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CEMENT MODIFIED EARTHEN MORTAR – AN INVESTIGATION OF SOIL - CEMENT PERFORMANCE CHARACTERISTICS AT THREE SOUTHWESTERN NATIONAL MONUMENTS

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Chapter 1 – Introduction

> The practice of ruins preservation is becoming a unique component of cultural resource management and historic preservation, incorporating perspectives of both conservation and archaeology. The goal now is to preserve the scientific and heritage values in the original construction materials by using compatible materials and technique (to) duplicate the original architecture. The results of achieving this goal can be the perpetuation of unimpaired architectural resources, which will continue to provide the opportunity for future visitors and researchers to explore questions yet to be defined.[1]

Ruins stabilization in the Southwestern United States is a practice that has been developing for nearly 120 years. This practice was a logical outgrowth of the initiative to maintain the archaeological remnants of ancient Native American culture. Since the first known stabilization work at the site of Casa Grande in southern Arizona in 1891, the materials and methods that are used for stabilization work have evolved both theoretically and practically. The above statement from the ruins preservation guidelines “draft” of the Vanishing Treasures program of the National Park Service (NPS) illustrates one common view regarding the management of cultural resources and heritage and stresses the underlying importance of material and visual compatibility in the preservation and display of archaeological architecture.

The first priority in the effort to stabilize archaeological ruins is always to address the mechanisms that cause deterioration of a structure. Despite

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[1] U.S. Department of the Interior. *Vanishing Treasures: A Legacy in Ruins, In-House Draft* (1997), p. 10.

stabilization efforts, there is no guarantee that deterioration will not continue. However, even if the mechanisms of building deterioration are properly addressed exposure of aboriginal structures to the natural processes of weathering can still be expected to cause decay over time.

> The original inhabitants did not build their homes and Kivas just once, they were constantly rebuilding them… I doubt seriously if any of the structures of the olden days were entirely waterproof.[2]

Hence the practice of stabilization of the remnants of indigenous architecture should be considered as an aspect of routine maintenance for archaeological sites.

The goal of building maintenance is to sustain architectural systems in their optimal working condition. In the case of archaeological ruins, this means sustaining the structures in conditions as close as possible to those in which they were discovered, rather than attempting to restore them to their original, habitable forms. To that end, replacement of failing building material such as mortars for pointing, bedding, and capping of wall structures is necessary. Ideally this should involve the most infrequent and minimal intrusion on the original fabric of these buildings as possible. Unfortunately, the use of wholly original replacement materials in the process of stabilization is not frequently conducive to minimizing intervention. As J.W. Hendron claimed, ancestral Puebloans of the southwest were regularly involved in the maintenance and rebuilding of their dwellings and public spaces. Compared to what we see of these structures today,

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[2] J. W. Hendron (1937).

the original forms would have been finished with regularly applied renders composed of soils similar to those used in masonry mortars. These protective and possibly symbolic non-structural finishes are lost fabric. The remaining masonry, especially earthen mortars, must continue to provide structural support to the architecture while exposed to the elements. Consequently, stabilizing Puebloan structures requires materials that can provide support to the building structures and that display durability against natural weathering. This requirement led to the consideration of amending soil mortars with modern materials to increase their durability.

The addition of amendments to soil mortars has been practiced in the stabilization of Puebloan archaeological sites since early stabilization work at Casa Grande in 1889.[3] Currently, a number of materials are commonly used as amendments to soil mortars. The two most notable types of amendment materials are Portland cement and synthetic resin dispersions – most notably acrylics and polyvinyl acetates (PVA). Portland cement was the favored amendment material of sites managed by the National Park Service from the 1890s until the mid 1970s.[4] The use of cements was subsequently scaled back at many sites and curtailed completely at some because of perceived deficiencies in the resulting soil-mortars that were linked to the amendment itself. Three particular shortcomings were associated with cement-amended soil mortars. The issue of color in these mortars was a key point of contention. The lightening effect that the addition of cement (white or grey) has on soils makes it

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[3] R. Richert and R. G. Vivian (1974), p. 2.

[4] T. R. Metzger (1988), p. 28.

difficult to maintain homogeneity of appearance between original and stabilization materials at many sites. Strong mortar formulations also had the effect of doing damage to adjacent original material as a result of the thermal expansion and differential movement in site structures, whereby stronger materials transfer stress to weaker materials, which, are damaged in turn.[5] Many cementicious earthen mortars were also found to have lower capillary potential than the original materials surrounding them, resulting in the transfer of absorbed water onto these materials, causing water damage to original fabric.[6]

Since the 1970s acrylic and PVA admixtures have become a common amendment material for stabilization work at the NPