**Results**

The apparent porosity, water absorption, bulk specific gravity and bulk density were determined for each assembly and the mean value, standard deviation and standard error were calculated for each group of assembly types. The standard Q test was used prior to calculating the mean, standard deviation and standard error in order to determine any results to be rejected. No results were rejected.
TABLE 2: MEAN APPARENT POROSITY, WATER ABSORPTION, APPARENT SPECIFIC GRAVITY AND BULK DENSITY

<table>
<thead>
<tr>
<th>TEST</th>
<th>MEAN</th>
<th>STANDARD DEVIATION</th>
<th>STANDARD ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPARENT POROSITY</td>
<td>18.4%</td>
<td>± .57</td>
<td>.29</td>
</tr>
<tr>
<td>WATER ABSORPTION</td>
<td>8.5%</td>
<td>± .26</td>
<td>0.13</td>
</tr>
<tr>
<td>APPARENT SPECIFIC GRAVITY</td>
<td>2.65cm³</td>
<td>± 0.01</td>
<td>0.005</td>
</tr>
<tr>
<td>BULK DENSITY</td>
<td>2.17cm³</td>
<td>± 0.01</td>
<td>0.005</td>
</tr>
</tbody>
</table>
3.5.2.  STRENGTH IN SHEAR BY COMPRESSION LOADING

Standardized Test Used


Purpose

To determine the shear properties of the epoxy and cementitious grouts as gap-filling adhesives.

Significance

In choosing an appropriate adhesive for reattaching delaminating layers of material to their substrate, assessing the mechanical properties of the adhesive as a joint is imperative. One of the defining characteristics of an effective adhesive joint is its ability to withstand shear stress. Measuring shear strength of an adhesive allows for an educated selection of the best adhesive for detached stone. Measuring the same adhesive using different application techniques would also provide insight into the best possible means of application, depending on the necessary strength requirements.

Apparatus

Instron Testing Machine 1331 Servo Hydraulic System. Load Cell capacity 22,000 lbs., X-Y recorder, speed 0.2 inches per minute. Steel shearing apparatus modeled after ASTM D 905.

Methodology

The shear properties of assemblies were determined following the ASTM D3931-90 with modifications in the fabrication of the assemblies as discussed in Section 3.4. of this thesis. A total of thirty two assemblies were made - four of each type, one of each type was used to adjust load applied by the testing machine. Once assemblies were placed in the shear apparatus a steel block was wedged in place between the assembly and the compression apparatus in
order to ensure the most even distribution of load and most parallel surface possible. Displacement was standard throughout the tests at 0.040”. The Instron Testing Machine measured the load applied to the assembly and the displacement achieved at a given load.

**Observations**

There were several factors in the preparation of the assemblies which should be noted here that may have effected the results of the shear test.

- irregular shape and size of the stone blocks
- uneven distribution of load due to not perfectly parallel surfaces of blocks
- varying amounts of adhesives within each type of assembly
- irregularities in the bedding of the stone or undetected flaws present in the stone
Results

The nominal shear stress at failure was calculated in psi for each assembly and the mean value, standard deviation and standard error were calculated within each group of assemblies types. The standard Q test was used to determine if any results should be rejected prior to calculating the mean, standard deviation and standard error. Only one result was rejected in type 5.

**TABLE 3: MEAN SHEAR**

<table>
<thead>
<tr>
<th>ASSEMBLY TYPE</th>
<th>MEAN SHEAR (psi)</th>
<th>STANDARD DEVIATION</th>
<th>STANDARD ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>336.8</td>
<td>122.2</td>
<td>61.1</td>
</tr>
<tr>
<td>2</td>
<td>430.6</td>
<td>170.9</td>
<td>85.5</td>
</tr>
<tr>
<td>3</td>
<td>419.1</td>
<td>63.3</td>
<td>37.2</td>
</tr>
<tr>
<td>4</td>
<td>1154.6</td>
<td>396.2</td>
<td>184.6</td>
</tr>
<tr>
<td>5</td>
<td>509.1</td>
<td>16.1</td>
<td>9.5</td>
</tr>
<tr>
<td>6</td>
<td>509.1</td>
<td>50.4</td>
<td>25.2</td>
</tr>
<tr>
<td>7</td>
<td>101</td>
<td>69.5</td>
<td>34.8</td>
</tr>
<tr>
<td>8</td>
<td>72.2</td>
<td>17.2</td>
<td>8.6</td>
</tr>
<tr>
<td>9</td>
<td>209.8/1168</td>
<td>48.4/269.5</td>
<td>24.2/134.8</td>
</tr>
<tr>
<td>10</td>
<td>174.7/972.7</td>
<td>19.6/109.3</td>
<td>11.5/64.3</td>
</tr>
</tbody>
</table>
The maximum load at failure was measured in psi for each assembly and the
mean value, standard deviation and standard error were calculated within
each group of assemblies types. The standard Q test was used to determine if
any results should be rejected prior to calculating the mean, standard
deviation and standard error.

**TABLE 4: MEAN LOAD**

<table>
<thead>
<tr>
<th>ASSEMBLY TYPE</th>
<th>MEAN LOAD (psi)</th>
<th>STANDARD DEVIATION</th>
<th>STANDARD ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4125</td>
<td>1497.3</td>
<td>748.7</td>
</tr>
<tr>
<td>2</td>
<td>5275</td>
<td>2093.3</td>
<td>1046.6</td>
</tr>
<tr>
<td>3</td>
<td>5133.3</td>
<td>776</td>
<td>456.5</td>
</tr>
<tr>
<td>4</td>
<td>2540</td>
<td>871.7</td>
<td>435.9</td>
</tr>
<tr>
<td>5</td>
<td>1090</td>
<td>60.4</td>
<td>30.2</td>
</tr>
<tr>
<td>6</td>
<td>1120</td>
<td>300.3</td>
<td>150.2</td>
</tr>
<tr>
<td>7</td>
<td>1238</td>
<td>920.2</td>
<td>460.1</td>
</tr>
<tr>
<td>8</td>
<td>888</td>
<td>211.2</td>
<td>105.6</td>
</tr>
<tr>
<td>9</td>
<td>2570</td>
<td>593</td>
<td>296.5</td>
</tr>
<tr>
<td>10</td>
<td>2140</td>
<td>240.6</td>
<td>141.5</td>
</tr>
</tbody>
</table>

**Discussion and Conclusions**

The shear tests demonstrated two important properties about each type of
assembly: the maximum load the joint could sustain before failure, and how
and where the joint failed (i.e. within the stone, within the adhesive or at the
interface between the adhesive and the stone). The desired test results for the
treatments were as follows:

- no or minimal damage to the stone at failure
- failure of the adhesive within the joint itself
- uniform failure within all assembly types
- demonstration of adequate strength in shear

In general, the epoxies exhibited much higher shear strength than did the
cementitious grouts, however it is inappropriate to assert that the epoxies are
superior based solely on this premise. All assembly types exhibited enough force to sustain the weight of the stone, plus an additional load ranging from 500 to 8500 pounds depending on the type of assembly. The loads applied to the stone during the shear test were used to test the limits of the system, and were probably greater than any load that would occur in nature. One could conclude that all applications of both epoxies and cementitious grouts tested would successfully accomplish the task of adhering the detaching layers of stone to the sound stone from a purely structural point of view.

The failure of all the types of joints tested was uniform within the type of application with regard to how the joints failed. The void-filling continuous films of epoxies of assembly types 1, 2 and 3 resulted in the stone breaking across the entire block of stone in a plane parallel to the joint approximately 2mm into the stone block. The spot welds of assembly types 4, 5, and 6 also resulted in stone failure. However the damage to the stone was minimal, confined to a thin layer of grains of stone adhered to the discrete spot welds. The damage to the stone in this instance did not go much beyond the diameters of the spot welds, containing the failure to a limited area. The overall coverage of cementitious grout in assembly types 7 and 8 displayed the ideal failure of an adhesive joint, as the failure occurred in all cases within the grout itself, causing no damage to the stone. Assembly types 9 and 10 exhibited a combination of the failure of epoxy spot welds as displayed in assembly types 4, 5 and 6, while the cementitious grout failed within the joint as in assembly types 7 and 8.

The failure exhibited in assembly types 1, 2 and 3 is unacceptable due to the notable destructive effects on the stone. Though assembly types 4, 5 and 6 also resulted in damage to the stone, the detriment is acceptable as it was isolated to the minimal contact area between spot weld and stone. Assembly types 7, 8, 9 and 10 also failed in an favorable manner.

In conclusion, although all the systems of grouting which were tested demonstrated adequate strength to sustain great amounts of load applied in shear, not all the systems failed in an acceptable fashion, namely assembly types 1, 2 and 3, making their use as adhesive grouts for detached stone inadvisable especially for relatively thin delaminations. Assembly types 4 - 10 would appear to be appropriate grouting systems based on this test alone.
3.5.3. WATER VAPOR TRANSMISSION

Standardized Test Used


Purpose

To measure the water vapor transmission rates of grout materials used in assemblies in conjunction with stone, and determine any significant differences in water vapor transmission between these materials.

Significance

In many cases, conservation treatments should not significantly affect the water vapor transmission of the material being conserved. When moisture has entry to a material it must also be provided with adequate exit from a material, especially in the case where water is deemed a significant deterioration mechanism. The decrease of water vapor transmission or formation of a water vapor barrier due to a conservation treatment is often considered deleterious to the historic fabric.

Apparatus

Glass tank, Airguide Humidity Indicator Model 605, Fisher Scientific Thermometer 14-985C (range -20°C to 150°C, tolerance ±1°C), Fisher Scientific scale model S400.

Methodology

Cores were drilled out of commercial stone using a hydraulic drill press and a 1 3/4"Rem Grit tungsten carbide hole saw. The stone was kept wet during drilling to keep the stone and bit cool. Cores were then mechanically sliced with a hacksaw with carbide blade to little over 1/4" in thickness. Cores were manually sanded to uniform thickness of 1/4" using 80 grade sandpaper. Disks were scrubbed with nylon bristle brush and soaked in deionized water for 24 hours to remove dirt and debris from pores. Disks were then taped around the outside with electrical tape, leaving over 1/4" lip above the disk.
Three disks each were then filled 1/4" high with Jahn M30, Jahn M40, Sikadur 22 or Sikadur 21. Disks were left to cure for over thirty days on plastic racks in the laboratory.

A total of twelve disks was made for testing. Samples measured 1 1/2" in diameter and were a total of 1/2" thick, with a surface area of 1.76" per side. 20 ml of deionized water was poured in 50 ml disposable plastic beakers. The grouted stone disks were placed at the mouth of the beakers and sealed with melted paraffin wax.

Three 8" square trays filled 1/2" with Drierite, an anhydrous calcium sulfate desiccant, in a ratio of 1:3, blue:white were placed at the bottom of a glass tank. Plastic racks were placed on top of the trays of desiccant for the placement of the samples. A thermometer and hygrometer were placed inside of the tank to measure the temperature and relative humidity fluctuations in the tank throughout the experiment. The samples were placed in the tank, and the tank was kept closed and sealed. Readings were taken daily at 5pm of the temperature, relative humidity and the weights of the samples for a period of thirty days. During this period the Rh averaged 16% and the temperature averaged 25°C. The samples were rotated throughout the tank during the testing period.

Sample weights were measured on an electronic scale that was calibrated before each weighing by adding or subtracting the differences in weight of the 147.56g weight.
Results

The daily rate of water loss due to vapor transmission was calculated for each sample. The mean value for each group was calculated and graphed.

GRAPH 1: MEAN WATER VAPOR TRANSMISSION

SIKADUR 21

SIKADUR 22

Mean 1

Mean 2

JAHN M30

JAHN M40

Mean 3

Mean 4
Discussion and Conclusions

The results revealed a significant difference in the WVT between the epoxy grouts and the cementitious grouts. While the WVT of the epoxy grouts was negligible (i.e., impermeable to water vapor), the Jahn cementitious grouts exhibited a more favorable steady rate of water vapor transmission throughout the testing period. Based on this test, the epoxies when applied as void-filling continuous films would decrease the WVT of the stone to almost zero, forming a vapor barrier. Therefore their use in this manner is inadvisable. By comparison the Jahn grouts appear to be much better suited to application as void-filling grouts, by allowing the water vapor to pass through the stone. However, while epoxies applied as void-filling grouts may be inappropriate, their application of spot welds would limit the area where WVT is hampered to the discrete area of contact between the welds and the stone, allowing for the transmission of moisture and water vapor through the untreated surface of the stone.
3.5.4. FREEZE THAW RESISTANCE

Standardized Test Used

ASTM C67 part 8 with modifications by the author

Purpose

To determine the relative resistance to freeze thaw cycling of the various types of adhesive joints of the assemblies treated with epoxies and cementitious grouts, and to compare differences in resistance to freeze thaw between the types of application (i.e. spot welds, continuous films of grout and combinations of spot welds and cementitious grout infill).

Significance

The stone at El Morro undergoes extremes of ambient temperatures from -32°F to over 100°F throughout the year. In the winter, the stone can undergo a freeze thaw cycle on a daily basis, making freeze thaw a primary suspect in the deterioration of the stone. An effective adhesive grout would therefore be one that is able to withstand freeze thaw cycles, and in the case of failure would occur either within the joint itself or at the interface of the joint and the stone, but not cause the stone itself to break or be damaged.

Observations

The following factors may contribute to the variability of resistance to freeze thaw cycles within the assembly types:

- irregular shape and size of the stone blocks
- varying amounts of adhesives within each type of assembly
- the presence of wood spacers in the assemblies may contribute to the premature failure of the joint due to the expansive nature of wood.
- exact control of the freeze thaw process.
Methodology

The ASTM C 67 part 8 Freezing and Thawing was used as a guideline with the following modifications. The samples tested were the assemblies of various types of grouts and commercial stone, as discussed in 3.4. A total of 24 assemblies were made, 3 of each type with the exception of those simulating 1mm detachment. Assemblies were dried in an oven for a period of 24 hours at the temperature of 70°F. The weight of each assembly was taken and recorded, using an electronic scale. The test specimens were then submerged in the water of plastic thawing tanks for a period of four hours. After the four hour wet thaw, the specimens were then removed and placed 1/2" apart in a freezer on plastic coated wire racks to allow for the circulation of air throughout the chamber and around the assemblies. After a period of twenty hours in the freezer, the assemblies were removed and once again immersed in the water of the thaw tanks. This 24 hour period completes one freeze thaw cycle. The water in the thaw tanks was maintained at a constant 24°C ± 5°, while the temperature in the freezer remained constantly below -10°C. The assemblies were subjected to a total of fifty freeze thaw cycles, unless they exhibited failure before the completion of fifty cycles at which point they were removed from the tanks.

Results

After fifteen cycles of freeze thaw, assembly F3.05 of assembly type 7 using continuous application of Jahn M40 failed. The failure occurred within the adhesive joint of the assembly in a plane parallel to the stone. There was no visible cracking or damage to the stone as a result. All other assemblies underwent fifty cycles of freeze thaw without any observable failures.

Discussion and Conclusion

With the exception of assembly F3.05, all of the assemblies tested underwent fifty cycles of freeze thaw with no observable damage to either the stone or the adhesive joint. The adhesives and the stone did not exhibit any visible cracking, nor was there any detachment observable at the interface between the stone and the adhesive. In all cases, the weight loss measured at the
completion of the test was limited to less than a few grams, probably due to loss of grains of the stone.

The cause of failure of F3.05, assembly type 7, is unknown, but because the other two assemblies of this type did not result in the same failure it may be concluded that the reason for failure was a consequence of improper application of the grout rather than inadequacies in the grout itself. It is important to note, however that the adhesive failed within the joint of the assembly, causing no damage to the stone itself.

In conclusion, the results of this test indicate that all the grouts and various application techniques tested would perform adequately under cyclical freezing and thawing. The different types of applications of the grouts did not exhibit differential failure, suggesting that the grouts perform equally as well whether they are applied as continuous films, as spot welds, or as combinations of both.
3.6. CONCLUSIONS

The results of the experimental program revealed several important differences between the different grouts tested and the various applications of these grouts. A comparison of the results of the shear test demonstrated that although all the grouting materials and application systems which were tested demonstrated adequate strength to sustain great amounts of load applied in shear, not all the systems failed in an acceptable fashion. The failure exhibited in assembly types 1, 2 and 3, which employed a continuous film application of epoxy, resulted in excessive damage to the stone making their use as adhesive grouts for detached stone inadvisable. Assembly types 4 - 10, which employed either continuous film application of cementitious grout, epoxy spot welds alone or epoxy spot welds in combination with grout infill, displayed failure which caused little or no damage to the stone itself, making those systems more desirable as grouting systems based on this test.

A comparison of the resistance to freeze thaw of the various grouts and application methods did not exhibit differential failure, suggesting that the grouts performed equally well whether they were applied as continuous films, as spot welds, or as combinations of both.

Significant differences in the rate of water vapor transmission were observed between grouting materials. Both epoxies tested significantly reduced the water vapor transmission of the stone while the cementitious grouts exhibited a more favorable water vapor transmission. On the basis of these results, the application of epoxies as a continuous film would not be advisable because it would hamper the transmission of liquid and water vapor by forming a water vapor barrier. However, application of the epoxies as spot welds would limit the area where water vapor transmission is hampered, allowing the escape of liquid and water vapor moisture through the more porous surrounding substrate.

On the basis of the results of the experimental program it is recommended to field test epoxies as spot welds, cementitious grouts as void-filling continuous films and a combination of epoxy spot welds with a cementitious grout infill. With all of these systems of reattachment there are inherent advantages and disadvantages which must be further considered in a field context.
The use of epoxy spot welds alone has the advantage of introducing a limited amount of material into an already weakened system. This would reduce the amount of hazardous waste and cost. This approach would also limit the area of contact between the two materials (i.e. the epoxy and the stone), reducing the potential problems associated with differences in thermal coefficient of expansion of the two materials. The modulus of elasticity of the epoxies is lower than that of the stone, making epoxy desirable as a joint forming material as it would withstand the stress of expansion of the stone. Again the water vapor transmission of a spot weld system would be desirable because the epoxies would be limited to discrete areas surrounded by a field of evaporative surface of stone. One of the major problems with blind application of grouts is that it is difficult to evaluate the installation of grouting. The epoxy spot weld would increase the potential of successful contact between the epoxy and the stone because of its thixotropic nature. The disadvantages of using epoxy spot welds are the use of hazardous materials and difficult clean up. Another disadvantage is that by limiting the contact area between the grout and the stone, the system is dependent solely on the a successful contact of the welds.

A system of a continuous void-filling film using a cementitious grout has the advantage of sealing the void or detachment from water, which could be harmful to the stone possibly making the voids larger through water based chemical dissolution or the internal disruptive processes of cyclical crystallization of ice and salts. Cementitious grouts are easy to handle, apply and clean up and are relatively low in toxicity. Unlike the epoxy spot welds, a continuous film of cementitious grout increases the area of contact between the grout and the stone, ensuring a higher percentage of successful adhesion between the two surfaces. Although no data was found on the modulus of elasticity or thermal coefficients of expansion of Jahn cementitious grouts, one could infer similarities of these properties for the cementitious grouts and stone because both are inorganic siliceous materials. A potential disadvantage of using a cementitious grout as a continuous film is that eventually the system will fail and when failure occurs the weight of the grout could prove to be damaging to the stone.
A combination reattachment system of the epoxy spot welds and the cementitious grout infill would offer the advantages of the concentrated strength of the epoxy and the support and water sealing properties of the cementitious grout without the disruption of the water vapor transmission. However a grouting system comprised of three different materials might introduce higher potential of failure due to mechanical difference between the epoxy, cementitious grout and the stone.

It is not recommended to use Jahn M30 in any further testing for this project due to its tendency toward bleeding and segregation. These are not desirable properties in a grout and could be damaging to any grouting system.

3.7. RECOMMENDATIONS FOR FUTURE RESEARCH

Future research and experimentation would help to clarify the differences in results between the grouts tested and their ultimate suitability as grouting materials. Test conducted in this program could be made applicable to specific types of stone if weathered samples of stone were used rather than commercial stone.

Other tests not included in this testing program which would be of particular relevance to evaluating the effectiveness of the different grouting materials and systems would be to determine the specific modulii of elasticity and thermal coefficients of expansion of the grouts and the stone being tested. It is essential that any grouting system designed be comprised of materials which would undergo compatibility of deformation under stress. Also the testing of the system with cyclic loading and thermal fluctuations would be useful in determining the long range effectiveness of the systems.

It is also recommended to investigate other systems of reattachment of exfoliating layers of stone, i.e. non-corrosive rigid reinforcement such as pinning. In addition to the problem of detachment and delamination of layers of stone, further research needs to be done to address other forms of deterioration such as disaggregation and biological growth. In any conservation treatment considered it is imperative to keep in mind the microgeological variables in the stone, as well as its high clay content. Treatments should always strive to be as visually unobtrusive as possible.
4. CASE STUDY: FIELD TESTING PROGRAM OF GROUTING SYSTEMS AT EL MORRO NATIONAL MONUMENT
4.1. OVERVIEW

The Architectural Conservation Laboratory of the University of Pennsylvania and the Southwest Regional Office of the National Park Service undertook a joint research and training program to develop and test possible treatments in response to the ongoing deterioration of the petroglyphs and inscriptions carved into the surfaces of Inscription Rock, part of El Morro National Monument in New Mexico. The project was conducted under a cooperative agreement established in 1992 between the university and the National Park Service providing research and practical conservation training. The project was undertaken from July - August 1994. Team members included: Frank G. Matero (U/Penn), Jake Barrow (NPS/SWRO), project directors; Dawn Melbourne (U/Penn), and Angeline Bass (NPS/SWRO), project interns; Dennis Sack (Olson Engineering) and Marie Ennis P.E., non-destructive testing.

Although Inscription Rock suffers from a multitude of deterioration phenomena, the problem of detachment and subsequent exfoliation of layers of sandstone can be considered to be of considerable urgency, deserving immediate attention. From September 1993 to July 1994, under Subagreement 5, a student intern from the University of Pennsylvania undertook a research and laboratory testing program designed to address the problem of reattaching exfoliating layers of sandstone and re-establishing adhesion between the detached layers and the sound stone.

The choice of conservation treatments and materials tested, was based on four criteria: the characterization of the stone and its mechanical and physical properties, the mechanisms of deterioration responsible for the primary weathering and detachment of the stone, environmental conditions on site, and assessment of past treatments of the observed deterioration. An experimental program was designed to investigate and compare the properties of epoxy and cementitious grouts applied as continuous films, epoxy "spot welds" and a combination of both epoxy "spot welds" and cementitious grout infill, and to assess the physical and mechanical properties of these various methods of application and their relative effects on the stone. The ultimate objective of the experimental program was to determine the
minimum amount of adhesive required for readhesion, and to assess
whether epoxies applied as spot welds were more or as effective as epoxies
and cementitious grouts applied as continuous adhesive films. Ultimately,
Sikadur Lo Mod epoxies and Jahn cementitious grouts were selected for the
testing program.

The results of the experimental program revealed several significant
differences between mechanical properties of the epoxies and cementitious
grouts and the effectiveness of the various applications methods tested. On
the basis of the results of the experimental program, only two materials were
chosen for further field testing (Sikadur 22 Lo Mod Epoxy and Jahn M40
Cementitious Grout) and it was recommended to field test only three systems
of application: 1. epoxies as spot welds 2. cementitious grouts as void-filling
adhesives and 3. a combination of epoxy spot welds with a cementitious grout
infill.

The purpose of this second phase of the project was to develop a field testing
program at Inscription Rock utilizing the grouting materials and systems of
application recommended as a result of the research and testing carried out
under Subagreement 5. A program of field testing would provide the
opportunity for in situ evaluation of the facility of grout application,
verification of the success of grouting and assessment of the weathering of the
systems.

The test site, chosen by members of the National Park Service, was located in
an area removed from the visitor's trail, devoid of any historic carvings. The
conditions of the stone at the selected test site were thought to be
representative of conditions found in association with the majority of
inscriptions. Several discrete areas were selected from the site for treatment.
Prior to treatment, the test areas were photographed and the existing
conditions of the stone were documented graphically. Selected test areas and
areas of sound stone were then investigated by Dennis Sack of Olson
Engineering Inc. and Marie Ennis, P.E. using a combination of non-
destructive techniques (NDT): Impact Echo (IE), Spectral Analysis of Surface
Waves (SASW) and Ultrasonic Pulse Velocity (UPV). The NDT provided
information about the area of detachment and the thickness of the detached
stone, which was then recorded graphically. In some areas cores were drilled

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to verify the findings of the NDT. Test areas were then grouted and left to cure overnight. The next day the treated areas were retested using NDT to determine the success of grouting. Test areas were photographed after treatment.

4.2. PRETREATMENT DOCUMENTATION AND ANALYSIS

Initially, two sites were chosen for field testing by members of the National Park Service. Both sites were located off the visitor's trail devoid of any historical inscriptions. (See Appendix A) Prior to treatment, both locations were reviewed by members of the team to determine their suitability for treatment. It was decided that the condition of the stone existing at Location 1, which suffered from complex cracking and multi-layered detachment, was not representative of the conditions observed in association with the majority of inscriptions. Location 2 was therefore selected as the sole area in which to conduct the field tests.

Location 2 was then surveyed for potential treatment areas. Several discrete areas were chosen for treatment which were felt to be representative of the conditions observed in association with the majority of inscriptions. (See Appendix B) Due to time constraints, only three areas were fully investigated by NDT and grouted (test areas C, G & J). Prior to treatment, the selected test areas were photographed using 35mm photography.

Initial mapping of the conditions in selected areas was carried out by visual observation and percussive tapping on the stone to determine the areas of blind detachment. Observable conditions consisted of biological growth, edge detachment, blind detachment, flaking and cracking. These conditions were documented on Polaroid photographs of the test areas utilizing a system of graphic symbols representing the observed conditions.

Selected test areas and areas of sound stone were then investigated by Dennis Sack of Olson Engineering INC. and Marie Ennis, P.E. using a combination of non-destructive techniques: Impact Echo (IE), Spectral Analysis of Surface Waves (SASW) and Ultrasonic Pulse Velocity (UPV). In most cases, the NDT yielded information about the area of detachment and the thickness of the detached stone. Data collected was recorded for comparison with post
treatment data. A detailed explanation of these techniques and a complete survey of results using NDT can be found in a report (Appendix D) by Olson Engineering, Inc.

In all cases, the boundaries of blind detachment were found to be the same by means of manual tapping on the stone and by electronic NDT. In all test areas either cores or injection portholes were drilled into the area of blind detachment to verify the findings of the NDT and to determine the depth of the void. It was important to determine the depth of the detachment in order to select the appropriate grouting materials; epoxy spot welds would be used on detachment less than 1/8" and cementitious grouts would be used on detachment thickness greater than 1/8". Because the depth of the void was unable to be determined by means of electronic NDT, destructive means of investigation in the form of cores or portholes were necessary. It is interesting to note that the different methods of investigation often resulted in slightly different results. These inconsistencies may be attributed to the fact that the cores and portholes provided only one, isolated measurement while the results of NDT were a compilation of a series of readings. Following are the measurements taken manually through the drilled holes and those determined by Impact Echo (found in Table 1 of Olson Engineering's Report).

**LOCATION 2**

**Test Area C:**

A core of 3/4" diameter was drilled in center of the blind detachment in area C to determine the thickness of the detachment. Measurements were made by inserting a hooked flexible metal wire into the core. The thickness of blind detachment was a hairline crack, while the thickness of the detached stone measured through the core was 2 1/2". Edge detachment at its maximum was 5/16" and 3/16" at its minimum.

(IE) Thickness of detached stone 1.8"
Test Area F:

Thickness of blind detachment was measured through 1/4" holes drilled into the area for injection grouting. Measurements were made by inserting a hooked flexible metal wire into the port holes. The thickness of detached stone measured 3/4 - 1 1/2" while detachment was less than 1/16". Edge detachment was less than 1/8" in thickness.

(IE) Not performed on this area.

Test Area G:

Thickness of blind detachment was measured through 1/4" holes drilled into the area for injection grouting. Measurements were made by inserting a hooked flexible metal wire into the port holes. The thickness of detached stone measured 2 7/16" while detachment was hairline. Edge detachment was less than 1/8" in thickness.

(IE) Thickness of detached stone 2.6 - 3.6"

Test Area I:

A core of 3/4" diameter was drilled in center of the blind detachment in area C to determine the thickness of the detachment. Measurements were attempted by inserting a hooked flexible metal wire into the core, however the core was not deep enough to locate the detachment. Therefore, this area was not treated.

Test Area J:

Thickness of blind detachment was measured through 1/4" holes drilled into the area for injection grouting. Measurements were made by inserting a hooked flexible metal wire into the port holes. The thickness of blind detachment was a 1/8", while the thickness of the detached stone measured through the core was 3/4 - 1 1/4". Edge detachment was measured at 1/4 - 3/4" thick.

(IE) Thickness of detached stone 1.8 - 2"
4.3. SURVEY OF PRETREATMENT CONDITIONS

A survey of pretreatment conditions of the Zuni Sandstone in Location 2 was conducted visually and recorded in graphic format. The conditions observed in the test areas, specifically the depth of blind detachment, determined the nature of the grouting materials and their application.

Explanation of Conditions and Graphic Key

**Biological Staining:** Distinct greenish or blackish discoloration from biological or organic growth, this growth covered most of the treated areas.

**Cracking:** Fractures of variable widths and dimensions. Cracking was often observed in association with detachment.

**Blind Detachment:** The separation of a layer or layers of stone from the sound stone beneath, detected by a hollow sound upon tapping. Areas of detachment were often filled with loose debris in the form of clay, dirt and small pieces of stone.

**Edge Detachment:** The separation of a layer or layers of stone from the sound stone beneath where the boundary or edge of detachment is visually observable by a hollow space between the detaching layer and stone beneath.

**Flaking:** The detachment of small, thin layers of stone. Not a condition associated with many tested areas.
<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>CONDITION</th>
<th>SYMBOL COLOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Symbol]</td>
<td>biological growth</td>
<td>green</td>
</tr>
<tr>
<td>![Symbol]</td>
<td>cracking</td>
<td>black</td>
</tr>
<tr>
<td>![Symbol]</td>
<td>blind detachment</td>
<td>purple</td>
</tr>
<tr>
<td>![Symbol]</td>
<td>edge detachment</td>
<td>purple</td>
</tr>
<tr>
<td>![Symbol]</td>
<td>flaking</td>
<td>green</td>
</tr>
</tbody>
</table>

NOTE: On the pretreatment conditions survey photographs, a box has been drawn around the area of study for each test area.
Fig. 1. Field Testing Program Test Station C, before treatment.
Fig. 1. Field Testing Program Test Station C, before treatment.
Fig. 2. Field Testing Program Test Station F, before treatment.
Fig. 2. Field Testing Program Test Station F, before treatment.
Fig. 3. Field Testing Program Test Station G, before treatment.
Fig. 3. Field Testing Program Test Station G, before treatment.
Fig. 4. Field Testing Program Test Station I, before treatment.
Fig. 4. Field Testing Program Test Station I, before treatment.
Fig. 5. Field Testing Program Test Station J, before treatment.
Fig. 5. Field Testing Program Test Station J, before treatment.
4.4. TREATMENT

JULY 26, 1994/LOCATION 2

Test Area C:

Three port holes were drilled in a triangular grid into the area of blind detachment for injection grouting using a hand held masonry drill with a 1/4" bit. The drilling was done with water, which presented a problem as the cracks and portholes were filled with clay and loose debris and this prohibited adequate flushing of the detached area. Water was therefore eliminated in the drilling process for the other test areas. Detached areas were attempted to be flushed clean with water through the port holes but the water only came back out through the holes and did not flow out the bottom edge detachment. Edge detachment was cleaned by inserting a metal spatula to remove loose debris. Note that slightly aggressive cleaning with the spatula was required before water would flow from the port holes to the bottom edge detachment. This might prove harmful to the already weakened stone. The area was allowed to dry for one hour. The three holes were then manually injected with Sikadur 22 Lo Mod epoxy, modified with 5% Cab-O-Sil Fumed Silica by weight, using a 60cc medical syringe. Cotton was used for back pressure during injection. The top hole accepted 3cc of grout, the bottom left hole 4cc and the bottom right hole 4cc. It should be noted here that the injection of the epoxy was difficult and the port holes filled up with epoxy. This may be due to the inability to adequately clean the detached areas due to wet drilling or the hairline nature of the crack. After grouting the stone was sprayed clean with water.

Test Area G:

Four port holes were dry drilled in an inverted triangular grid into the area of blind detachment for injection grouting using a hand held masonry drill with a 1/4" bit. Edge detachment was cleaned by inserting a metal spatula to remove loose debris. Detached areas were flushed clean with water through the port holes until water flowed out from side and bottom edge detachment. The holes appeared to have been drilled into an area of connected detachment. The area was let to dry for one hour. Three holes were then
manually injected with Sikadur 22 Lo Mod epoxy, modified with 5% Cab-O-Sil Fumed Silica by weight, using a 60cc medical syringe. Cotton was used for back pressure during injection. The top left hole accepted 4cc of grout, the top right hole 2cc and the bottom hole 4cc. The area was left for three hours to dry and then prewet with water through the remaining porthole and edge detachment areas in preparation for the Jahn M40 cementitious grout. The areas of edge detachment were then sealed with cotton to prevent grout from escaping. Grouting with Jahn M40 was done through the port hole and in areas of edge detachment until no more grout was accepted. A total of 80cc of Jahn grout was injected. After grouting the stone was sprayed clean with water and the cotton was removed.

**Test Area J:**

Three port holes were dry drilled in a triangular grid into the area of blind detachment for injection grouting using a hand held masonry drill with a 1/4" bit. Edge detachment was cleaned by inserting a metal spatula to remove loose debris. Detached areas were flushed clean with water through the port holes until water flowed out from bottom edge detachment. The holes appeared to have been drilled into an area of connected detachment. The areas of edge detachment were then sealed with cotton to prevent grout from escaping. Three holes were then manually injected with Jahn M40 cementitious grout using a 60cc medical syringe. Cotton was used for back pressure during injection. Grouting with Jahn M40 was performed until no more grout was accepted. A total of 292cc of Jahn grout was injected. After grouting the stone was sprayed clean with water and the cotton was removed.

**Test Area F:**

NDT was not performed on this area as it was not intended to be grouted. It was decided to use this area to experiment with epoxy modified with a lower percentage of fumed silica. This was done because the epoxy modified with 5% fumed silica seemed difficult to inject in the other areas. Although a scale was not available on site to measure the exact percentage of epoxy added, approximately 3% by weight was added judged by the consistency of the modified epoxy and the experimentation with these materials done at the University of Pennsylvania. Three port holes were drilled in a triangular grid
into the area of blind detachment for injection grouting using a hand held masonry drill with a 1/4" bit. Edge detachment was cleaned by inserting a metal spatula to remove loose debris. The detached area was flushed clean with water through the port holes until the water flowed out the bottom edge detachment. The area was let to dry for one hour. The three holes were then manually injected with Sikadur 22 Lo Mod epoxy, modified with approximately 3% Cab-O-Sil Fumed Silica by weight, using a 60cc medical syringe. Cotton was used for back pressure during injection. The top hole accepted 2cc of grout, the bottom left hole 8cc and the bottom right hole 4cc. The lower percentage of fumed silica added to the epoxy did not prove to be more effective as the epoxy did not form spot welds as intended, instead it flowed out the bottom edge detachment and had to be stopped with cotton. After grouting the stone was sprayed clean with water and the cotton was removed.

**JULY 27, 1994 LOCATION 2**

All of the drilled and cored holes made in the test areas were prewet with water and filled with a patching mortar designed at the University of Pennsylvania to match in color and texture as closely as possible Zuni Sandstone. The patching mortar was composed of one part Riverton hydrated hydraulic lime and three parts S23 sand.\(^7\) The stone was then wiped clean with a soft sponge and water.

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\(^7\)S23 refers to the catalogue number of the sand chosen form the sand library at the University of Pennsylvania. S23 is sold by the Morie Co., Inc., located at 1201 North High Street, Millville, NJ 08332. The phone number of the company is (609) 327-4500. S23 is light brown in color and is sold as sand #100.
4.5. TREATMENT ASSESSMENT AND CONCLUSIONS

After a period of 24 hours during which the epoxies and cementitious grouts were allowed to cure, test areas C, G and J were again subjected to NDT to establish the effectiveness of the repairs. This was determined by comparing the pregrouted and postgrouted readings of selected areas taken using IE and SASW. Both methods of analysis showed that the treated sandstone displayed greater physical continuity than the untreated sandstone for both the areas treated with epoxy spot welds and those treated with cementitious grout. (Olson Engineering 1994) This would imply that the grout injected into the areas of detachment improved the structural integrity of the areas of detachment.

Although NDT was instrumental in determining that the presence of grout injected into the voids added to the structural soundness of the weak stone, it was unable to determine what percentage of the voids were filled with cementitious grout or if the epoxy formed spot welds successfully. It is intended to review the performance of these repairs after one year of weathering through repeated NDT and possibly destructive investigation. It is hoped that this future investigation will provide the answers to some of these remaining questions.

The field testing program revealed several important factors about the grouting methods and materials intended for treatment of delaminating stone at El Morro. One of the most important issues which must be considered in future conservation treatments is that the Zuni Sandstone does not display homogeneous characteristics throughout the outcrop. The bedding orientation, mineral composition and friability of the stone fluctuates substantially. Thus, each area intended for treatment must be regarded as unique and treated according to the specific characteristics of the stone as well as its conditions.

The high content of clay in the Zuni Sandstone also proved to be another important factor in treatment. The depth of detachment was found in most cases to be less than 1mm. If water is introduced into the system as in preparation for grouting, it is possible that the clay present in the voids might swell, making the injection of grout difficult or impossible from the filling of
the narrow void. It is also possible that these clayey interstices would impede good adhesion between the grout and the stone. This is especially problematic in the case of epoxy spot welds where the surface area for adhesion is limited to small discrete areas of contact between layers.

If the application of epoxy as spot welds or cementitious grouts as continuous void filling materials are found to be inappropriate repair techniques with future investigations, it is recommended to investigate the use of mechanical pinning as an alternative treatment. Mechanical pinning might prove to be especially instrumental in the treatment of exfoliating stone whose depth of detachment is less than 1mm.
BIBLIOGRAPHY


Down, J.L. "Adhesive Testing at the Canadian Conservation Institute, Past and Future,"


Padgett, Antoinette, "Assessment of Deteriorative factors Affecting the Inscriptions, El Morro National Monument, New Mexico with


### APPENDIX A: PRODUCT INFORMATION

#### A.1. PRODUCT INFORMATION

(information as supplied by manufacturers)

<table>
<thead>
<tr>
<th>PRODUCTS</th>
<th>SIKADUR 21 LO MOD LV</th>
<th>SIKADUR 22 LO MOD</th>
<th>JAHN M30</th>
<th>JAHN M40</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPR.</td>
<td>7243 psi</td>
<td>6960 psi</td>
<td>98 N/mm²</td>
<td>10-30 N/mm²</td>
</tr>
<tr>
<td>TENSILE</td>
<td>5807 psi</td>
<td>3546 psi</td>
<td>11 N/mm²</td>
<td>2-5 mm²</td>
</tr>
<tr>
<td>SHEAR</td>
<td>5676 psi</td>
<td>5408 psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VISCOSITY</td>
<td>1400 cps</td>
<td>3500 cps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WATER</td>
<td>1.17% neat</td>
<td>1.3% neat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABSORPTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M O D</td>
<td>2.58X10⁵ psi</td>
<td>1.66X10⁵ psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ELASTICITY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHRINKAGE</td>
<td>none</td>
<td>none</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>INITIAL SET</td>
<td>24hrs</td>
<td>24hrs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CURE TIME</td>
<td>28 days</td>
<td>28 days</td>
<td>28 days</td>
<td>28 days</td>
</tr>
<tr>
<td>CRACK SIZE</td>
<td>max 1/2&quot;</td>
<td>max 1/2&quot;</td>
<td>0-5mm</td>
<td>5-10mm</td>
</tr>
<tr>
<td>MIXING</td>
<td>3 mins low speed paddle</td>
<td>3 mins low speed paddle</td>
<td>add A to B, 3000 rotations with high speed paddle</td>
<td>add cement to water and mix</td>
</tr>
<tr>
<td>POT LIFE</td>
<td>25 mins</td>
<td>30 mins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SURFACE PREP</td>
<td>Degrease</td>
<td>Degrease</td>
<td>Clean with compressed air and water, flush with water before injection</td>
<td>Clean with compressed air and water, flush with water before injection</td>
</tr>
<tr>
<td>STRUCTURAL</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>semi</td>
</tr>
<tr>
<td>MOISTURE SENSITIVE</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
A.2. MANUFACTURER'S PRODUCT INFORMATION
**Sikadur® 21, Lo-Mod LV**

New, improved, 1:1 ratio, low-modulus, low-viscosity, epoxy resin binder

**Technical Data**

<table>
<thead>
<tr>
<th>Description:</th>
<th>Sikadur 21, Lo-Mod LV, is a 2-component, solvent-free, moisture-insensitive, epoxy resin binder. It meets ASTM C-881, Type III, Grade 1, Class C, epoxy adhesive binder.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Where to Use:</td>
<td>Use as a binder for epoxy mortar and concrete for patching and overlays.</td>
</tr>
</tbody>
</table>
| Advantages:  | • Insensitive to moisture both before and after cure.  
• New easy mix B:A = 1:1 volume ratio.  
• Excellent strength development.  
• Low viscosity gives you easy handling, high-yield epoxy mortar.  
• Material is USDA-approved. |
| Coverage:    | Prime Coat - 400-600 sq ft/gal.  
Mortar Binder - 1 gal of mixed Sikadur 21, with the addition of 6 parts by loose volume of an oven-dried sand, will yield 924 cu in. |
| Packaging:   | 4-gal units; 1-qt units, 12/case.                                                                                                                                                                   |
Typical Data for Sikadur 21, Lo-Mod LV:
(Material and curing conditions @ 73°F and 50% R.H.)

**Shelf Life:** 2 years in original, unopened containers.

**Storage Conditions:** Store dry at 40-95°F. Condition material to 65-85°F before using.

**Color:** Clear, amber.

**Mixing Ratio:** Component 'A':Component 'B' = 1:1 by volume.

**Viscosity:** Approximately 1,400 cps.

**Pot Life:** Approximately 25 minutes.

**Tack-Free Time:** Approximately 3 hours.

**Traffic Time:** 4-5 hours.

---

**Compressive Properties Mortar 1:6, (ASTM D-695):**

<table>
<thead>
<tr>
<th>Time</th>
<th>40°F*</th>
<th>73°F*</th>
<th>90°F*</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 hour</td>
<td>-</td>
<td>-</td>
<td>500</td>
</tr>
<tr>
<td>8 hour</td>
<td>-</td>
<td>400</td>
<td>2,200</td>
</tr>
<tr>
<td>16 hour</td>
<td>20</td>
<td>2,100</td>
<td>4,600</td>
</tr>
<tr>
<td>1 day</td>
<td>40</td>
<td>2,600</td>
<td>4,700</td>
</tr>
<tr>
<td>3 day</td>
<td>1,400</td>
<td>4,900</td>
<td>5,500</td>
</tr>
<tr>
<td>7 day</td>
<td>3,500</td>
<td>5,400</td>
<td>6,200</td>
</tr>
<tr>
<td>14 day</td>
<td>4,500</td>
<td>6,000</td>
<td>6,200</td>
</tr>
<tr>
<td>28 day</td>
<td>4,600</td>
<td>6,100</td>
<td>6,200</td>
</tr>
</tbody>
</table>

**Modulus of Elasticity, psi:**
28 days 7.6 x 10^6 psi

---

**Tensile Properties Mortar 1:6, (ASTM D-638):**

<table>
<thead>
<tr>
<th>Time</th>
<th>Tensile Strength</th>
<th>Elongation at Break</th>
<th>Modulus of Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 day</td>
<td>1,300 psi</td>
<td>0.2 %</td>
<td>6.6 x 10^6 psi</td>
</tr>
</tbody>
</table>

---

**Flexural Properties Mortar 1:6, (ASTM D-790):**

<table>
<thead>
<tr>
<th>Time</th>
<th>Flexural Strength (Modulus of Rupture)</th>
<th>Tangent Modulus of Elasticity in Bending</th>
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</thead>
<tbody>
<tr>
<td>14 day</td>
<td>2,300 psi</td>
<td>1.2 X 10^6 psi</td>
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</tbody>
</table>

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**Shear Strength Mortar 1:6, (ASTM D-732):**

<table>
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<tr>
<th>Time</th>
<th>Shear Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 day</td>
<td>2,000 psi</td>
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</tbody>
</table>

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**Water Absorption Neat, (ASTM D-570):**

<table>
<thead>
<tr>
<th>Time</th>
<th>Total Water Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 day</td>
<td>1.17%</td>
</tr>
<tr>
<td>Property</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>14 day Deflection Temperature (fiber stress loading = 66 psi)</td>
<td>111°F</td>
</tr>
<tr>
<td>Bond Strength (ASTM C-882): Hardened concrete to hardened concrete</td>
<td></td>
</tr>
<tr>
<td>2 day (dry cure) Bond Strength</td>
<td>1,100 psi</td>
</tr>
<tr>
<td>14 day (moist cure) Bond Strength</td>
<td>1,600 psi</td>
</tr>
<tr>
<td>Abrasion Mortar 1:6. (Taber Abrader):</td>
<td></td>
</tr>
<tr>
<td>14 day Weight loss, 1,000 cycles</td>
<td>4.1 gm</td>
</tr>
</tbody>
</table>

*Material cured and tested at the temperatures indicated.

## How To Use

### Surface Preparation:
Surface must be clean and sound. It may be dry or damp, but free of standing water. Remove dust, laitance, grease, curing compounds, impregnations, waxes, foreign particles, disintegrated materials.

- **Preparation Work: Concrete** - Sandblast or use other approved mechanical methods.
- **Steel** - Sandblast to white-metal finish.

### Mixing:
Pre-mix each component. Proportion equal parts by volume of Component 'A' and 'B' into clean pail. Mix thoroughly for 3 min with Sika paddle on low-speed (400-600-rpm) drill until uniformly blended. Mix only that quantity that you can use within pot life.

- **To prepare epoxy mortar** - Slowly add 6 parts by loose volume of oven-dried sand to 1 part of mixed Sikadur 21. Mix until uniform in consistency.
- **To prepare epoxy concrete** - Consult Technical Service for mix designs and procedures.

### Application:
- **Epoxy Mortar** - Prime prepared surface with mixed Sikadur 21. Apply epoxy mortar by trowel or vibrating screed before primer becomes tack-free. Finish with finishing trowel.
- **Epoxy Concrete** - Consult Technical Service for placement and finishing of epoxy concrete.

### Limitations:
- Minimum surface temperature 40F.
- Test porous substrates for moisture-vapor transmission prior to any application.
- Minimum age of concrete before application is 21-28 days depending upon curing, drying conditions.
- Do not apply to exterior slab on grade.
- Maximum application thickness on exterior substrates exposed to thermal change is ½ in.
- Do not dilute...solvents will prevent proper cure.
- Use oven-dried aggregates only.
- Material is a vapor barrier after cure.

---

-101-
Caution:

Component 'A' - Irritant - Prolonged contact with skin may cause irritation. Avoid eye contact.
Component 'B' - Corrosive - Contact with skin may cause severe burns. Avoid eye contact.
Product is a strong sensitizer. Use of safety goggles and chemical-resistant gloves recommended. Remove contaminated clothing. Avoid breathing vapors. Use adequate ventilation. Use of a NIOSH/MSA organic vapor respirator recommended.

First Aid:

In case of skin contact, wash thoroughly with soap and water. For eye contact, flush immediately with plenty of water for at least 15 minutes; contact physician immediately. For respiratory problems, remove person to fresh air. Wash clothing before re-use.

Clean Up:

Collect with absorbent material, flush area with water. Dispose of in accordance with local disposal regulations. Uncured material can be removed with approved solvent. Cured material can only be removed mechanically.

KEEP CONTAINER TIGHTLY CLOSED
KEEP OUT OF REACH OF CHILDREN
NOT FOR INTERNAL CONSUMPTION
CONSULT MATERIAL SAFETY DATA SHEET FOR MORE INFORMATION

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### Executive Office
P.O. Box 297, Lyndhurst, NJ 07071 - Tel 201-933-8800 - FAX 201-933-9379

### Regional* and District Sales Offices

<table>
<thead>
<tr>
<th>State</th>
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### Export Division
NJ, Lyndhurst 201-933-8800

June, 1990
**Sikadur® 22, Lo-Mod**

New, improved, low-modulus, medium-viscosity, epoxy resin binder

**Technical Data**

<table>
<thead>
<tr>
<th>Description:</th>
<th>Sikadur 22, Lo-Mod, is a 2-component, solvent-free, moisture-insensitive, epoxy resin binder. It meets ASTM C-881, Type III, Grade 2, Class B and C, epoxy adhesive binder.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Where to Use:</td>
<td>Use neat as the binder resin for a skid-resistant broadcast overlay. Use also as the binder resin for epoxy mortar and concrete for patching and overlays.</td>
</tr>
</tbody>
</table>
| Advantages: | • Insensitive to moisture both before and after cure.  
  • Easy mix B:A = 1:1 volume ratio.  
  • Excellent strength development.  
  • Leveling viscosity for easy, efficient application of a broadcast overlay.  
  • Material is USDA-approved. |
| Coverage: | Prime coat - 300-500 sq ft/gal.  
  Broadcast Binaer Coat - 32 sq ft/gal.  
  Mortar Binder - 1 gal of mixed Sikadur 22, with the addition of 5 gal by loose volume of an oven-dried sand, will yield 808 cu in. of epoxy mortar. |
| Packaging: | 4-gal units; 1-qt units, 12/case. |
Typical Data for Sikadur 22, Lo-Mod:
(Material and curing conditions @ 73F and 50% R.H.)

Shell Life: 2 years in original, unopened containers.

Storage Conditions: Store dry at 40-95F. Condition material to 65-85F before using.

Color: Clear, amber.


Viscosity: Approximately 3,500 cps.

Pot Life: Approximately 30 minutes.

Tack-Free Time: Approximately 4 hours.

Traffic Time: 4-5 hours.

Compressive Properties Mortar 1:5, (ASTM D-695):
Compressive Strength, psi

<table>
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<tr>
<th></th>
<th>40F*</th>
<th>73F*</th>
<th>90F*</th>
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<tr>
<td>4 hour</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>8 hour</td>
<td>-</td>
<td>100</td>
<td>1,100</td>
</tr>
<tr>
<td>16 hour</td>
<td>-</td>
<td>2,700</td>
<td>4,300</td>
</tr>
<tr>
<td>1 day</td>
<td>30</td>
<td>3,500</td>
<td>5,200</td>
</tr>
<tr>
<td>3 day</td>
<td>600</td>
<td>4,600</td>
<td>6,000</td>
</tr>
<tr>
<td>7 day</td>
<td>4,200</td>
<td>5,400</td>
<td>6,200</td>
</tr>
<tr>
<td>14 day</td>
<td>6,200</td>
<td>6,000</td>
<td>6,200</td>
</tr>
<tr>
<td>28 day</td>
<td>6,300</td>
<td>6,100</td>
<td>6,200</td>
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Modulus of Elasticity, psi:

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<tbody>
<tr>
<td>28 days</td>
<td>7.7 x 10^5 psi</td>
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</table>

Tensile Properties Mortar 1:5, (ASTM D-538):

14 day

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<tbody>
<tr>
<td>Tensile Strength</td>
<td>1,100 psi</td>
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<tr>
<td>Elongation at Break</td>
<td>0.2 %</td>
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<tr>
<td>Modulus of Elasticity</td>
<td>5.4 x 10^5 psi</td>
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Flexural Properties Mortar 1:5, (ASTM D-790):

14 day

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<td>Flexural Strength (Modulus of Rupture)</td>
<td>2,600 psi</td>
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<tr>
<td>Tangent Modulus of Elasticity in Bending</td>
<td>1.1 X 10^6 psi</td>
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Shear Strength Mortar 1:5, (ASTM D-732):

14 day

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<tbody>
<tr>
<td>Shear Strength</td>
<td>2,700 psi</td>
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Water Absorption Test, (ASTM D-570):

7 day

<p>| | |</p>
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<td>Total Water Absorption (2 hour Boil)</td>
<td>1.3%</td>
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</table>
Deflection Temperature Mortar 1:5, (ASTM D-648):

| 14 day | Deflection Temperature (fiber stress loading = 66 psi) | 108 F |

Bond Strength (ASTM C-882): Hardened concrete to hardened concrete

| 2 day (dry cure) | Bond Strength | 1,100 psi |
| 14 day (moist cure) | Bond Strength | 2,000 psi |

Abrasion Mortar 1:5, (Taber Abrader):

| 14 day | Weight loss, 1,000 cycles (H-22 wheel; 1,000 gm weight) | 4.6 gm |

*Material cured and tested at the temperatures indicated.

**How To Use**

**Surface Preparation:** Surface must be clean and sound. It may be dry or damp, but free of standing water. Remove dust, laitance, grease, curing compounds, impregnations, waxes, foreign particles, disintegrated materials.

**Preparation Work:**
- Concrete - Sandblast or use other approved mechanical methods.
- Steel - Sandblast to white-metal finish.

**Mixing:** Pre-mix each component. Proportion equal parts by volume of Component ‘A’ and ‘B’ into clean pail. Mix thoroughly for 3 min with Sika paddle on low-speed (400-600-rpm) drill until uniformly blended. Mix only that quantity that you can use within pot life.

To prepare epoxy mortar - Slowly add 5 parts by loose volume of oven-dried sand to 1 part of mixed Sikadur 22 until uniform in consistency.

To prepare epoxy concrete - Consult Technical Service for mix designs and procedures.

**Application:**
- Broadcast Overlay - Prime the prepared substrate with Sikadur 22. While primer is still tacky, spread mixed Sikadur 22 with a 3/16-in. notched squeegee.
  When material levels, broadcast the oven-dried aggregate slowly allowing it to settle in the epoxy binder. Ultimately the broadcast aggregate should be applied to excess at a rate of 2 lb/sq ft.
  Remove excess broadcast aggregate after epoxy has set.
- Epoxy Mortar - Prime prepared substrate with mixed Sikadur 22.
  Before the primer becomes tack-free, apply epoxy mortar by trowel or vibrating screed.
  Finish with finishing trowel.
- Epoxy Concrete - Consult Tech Service for placement and finishing of epoxy concrete.

**Limitations:**
- Minimum surface temperature 40F.
- Porous substrates must be tested for moisture-vapor transmission prior to any application.
- Minimum age of concrete before application is 21-28 days depending upon curing and drying conditions.
- Do not use on exterior slab on grade.
- Maximum thickness ½ in. exterior exposed to thermal change.
- Do not dilute. Solvents will prevent proper cure.
- Use oven-dried aggregates only.
- Material is a vapor barrier after cure.
Caution: Component ‘A’ - Irritant - Prolonged contact with skin may cause irritation. Avoid eye contact. Component ‘B’ - Corrosive - Contact with skin may cause severe burns. Avoid eye contact. Product is a strong sensitizer. Use of safety goggles and chemical-resistant gloves recommended. Remove contaminated clothing. Avoid breathing vapors. Use adequate ventilation. Use of a NIOSH/MSA organic vapor respirator recommended.

First Aid: In case of skin contact, wash thoroughly with soap and water. For eye contact, flush immediately with plenty of water for at least 15 minutes; contact physician immediately. For respiratory problems, remove person to fresh air. Wash clothing before re-use.

Clean Up: Collect with absorbent material, flush area with water. Dispose of in accordance with local disposal regulations. Uncured material can be removed with approved solvent. Cured material can only be removed mechanically.

KEEP CONTAINER TIGHTLY CLOSED NOT FOR INTERNAL CONSUMPTION KEEP OUT OF REACH OF CHILDREN FOR INDUSTRIAL USE ONLY CONSULT MATERIAL SAFETY DATA SHEET FOR MORE INFORMATION

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*CA, Santa Fe Springs ......... 213-941-0231 *MI, Southfield ......... 313-354-6555 SC, Spartanburg ......... 803-573-8867
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CT, Hartford ................ 203-560-2124 MO, St. Louis ......... 314-231-5499 TX, Houston ........ 713-461-3010
*FL, Tampa .................. 813-933-5259 NY, Albany .............. 518-452-7453 VA, Midlothian ......... 804-379-9843
GA, Atlanta ................ 404-761-7143 NC .................... 803-581-0223 VT, Montpelier ......... 802-229-4905
IL, St. Charles ............... 708-513-0570 OH, Brooklyn Heights .... 216-749-7225 WA, Seattle ......... 206-762-3829
IN, Indianapolis ............. 317-843-0274 *OH, Columbus ......... 614-476-3335 WI, Milwaukee ......... 414-272-3100

Export Division
NJ, Lyndhurst ............... 201-933-8800 Telex .................. 201-804-1020

June, 1990
JAHN INJECTION GROUTES

Application Instructions

M30 - Injection Grout for Hairline and Microscopic Cracks 0.2 - 5.0 mm
M40 - Injection Grout for Cracks 5.0 mm - 10.0 mm
M50 - Injection Grout for Cracks or Voids 10.0 mm or Larger

INTRODUCTION

Injection is the process by which a viscous material is inserted into cracks and voids in an existing structure in order to stabilize or preserve deteriorated masonry. The grout fills the cracks and voids in order to prevent the penetration of moisture on a large scale. This method of repair is particularly useful in restoring or conserving buildings or structures of historic value. Jahn M30, M40, and M50 are all injection grouts that can be used to repair cracks and voids in masonry building materials, including brick, terra cotta, natural stone, and concrete.

Jahn M30 is a cement-bound injection grout which contains no chlorides, bromides, or fluorides. It is used for injecting hairline and microscopic cracks in masonry building materials 0.2 - 5.0 mm in width (up to approximately 3/16"). The M30 grout is a two-component system that contains a small amount of a synthetic additive (about 3-5% of the cement weight) to promote fluidity and adhesion. Jahn M30 injection grout possesses extraordinary flow capability, penetration, and bond strength and undergoes minimal shrinkage. In spite of its low water/cement ratio of 0.32 - 0.35, Jahn M30 maintains its extraordinary flow capacity longer than conventional materials, making separation of the grout practically impossible.

Jahn M40 and M50 are cement-based grouts that contain no chlorides, metal compounds, or synthetic polymers additives or bonding agents. In hardened condition the material remains porous and does not interfere with the transport of water vapor or detrimental soluble salts. Moreover, the material is salt and frost resistant and shows minimal signs of shrinkage. Jahn M40 injection grout is formulated for cracks larger than 5 mm but smaller than 10 mm (approximately 3/16" - 3/8"), while Jahn M50 is only suitable for cracks larger than 10 mm (approximately 3/8").

INJECTION EQUIPMENT

The Jahn grouts can be injected using either low or high-pressure techniques and can be accomplished using a syringe or gravity for more delicate jobs or any suitable injection apparatus or grouting pump with standard injection-connections. Good results are obtained when the grouts are injected using a diaphragm pump. The flexible hoses or tubes should be approximately 20 mm (¾") in diameter, a smaller diameter should be used when injecting M30. The method chosen depends on the size of the crack and the condition of the masonry being repaired.

SURFACE PREPARATION

Transverse Cracking: For a crack across the face of the masonry unit, drill a series of injection ports approximately 20 mm (¾") in diameter through the heart of the transverse crack with a distance of approximately 300 - 500 mm (12" - 20") between centers. The holes should be drilled on an angle sloping down. Clean the crack and drill holes well using compressed air, where possible, and potable water before injecting the grout.

Seal the crack (between the drill holes) with clay, mortar, or any nonstaining removable material in order to prevent the grout from overflowing. Another way to seal the crack is to finish the outer surface using Jahn Restoration Mortar to match the color and texture of the surrounding masonry and...
then complete the entire injection procedure described above. Upon completion, only the

**INJECTION PROCEDURE**

Flush the drill holes and crack with potable water before beginning the injection procedure.

**Transverse Cracking:** (Cracking across the face of the masonry unit.) The nozzle of the injection apparatus should be connected to the first drill hole, preferably one at the lowest point. Inject the grout into the hole until it begins flowing back out the drill hole(s), indicating that a crack has been filled. Seal the drill holes using clay or any nonstaining removable material. Repeat procedure until the crack and last drill hole are filled with grout.

**Lateral Cracking:** (Delaminating masonry with cracks parallel to the face of the masonry unit.) Begin the injection process at the bottom left of the “drill frame” using a low-pressure technique. As the crack is filled, the grout will begin to flow out from various holes. Seal those holes using clay or any nonstaining removable material. The injection apparatus should then be moved to the bottom right hole of the “drill frame” and the injection procedure should be repeated.

**Voids:** Begin the injection procedure at the bottom left of the “drill frame” using a low-pressure technique. As the void is filled, the grout will begin to flow out from various holes. Seal those holes using clay or any nonstaining removable material. The injection apparatus should then be moved to the bottom right hole of the “drill frame” and the injection procedure should be repeated. For large voids, to prevent excessive pressure build up in the cavity, fill approximately 1 meter high at a time and let it set for approximately one day before additional grout is injected.

**CLEAN UP**

Clean any grout residue from the masonry surrounding the injection ports and adjacent area by sponging the area as many times as

---

**Lateral Cracking:** For delaminating masonry with cracks parallel to the face of the masonry unit, create a “drill frame” by drilling approximately 20 mm (⅞") diameter holes at a downward angle at a distance of approximately 500 mm (20") between centers, both horizontally and vertically. Clean the crack and drill holes well using compressed air, where possible, and potable water before injecting the grout.

**Voids:** Create a “drill frame” by drilling approximately 20 mm (⅞") diameter holes at a downward angle at a distance of approximately 500 - 1000 mm (20" - 40") between centers, both horizontally and vertically. Clean the crack and drill holes well using compressed air, where possible, and potable water before injecting the grout.

**MIXING**

It is recommended that a dust mask be worn while mixing. In a clean bucket, add the liquid to the cement and mix the grout. Do not add any bonding agents, accelerators, or retarders to the grout.

**Jahn M30:** Must mix the components using an electric drill with a paddle or hand mixer at a speed of approximately 3,000 rotations per minute for several minutes until a frothy, creamy consistency is obtained. Add part A (liquid) to part B (cement). Stir grout just before injection to redistribute any cement that has settled.

**Jahn M40:** Add approximately 2 parts cement to 1 part water by volume and mix. Must stir grout just before injection to redistribute any cement that has settled.

**Jahn M50:** Add approximately 2 - 2.5 parts cement to 1 part water by volume and mix. Must stir grout just before injection to redistribute any cement that has settled.
necessary with clean water. This should be done immediately before the material sets.

FINISHING
After the grout has set up (time varies depending on site conditions), remove the clay or other material. The drill holes and the surface of the crack where applicable should be filled and finished with Jahn Restoration Mortar to closely match the color and texture of the surrounding masonry. The patching mortar should be allowed to set, scraped, finished, and dampened to cure according the manufacturers printed instructions. (See Application Instructions for Patching.)

COVERAGE
Coverage varies with they type of masonry being repaired, the porosity of the substrate, the depth of crack or void, the amount of moisture in the wall, and the temperature and relative humidity. It is therefore difficult to estimate the amount of material needed for a given job.

STORAGE
Store unused mortar in tightly sealed containers and keep dry. Shelf storage should not exceed six month from purchase date.

PRECAUTIONS
- Cold Weather Requirements: Do not work in temperatures below 40°F, when the stone is colder than 40°F, or when the temperature is expected to fall below 40°F for 48 hours after injection of grout.

- Hot Weather Requirements: Protect grout from direct sunlight and wind using protection measures submitted and approved when the ambient air temperature exceeds 70°F. Do not use or prepare grout when ambient air temperature is above 90°F at the location of the work.

TECHNICAL ASSISTANCE
For technical assistance please call: (301) 317-4658.

PLACING AN ORDER
All material orders should be placed by facsimile machine (fax) or by sending a written order to:

Cathedral Stone Products, Inc.
8332 Bristol Court, #107
Jessup, MD 20794
Fax: (301) 317-4670

DISCLAIMER/WARRANTY
The information herein is accurate and reliable to the best of our knowledge. Because Cathedral Stone Products, Inc. has no control over installers ability to follow common masonry industry practices or these instructions for installation, workmanship, accessory materials, or conditions of application, no presentation or warranty, expressed or implied, either as to merchantability or fitness for a particular purpose is made as to the performance or results of an application containing its product which extends beyond the description on the face hereof.

Defective material will be replaced, upon verification, if notified in writing within 15 days.

CATHEDRAL STONE PRODUCTS, INC. JESSUP, MD (301) 317-4658
Jahn Restoration Mortars
CAB-O-SIL® TS-720
Treated Fumed Silica

General Properties
CAB-O-SIL® TS-720 treated fumed silica is a high-purity silica which has been treated with a dimethyl silicone fluid. The treatment replaces many of the surface hydroxyl groups on the fumed silica with a polydimethyl siloxane polymer. This treatment makes the silica extremely hydrophobic.

The specifications of TS-720 are:

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<th>Specification</th>
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<tr>
<td>Surface area (BET) (m²/g)</td>
<td>100 ± 20</td>
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<tr>
<td>Carbon (wt.%)</td>
<td>5.3 ± 0.8</td>
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<tr>
<td>Loss on Heating (1)(2)</td>
<td>&lt;0.6 wt.%</td>
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(1) 2 hours at 105°C
(2) at time of packaging
Test methods available upon request

The typical properties of TS-720 include:

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<th>Specification</th>
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<tr>
<td>Appearance</td>
<td>Fluffy white powder</td>
</tr>
<tr>
<td>Bulk Density(1)</td>
<td>3.0 lbs./ft.³</td>
</tr>
<tr>
<td></td>
<td>50 g/l</td>
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</table>

(1) at time of packaging
Test methods available upon request

Surface Chemistry
TS-720 has a surface chemistry which is different from the base silica, CAB-O-SIL M-5 fumed silica, and from that of the other treated silicas. During the manufacture, the surface of the silica is completely coated with the silicone fluid treating agent. The silicone fluid reacts with the surface hydroxyl groups. Figure 1 illustrates the surface chemistry of TS-720. This changes the nature of the silica surface from hydrophilic to extremely hydrophobic.

TS-720 does not thicken liquid systems by hydrogen bonding, as do the untreated grades such as M-5. Rather, it relies on the interaction of its modified surface chemistry with the liquid system.

Figure 1
Surface chemistry of TS-720
APPENDIX B: EXPERIMENTAL TESTING PROGRAM DATA

B.1. ASSEMBLY TYPES

<table>
<thead>
<tr>
<th>1 mm Detachment</th>
<th>3.5 mm Detachment</th>
<th>7 mm Detachment</th>
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</thead>
<tbody>
<tr>
<td>Sikadur 21 LoMod</td>
<td>Sikadur 21 LoMod &amp; Jahn M30</td>
<td>Sikadur 22 &amp; Jahn M40</td>
</tr>
</tbody>
</table>

**LEGEND:**

- **100% of Joint Epoxy Grout Only**
- **Epoxy Spot Weld**
- **100% of Joint Cementitious Grout Only**
- **Epoxy Spot Weld & Cementitious Grout Infill**

<table>
<thead>
<tr>
<th>Type number listed under each assembly</th>
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<tr>
<td>Type 1</td>
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<td>Type 4</td>
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<td>Type 7</td>
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<td>Type 10</td>
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B.2. ASSEMBLY DIMENSIONS

LEGEND

- wood spacer
- epoxy weld
B.3. MEASUREMENTS OF GROUTS INJECTED INTO ASSEMBLIES, CURE TIME AND CONDITION OF ASSEMBLIES AT TIME OF CURE

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>JOINT</th>
<th>GROUT TYPE</th>
<th>VOL. GROUT</th>
<th>TOTAL CURE DAYS</th>
<th>OBSERV.</th>
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<tbody>
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<td>VOL. GROUT</td>
<td>TOTAL CURE DAYS</td>
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<td>VOL. GROUT</td>
<td>TOTAL CURE DAYS</td>
<td>OBSERV.</td>
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| S4.01   | 35mm  | SIKADUR 21 CABSilts720 JAHN M30 | EPOXY = 10cc GROUT = 34cc | EPOXY = 45 GROUT = 41 | GROUT BLED & SETTLED |
| S4.02   | 35mm  | SIKADUR 21 CABSilts720 JAHN M30 | EPOXY = 10cc GROUT = 38cc | EPOXY = 45 GROUT = 41 | GROUT BLED & SETTLED |
| S4.03   | 35mm  | SIKADUR 21 CABSilts720 JAHN M30 | EPOXY = 10cc GROUT = 34cc | EPOXY = 45 GROUT = 41 | GROUT BLED & SETTLED |
| S4.04   | 35mm  | SIKADUR 21 CABSilts720 JAHN M30 | EPOXY = 10cc GROUT = 37cc | EPOXY = 45 GROUT = 41 | GROUT BLED & SETTLED |

| S4.05   | 7mm   | SIKADUR 22 CABSilts720 JAHN M40 | EPOXY = 15cc GROUT = 47cc | EPOXY = 67 GROUT = 62 |
| S4.07   | 7mm   | SIKADUR 22 CABSilts720 JAHN M40 | EPOXY = 15cc GROUT = 47cc | EPOXY = 67 GROUT = 62 |
| S4.08   | 7mm   | SIKADUR 22 CABSilts720 JAHN M40 | EPOXY = 15cc GROUT = 51cc | EPOXY = 67 GROUT = 62 |

<p>| F1.01   | 35mm  | SIKADUR 21 LO MOD                  | 43cc                      | 55              | AIR BUBBLES IN JOINT |
| F1.02   | 35mm  | SIKADUR 21 LO MOD                  | 45cc                      | 55              | AIR BUBBLES IN JOINT |
| F1.03   | 35mm  | SIKADUR 21 LO MOD                  | 46cc                      | 55              | AIR BUBBLES IN JOINT |</p>
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<th>VOL. GROUT</th>
<th>TOTAL CURE DAYS</th>
<th>OBSERV.</th>
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<td>SAMPLE</td>
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B.4. ASSEMBLY STRENGTH IN SHEAR BY COMPRESSION LOADING
STRENGTH IN SHEAR BY COMPRESSION LOADING
ASSEMBLY TYPE 1

LOAD (psi)

4000
3000
2000
1000
0
S1_01  S1_02  S1_03  S1_04

SAMPLE

DISPLACEMENT

0.040"
STRENGTH IN SHEAR BY COMPRESSION LOADING
ASSEMBLY TYPE 2
STRENGTH IN SHEAR BY COMPRESSION LOADING
ASSEMBLY TYPE 3

LOAD (lbs)

5000
4000
3000
2000
1000
0

S1 09
S1 11
S1 12

SAMPLE

DISPLACEMENT
0.040"
STRENGTH IN SHEAR BY COMPRESSION LOADING
ASSEMBLY TYPE 4
STRENGTH IN SHEAR BY COMPRESSION LOADING
ASSEMBLY TYPE 5

[Diagram showing load-displacement relationship for shear strength testing]
STRENGTH IN SHEAR BY COMPRESSION LOADING
ASSEMBLY TYPE 6

LOAD (psi)

S2 09  S2 10  S2 11  S2 12

MEAN LOAD

DISPLACEMENT
0.040"
STRENGTH IN SHEAR BY COMPRESSION LOADING
ASSEMBLY TYPE 7

LOAD (psi)

0 400

S3 01 S3 02 S3 03 S3 04

SAMPLE

MEAN LOAD

DISPLACEMENT
0.040"
STRENGTH IN SHEAR BY COMPRESSION LOADING
ASSEMBLY TYPE 8

![Graph showing load vs. displacement for different samples S3.05, S3.06, S3.07, S3.08, with a dashed line indicating mean load.]
STRENGTH IN SHEAR BY COMPRESSION LOADING
ASSEMBLY TYPE 9

LOAD (lbf)

SAMPLE

S4 01  S4 02  S4 03  S4 04

MEAN LOAD

DISPLACEMENT

0.040"
STRENGTH IN SHEAR BY COMPRESSION LOADING
ASSEMBLY TYPE 10
B.5. SHEAR CALCULATIONS

"Load" represents the maximum load applied at failure in units of psi. "Shear" represents the nominal shear stress at failure in units of psi. for each given assembly.

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B.7. MEASUREMENTS OF DELAWARE VALLEY SANDSTONE - APPARENT POROSITY, WATER ABSORPTION, APPARENT SPECIFIC GRAVITY AND BULK DENSITY

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APPENDIX C: MAPS OF EL MORRO

C.1. EL MORRO - LOCATIONS OF TEST SITES
Note: "X" marks a large crack in the formation which was point zero for measurements.

Scale 1" = 32'
APPENDIX D: PHOTOGRAPHS
D.1. Flow of Sikadur 22 Lo-Mod Epoxy modified with various percentages of Cab-O-Sil S 720.
D.2. Model of assembly injected with fumed silica modified epoxy
D.3. Pregrounded assemblies in the laboratory.
D.4. Injection grouting of assemblies with fumed silica modified epoxies in the laboratory.
D.7. Field Testing Program Test Station C, during treatment
D.8. Field Testing Program Test Station C, after treatment
D.9. Field Testing Program Test Station F, after treatment
D.10. Field Testing Program Test Station G, during treatment
D.11. Field Testing Program Test Station G, after treatment
D.12. Field Testing Program Test Station I, during treatment
D.13. Field Testing Program Test Station I, after treatment
D.14. Field Testing Program Test Station J, during treatment
D.15. Field Testing Program Test Station J, after treatment
APPENDIX E: OLSON ENGINEERING, INC. "NONDESTRUCTIVE TESTING INVESTIGATION SANDSTONE STABILIZATION EVALUATION EL MORRO NATIONAL MONUMENT NEW MEXICO
NONDESTRUCTIVE TESTING INVESTIGATION
SANDSTONE STABILIZATION EVALUATION
EL MORRO NATIONAL MONUMENT
NEW MEXICO

Prepared for:

University of Pennsylvania
Graduate Program in Historic Preservation
The Graduate School of Fine Arts
115 Meyerson Hall
Philadelphia, PA 19104-6311

Attn: Mr. Frank G. Matero

Ofc: 215/898-3169
Fax: 215/898-9215

Olson Engineering Job No. 301

August 25, 1994
EXECUTIVE SUMMARY

The following report contains data obtained at El Morro National Monument during a test application of stabilization techniques at a non-historic area of sandstone cliff faces. The areas selected for testing represent a variety of conditions which are present in other areas where historic carvings are present. The test areas, as well as the stabilization treatments, were selected by the project team from the University of Pennsylvania. Marie Ennis, P.E., assisted in selecting non-destructive techniques which could be utilized at this particular site. Dennis Sack of Olson Engineering, Incorporated, performed the on-site testing and data interpretation for the experiment.

The objective of the experiment was to ascertain whether currently available non-destructive techniques can be used to assist in defining the extent of delaminations prior to stabilization treatments and subsequently to verify the effectiveness of the various treatments. The initial trial was undertaken in July 26th to 28th, 1994. A follow up survey will be undertaken in July of 1995 to evaluate the durability of the treatments after one year of weathering.

Three representative areas were selected for testing both before and after treatment. In addition, one area of sound sandstone was selected for testing in order to obtain characteristic responses for "competent" stone for comparative purposes.

The non-destructive techniques (NDT) employed at the site were:

- Impact Echo (IE)
- Spectral Analysis of Surface Waves (SASW)
- Ultrasonic Pulse Velocity (UPV)

The initial NDT investigation yielded useful information. Testing in the area of competent or sound sandstone provided baseline data about the material. The sandstone in the areas where historic carvings are present can be classified as a low strength, weathered sandstone. Where delamination of the stone face has occurred, the NDT yielded results which can define the extent of delamination over the surface area. In some cases the thickness of the delaminated sheet can be quantified. After stabilization treatments were completed, the NDT results indicated a definite increase in competency, or structural integrity, of the treated delaminations.

The report describes the methodology employed at the site as well as an interpretation of the data collected. A technical description of the test methods is included in Appendix A.

If the treated areas yield similar readings of improved competency after exposure to weathering for one year, it is hoped that these treatments can be implemented in areas where historic carvings are in imminent danger of detachment from the base stone. NDT allows for both pre-treatment and post-treatment survey without destroying historic fabric.
BACKGROUND/SCOPE

This report presents the results of nondestructive testing (NDT) to evaluate the conditions of weathered sandstone at the El Morro National Monument. The testing was done both before and after the application of one or more stabilization methods. The stabilization methods included epoxy injection "spot welds" and micro-grouting (grouting through a syringe or other small applicator). The stabilization experiments and associated NDT were conducted to evaluate the performance of these methods for possible future use on historically significant sandstone faces at a later time.

Observed surface conditions of the test areas were generally as expected for exposed, weathered, uncut sandstone: rough surface conditions with some organic material present, with the stone surface at the actual transducer mounting locations selected to be generally sound. The field NDT investigation was performed on July 25-27, 1994, by Mr. Dennis Sack, Project Manager, of our firm. He was assisted in the NDT by Ms. Marie Ennis, P.E. and by personnel from the National Park Service.

NDT INVESTIGATION OVERVIEW

This NDT investigation was undertaken to evaluate the before and after repair conditions of representative sandstone areas which are delaminating from the base stone at El Morro National Monument and were repaired during the course of this investigation. The test areas selected during the course of this investigation were selected to be representative of historically significant rock faces in other areas of the monument, but were not historically significant in themselves. The NDT investigation used the Impact Echo (IE) and Spectral Analysis of Surface Waves (SASW) methods before and after trial stone repair operations (epoxy injection and grouting). The NDT compared the stiffness and surface wave velocity profiles of the repair locations before and after the repairs. The NDT methods used are discussed in Appendix A, while summaries of the test results are presented below.

IMPACT ECHO (IE) RECORDS AND RESULTS

The investigation used the Impact Echo (IE) method to compare the stiffness of the delaminated sandstone areas before and after testing. This method also gave some indication
of the thickness of the stone above the delamination, although these thicknesses were not always able to be determined due to the strong delamination resonances. Test point layouts for each of the repair areas (Areas C, G, and J) both before and after repairs are presented in Figs. 15-20. Tests were also conducted on Area I, but since no repairs were attempted on this area, the results are not presented herein. Note that the test areas were purposely selected to be severely delaminated, and thus the IE test results typically show delamination-type responses (as discussed below) for most points. The IE method is discussed in Appendix A-1.

IE Test Results

The IE results were analyzed to identify significant echo peak frequencies and to evaluate the peak acceleration amplitudes from the delamination resonance peaks. As discussed in Appendix A-1, the IE method is generally used for determining the depth to a flaw based on the relationship between displacement echo frequency peaks and flaw depth. For use over delaminations, however, the IE method can also give an indication as to the resonant frequency and amplitude of the vibrations of the delaminated material sections by measuring the acceleration. These vibrations are due to the entire delaminated stone vibrating as a unit, rather than from echoes between the front and back faces as is typical for conventional IE tests. The relative frequency and amplitude of these acceleration vibrations gives some indication as to the overall stiffness of the material system, with higher frequencies and lower amplitudes being associated with stiffer (and thus relatively more sound) systems.

The IE results as presented in Table I show clearly that the test areas are significantly more stiff after the repairs than before. This is true for locations which were epoxied as well as for those which were grouted. Note that for both test areas G and J, test points further into the delamination region were tested after the repair process. The results after repair showed generally moderate stiffnesses, compared to the ringing, hollow responses typical of these points before the repairs. Sample before and after IE plots are presented in Figs. 1-6. These figures show the spectra of the IE test results (acceleration versus frequency) and typical time domain traces from which the spectra were computed. The after-repair plots typically have the higher
frequency, lower amplitude spectral peaks which are associated with stiffer structural systems. The IE test results thus show significant material improvement after both types of repairs.

A typical IE test record as presented in Figs. 1-6 includes two traces. The top trace in the figures is the acceleration spectra, giving vertical axis units of inches/second/second of the surface. Normally, displacement (doubly integrated acceleration) is used for presenting IE results rather than acceleration. For areas such as these where the delamination response dominates the data, however, the acceleration spectra shows the peak frequencies and relative system stiffnesses clearer than displacement. The horizontal axis is linear frequency measured in thousands of Hz (kiloHertz, kHz). The bottom trace in each figure is a typical time domain trace of the accelerometer in response to the impactor hit to the stone. This trace is in units of millivolts on the vertical axis versus time on the horizontal axis.

In addition to the spectral peak information, some of the IE results also showed thickness echo peaks from the backside of the delaminated stones. These echo peaks were typically weak relative to the delamination resonances, but were high enough in frequency to be separated out and resolved independently. Typical thicknesses as determined by the IE results are presented in Table I where the data was sufficiently clear to process. Typical thicknesses for delaminated sections with clear thickness IE response data were 2-3 inches based on a measured compression wave velocity of 5,500 feet per second (fps). Thinner rock sections typically did not produce clear IE thickness response data, presumably due to the higher-amplitude delamination response typical of thinner sections and due to practical limitations on the minimum echo measurement depth, estimated to be 2.0-2.5 inches at this site. Compression wave velocities were measured by performing surface pulse velocity tests across 0.5, 1.0, and 1.5 foot spacings on a sound sandstone location.

SASW TEST RECORDS AND RESULTS

A comparatively new seismic method known as the Spectral-Analysis-of-Surface-Waves (SASW) method has been developed by Dr. Kenneth H. Stokoe II and his colleagues and students, of the University of Texas at Austin for the determination of shear wave velocity and
modulus profiles with depth in layered systems such as pavements and the earth. The method is based upon the field measurement of surface wave velocity as a function of wavelength and allows subsequent theoretical modeling to determine the shear wave velocity profile versus depth. The SASW method is capable of determining the "stiffness" and thickness profiles for layered concrete, pavement, soil, and rock systems without drilling borings or cores. The SASW method is detailed in Appendix A-2 and illustrated in Fig. A-2. The results of SASW tests conducted on the stone at El Morro are discussed below.

SASW Phase Records

A sample phase record from the SASW testing is shown in Fig. 7, which is an example of a good quality phase data record. Fig. 7 is a plot of phase vs. frequency. The trace shows the phase difference between the two signals on the vertical axis in degrees, with phases of less than -180 degrees or greater than 180 degrees being "wrapped" around with a vertical line. The horizontal axis is the frequency in kiloHertz (kHz). A total of 360 degrees of phase (-180 to 180 degrees) represents one wavelength, which is equal to the receiver-to-receiver spacing for a given test, and one cycle of surface wave energy at a given frequency. The calculation of surface wave velocity is shown for various signal wavelengths (where 360 deg. = 1 wavelength) in the phase figure, Fig. 7, and is determined from the frequency and wavelength at each calculation point. Due to the relatively homogeneous nature of the stone at the point where this record was taken (an undamaged sandstone location), the dispersion information (surface wave velocity versus wavelength) is expected to correspond closely with the actual shear wave velocity profile (shear wave velocity versus depth, see Appendix A-2) at this location.

SASW Test Results

The SASW method was used in 4 test areas, including 1 undamaged area, with 2 of the other areas tested both before and after repair. Tests after the repairs were performed about 24 hours after injection of grout and/or epoxy, which should have allowed the materials to adequately cure for testing. The results of the SASW testing are presented as dispersion curves in Figs. 8-13. The figures present the experimental dispersion curves computed from the test data at the locations noted. It should be noted that longer wavelengths correspond to deeper
signal penetration depths, although the velocity of a particular wavelength does not necessarily correspond directly to the velocity at that depth (Theoretical modeling is necessary to determine the velocity versus depth profile - see Appendix A-3). It should also be noted that the before-and after-repair SASW tests were taken at different points in each test area. The after-repair test locations were moved from the before-repair test locations so that the after-repair SASW tests would be performed over the actual epoxy or grout injected sites, rather than over potentially unfilled areas. The before-repair tests were selected before the actual injection points were selected. Note that the before-repair test locations were generally selected at points further away from the delamination edges than the points tested after the repairs, and thus the initial condition of the stone at the before-repair locations would be expected to be more sound than the initial condition of the after-repair test locations.

The SASW method worked well on all areas tested, with good data obtained for deeper depths at all locations. For shallower depths, the data quality was generally poor before the grouting and/or epoxying, except for test area G. This is expected as the delaminations and the associated air gaps under the SASW test points at areas C and J do not transmit surface waves well at shallow depths. For area G, the initial SASW test lines were performed on more sound sandstone further from the delamination edge. After the repairs, the SASW results typically showed a significant increase in shallow data quality, even though the test points were located in what were the most delaminated areas. This increase in data quality is directly due to the filling of air gaps, etc. by the repair materials, and indicates that the areas tested experienced a gain in rock competency at shallow depths after the repairs. The SASW results also show that the surface wave velocity of the repaired stone systems typically were somewhat higher at shallow depths (1-2 in.) than that of sound sandstone. This is likely due to the influence of the higher velocity repair materials relative to the lower velocity sandstone. Additional discussion of the SASW test results by test area is included below.

**Sound Sandstone Test Area.** The first area tested with the SASW method was an area with apparently sound stone conditions. This area was on the rock wall approximately 4 feet below test area "C". A dispersion curve presenting the results from a horizontal set of SASW
tests performed at this location is included as Fig. 7. As seen in this figure, the surface wave velocity of the sandstone at this location is relatively constant versus frequency and thus wavelength. This indicates that the sandstone surface wave velocity is also constant versus depth for a depth range of less than 0.5 inches out to at least 1 foot into the wall. The average surface wave velocity of about 2,700 fps is considered to be somewhat slow, but not unexpected. This indicates that the sandstone in this formation, although consistent, is relatively soft compared to other stone or concrete materials.

Test Area "C". The second test area was identified as Area "C". The testing in this area was centered on a delaminated rock section as diagramed in Figs. 15 and 16 (test location layouts before and after the repairs). SASW tests were performed both before and after the repair process. Repairs at this location consisted of epoxy injected "spot welds" at several points. The dispersion curve for this location prior to epoxy injection is presented in Fig. 8. This figure shows that no useable dispersion data was obtained for wavelengths of less than 0.15 feet, which corresponds to the depth of the rock delamination void based on the coring results. The dispersion curve for tests at a location after epoxy injection is shown in Fig. 9. This location is further into the delaminated region than the first test location, and thus would be expected to have poorer data quality if repairs were ineffective. As seen, this curve shows good quality data, including indications of higher-velocity material at a depth range of 0.1-0.15 feet, which corresponds to the depth of the epoxy injected into the delamination void space. The scatter of the data for this depth range is likely due to effects of the incomplete filling of the void space by the relatively small spot welds. For wavelengths of greater than 0.3 feet or so, the SASW data indicates a relatively consistent surface wave velocity of 2,500 - 3,000 fps out to wavelengths of 1 foot or more. This indicates that the delamination at the surface was the only damage present at this location at the time of testing and repair.

Test Area "G". The third test area was identified as Area "G". The testing in this area was centered on a large delaminated rock "flake" as diagramed in Figs. 17 and 18 (test location layouts before and after the repairs). SASW tests were performed both before and after the repair process for this area, with the before-repair tests being conducted on a more sound area.
of sandstone (further from the delamination edge) since testing near the injection points before repair would not give usable data due to the completely open delaminations there. Repairs at this location consisted of both grout and epoxy injected "spot welds". The dispersion curve for this, a vertical SASW line at a point at the edge of the delaminated area prior to epoxy injection, is presented in Fig. 11. This figure shows good data in a wavelength range of 0.05 to about 0.5 feet. The sandstone velocity for these wavelengths is fairly consistent, and matches the expected 2,700-3,000 fps velocity range for this sandstone. Only a small glitch appears in the data at the delamination depth of about 0.1-0.2 feet, indicating that the damage at this distance from the delamination edge consists of a closed crack rather than an open void. The dispersion curves for tests at the injection locations (close to the edge of the rock flake) after grouting and epoxy injection are presented in Figs. 12 and 13. The two curves are for vertically and horizontally oriented tests. As seen, the vertical test curve shows consistent velocity data for wavelengths of 0.07 feet and more. This indicates that for the vertical test path, the grout has filled the gap well. The lack of shallow data for the horizontal path indicates that the grout may not have penetrated into this test line area, which is further from the rock flake edge than the vertical line. This is not unexpected as the grout injection holes were located further from the horizontal test line than from the vertical line. It should also be noted that both the horizontal and vertical test lines show a drop in velocity for wavelengths greater than about 4 - 6 inches. This may indicate the presence of a softer and possibly weaker rock layer underneath the delaminated rock, or there may be another layer of cracking below the upper delamination.

Test Area "J". The third test area was identified as Area "J". The testing in this area was centered on a large delaminated rock area as diagramed in Figs. 19 and 20 (test location layouts before and after the repairs). SASW tests were performed only after the repair process for this area, due the extensive delamination of the upper stone from the underlying material. SASW tests on completely separated stones typically do not yield good data. Repairs at this location consisted of grouting of the delamination voids. The dispersion curve for tests at this location after grouting is presented in Fig. 14. The dispersion curve presented is for a horizontal orientation, with the test line centered over the area of grout-filled delamination. The SASW data dispersion curve shows consistent velocity data for wavelengths of 0.08 to 0.3 feet. At
shorter wavelengths, the velocity increases. This is presumably due to the influence of the higher velocity grout material. At longer wavelengths, the velocity begins to drop. This may be due to the presence of a somewhat softer and possibly weaker stone layer underneath the delaminated stone, or there may be another layer of cracking below the upper delamination.

**CONCLUSIONS**

The results of the testing of the El Morro sandstone before and after the stabilization procedures (repairs) lead to several conclusions in regards to the repair effectiveness as well as the in-situ conditions of the sandstone. Both the IE and SASW results clearly show that the repaired sandstone delaminations were more sound structurally when compared to the before-repair conditions. This observation is true for both spot-weld type repairs as well as for grout injection. The IE results showed a clear increase in structural stiffness after repair, as reflected by the decreased amplitude and higher frequency of the resonant vibration peaks of the delaminations. The SASW results showed a layer of higher-velocity material present after the repair procedures, which is consistent with the presence of the relatively higher-strength grout bonded to the sandstone. Note that testing of the repairs was conducted soon after grouting and epoxying. The performance of the repair materials over time will be studied in a set of planned follow-up tests at a later date.

In addition to the evaluation of the repair procedure effectiveness, the NDT investigation of the sandstone also yielded information as to some of it's material properties. Measurement of pulse velocity of sound stone near the surface gave a compression wave velocity of about 6.2 kilo feet per second (kfps). The SASW test results at the same location showed the rock to have a shear wave velocity of about 3.0 kfps. Taken together, these measurements indicate the sandstone to have a Poisson's ratio of about 0.35. These measurements are typical of low-strength, weathered rock, and are on the low end of the expected values for typical sandstones.
CLOSURE

The field portion of this NDT investigation was performed in accordance with generally accepted testing procedures. If we can provide additional consultation, or be of further service on this project, please call.

Respectfully submitted,

Olson Engineering, Inc.

-Dennis A. Sack
Project Manager

-Larry D. Olson, P.E.
Principal Engineer
TYPICAL IMPACT ECHO SPECTRUM AND TIME PLOTS
AFTER REPAIR, POINT 1, AREA 'G'
TYPICAL IMPACT ECHO SPECTRUM AND TIME PLOTS
BEFORE REPAIR, POINT 9, AREA 'J'
TYPICAL SASW PHASE AND COHERENCE PLOTS
SOUND SANDSTONE, 4 FEET BELOW AREA 'C'

Job No. 301
Sound Sandstone

Fig. 8
Location C, Before Epoxy

Fig. 9
Location G, Vertical, Before Grouting

Fig. 11
Location G, Vertical, After Grouting

Fig. 12
Location G, Horizontal, After Grouting

Fig. 13
Location J, After Grouting

Fig. 14
LOCATION 'C' TEST POINTS: BEFORE REPAIR

Fig. 15
LEGEND

+ Impact Echo Test Point
O SASW Receiver Mounting Location

LOCATION 'C' TEST POINTS: AFTER REPAIR

Fig. 16
LOCATION 'J' TEST POINTS: BEFORE REPAIR

Fig. 19
LOCATION 'J' TEST POINTS: AFTER REPAIR

LEGEND

- Impact Echo Test Point
- SASW Receiver Mounting Location

Note: Current test point 6 matches the pre-repair test point 9

Fig. 20
**IMPACT ECHO TEST RESULTS**

**EL MORRO SANDSTONE**

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<th>Thickness (inches)</th>
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| **Test Area G** |
| 1        | R1                                | 13.0                                 | 4.7            |                   |
| 2        | R2                                | 4.0                                  | 3.2            | 14.0              | 2.6 in. |
| 3        |                                   | 1.0                                  |                |                   |
| 4        |                                   | 3.0                                  |                |                   |
| 5        |                                   | 3.4                                  |                |                   |
| 6        |                                   | 2.6                                  |                |                   |
| 7        |                                   | 6.0                                  |                |                   |
| 8        |                                   | 0.7                                  |                |                   |
| 9        |                                   | 1.4                                  |                |                   |
| 10       |                                   | 2.0                                  |                |                   |
| 11       |                                   | 0.8                                  |                |                   |

| R3       |                                   | 4.7                                  | 9.9            | 3.6 in.           |
| R4       |                                   | 4.0                                  | 10.7           | 3.4 in.           |
| R5       |                                   | 3.6                                  |                |                   |

Job. No. 301
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Job. No. 301
APPENDIX A

Nondestructive Testing Methods
Stress Wave Velocity and Elastic Moduli

Pulse velocity (compression wave velocity) was determined during this project with direct measurement methods, i.e. the wave energy was generated by exciting the medium with a source at a known time and then identifying the arrival of the wave energy as sensed by receivers at known distances from the source. The velocity, \( V \), for P-wave energy is then simply the wave travel path distance, \( D \), divided by the arrival time, \( t \), as indicated in Eq. 1 below. Shear wave velocity was estimated as 10% faster than the SASW determined Rayleigh (surface) wave velocity (good approximation for the tested materials). The following equations from elastic theory illustrate the relationships between shear Moduli \( G \), mass density \( p \), unit weight divided by gravitational acceleration), shear wave velocity \( (V_s)\), Young's modulus of elasticity \( E \), Poisson's ratio \( \nu \), compression wave velocity \( (V_p)\), and constrained modulus \( M \):

Direct P- or S- Velocity: \( V = D / t \)  
Shear Modulus: \( G = p \ V_s^2 \)  
Young's Modulus: \( E = 2 \ p \ V_s^2 \ (1+\nu) = p \ V_p^2 \ [(1+\nu)(1-2\nu)/(1-\nu)] \)  
Constrained Modulus: \( M = p \ V_p^2 \)  
Poisson's Ratio: \( \nu = [0.5 \ (V_p/V_s)^2 - 1]/[(V_p/V_s)^2 - 1] \)  
P- and S-wave Velocities: \( V_p = V_s \ [2(1-\nu)/(1-2\nu)]^{0.5} \)

Values of these parameters determined from ultrasonic, and sonic measurements (UPV, IE, and SASW measurements) represent the material behavior at small shearing strains, i.e. strains less than 0.001 percent (Stokoe and Hoar, 1978). Thus, moduli calculated from pulse (compression) and shear wave velocities represent the maximum moduli of materials because of their low strain levels.

Two points are important in regard to elastic constants determined from wave velocities: as velocity increases, so does modulus (stiffness), and as strain increases for non-linear materials such as soil, concrete and rock, the material modulus will also decrease. This strain dependency is accounted for in soil dynamics by semi-empirical procedures for various soil types that allow one to accurately estimate the lower moduli at higher strains from the maximum moduli. Thus,
when predicting concrete or rock strength from pulse velocity, one is using a low-strain measurement of pulse velocity to predict a high-strain compressive strength.

A-1: Impact Echo (IE) Test Method

The IE tests typically involved hitting the surface of the test area at a given location with a small impactor which generated compression waves into the test surface, and recording reflected wave energy with an accelerometer receiver mounted with clay to the test element. A simplified diagram of the method is presented in Fig. A-1. Since the reflections are more easily identified in the frequency domain, the time domain test data of the impactor and receiver are processed with Fast Fourier Transform (FFT) operations by the dynamic signal analyzer for frequency domain analyses. A linear spectrum is then computed for the receiver showing amplitude as a function of frequency. Delamination resonance frequencies as well as reflections or "echoes" of the compression wave energy are typically indicated by pronounced "echo" peaks in the frequency spectrum test records. The delamination resonance peaks are typically strong, low frequency peaks which correspond to the overall resonant frequency of the delaminated section of stone vibrating as a unit. Lower frequency, higher amplitude delamination resonance responses are typically related to delaminated stone pieces which are less supported by the backing stone. Conversely, a drop in amplitude and/or a rise in frequency of these peaks indicates that a given stone piece is better bonded to the backing stone.

Reflections or "echoes" from the back sides of the stone elements are usually associated with higher frequency, lower amplitude spectral peaks that correspond to thickness or flaw depth resonant frequencies. If the velocity of the stone is known, the depth of a reflector can be calculated from the echo peak frequency. Material quality is related to compression wave velocity, with higher compression wave velocities generally correlated with increased material strength. Correspondingly, poor quality and/or damaged material result in slower wave velocities that are reflected by lower frequency thickness echo peaks for a given thickness.
At a stone-to-air interface, virtually all of the compression wave energy is reflected back into the stone. This near total energy reflection is due to the large difference in acoustic impedance, \( Z \), which equals velocity \( (v) \) * mass density \( (p) \), between the stone (high \( Z \)) and air (low \( Z \)). The geophysical equation governing the amount of energy reflected \( (R) \) back into material from an incident wave co-planar with the material 1 vs. 2 interface is as follows:

\[
R = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)} = \text{ratio of amount of reflected energy to incident energy} \quad (7)
\]

As an example of the simple IE thickness calculation for a flat slab or wall, if IE tests of a wall with thickness, \( T = 0.5 \) foot produced a time domain record with periodic echoes every \( t = 0.0001 \) seconds (0.1 milli-seconds, ms), then the concrete velocity would be \( V = 2*\frac{T}{t} = 2*0.5 \text{ ft/0.0001} = 10,000 \text{ feet per second} = 10 \text{ kilo-feet per second (kfps)} \) since the wave energy has reflected from the opposite side of the wall and thus traveled a total distance of 1.0 ft. Through frequency domain Fast Fourier Transform (FFT) processing, the periodic echo arrivals are more clearly identified as a thickness resonance return frequency, \( f \), that is related to the time period of the echoes, \( t \), by \( f = \frac{1}{t} = 1/0.0001 \text{ secs} = 10,000 \text{ Hz} \) (Hertz, cycles/second). Velocity is calculated from linear frequency spectra displacement or flexibility (displacement/force) plots of IE results as \( V = 2*T*f = 2*0.5 \text{ ft}*10,000 \text{ Hz} = 10 \text{ kfps} \).

A-2: Spectral Analysis of Surface Waves (SASW) Method

The SASW method is based upon measuring surface waves propagating in layered elastic media and is pictured in Fig. A-2. The ratio of surface wave velocity to shear wave velocity varies slightly with Poisson's ratio, but can be assumed to be equal to 0.90 with an error of less than five percent for most materials, including concrete and rock. Measurement of the surface wave velocity with the SASW method similarly allows calculation of compression wave velocity. Knowledge of the seismic wave velocities and mass density of the material layers allows calculation of shear and Young's moduli for low strain amplitudes.

A-3
Surface wave (Rayleigh; R-wave) velocity varies with frequency in a layered system with velocity contrasts, and this frequency dependence of velocity is termed dispersion. A plot of surface wave velocity versus wavelength is called a dispersion curve. The SASW tests and analyses are performed in up to three phases: (1) collection of data in situ; (2) construction of an experimental dispersion curve from the field data; and (3) inversion (forward modeling) of the theoretical dispersion curve, if desired, to match the experimental curve and provide the shear wave velocity versus depth profile.

The SASW field tests consisted of impacting the test surface to generate surface wave energy at various frequencies that was transmitted through the test material. Two accelerometer receivers were evenly spaced on the surface in line with the impact point to monitor the passage of the surface wave energy as illustrated on Fig. A-3. To obtain increasingly deeper data, several tests with different receiver spacings are performed by doubling the distance between the receivers about the imaginary centerline between the receivers. The receiver spacings used for tests on the stone in this investigation were typically 3 inches and 6 inches. For this project, 5-10 impacts and the associated receiver responses were obtained at each receiver spacing. Also, the impacts were applied typically at each end of a given receiver spacing with the distance from the impact point to the closest receiver about that of the receiver to receiver spacing.

A signal analyzer digitizes the analog receiver outputs and records the signals for spectral (frequency) analyses to determine the phase information of the cross power spectrum.

Figure A-3  SASW Test Method Diagram
between the two receivers for each frequency. The dispersion curve is developed by knowing the phase ($\phi$) at a given frequency ($f$) and then calculating the travel time ($t$) between receivers of that frequency/wavelength by:

\[ t = \frac{\phi}{360^\circ f} \]  

(8)

Surface wave velocity ($V_r$) is obtained by dividing the receiver spacing ($X$) by the travel time at a frequency:

\[ V_r = \frac{X}{t} \]  

(9)

The wavelength ($L_r$) is related to the phase velocity and frequency by:

\[ L_r = \frac{V_r}{f} \]  

(10)

By repeating the above procedure for any given frequency, the surface wave velocity corresponding to the given wavelength is evaluated, and the dispersion curve is determined.

Inversion is the process of determining the "true" shear wave velocity profile from the "apparent" velocity of the dispersion curve. Inversions were not performed on the SASW data gathered in this investigation due to the limited additional information to be gained versus the cost to perform them. The forward modeling inversion process is iterative and involves assuming a shear wave velocity profile and constructing a theoretical dispersion curve. The experimental (field) and theoretical curves are compared, and the assumed theoretical shear wave velocity profile adjusted until the two curves match. The SASW method and an interactive computer algorithm for both 2-dimensional and 3-dimensional analyses have been developed by Dr. Jose Roesset of the University of Texas at Austin to compute a theoretical dispersion curve based upon an assumed shear wave velocity and layer thickness profile.
References

Impact Echo


Spectral Analysis of Surface Waves


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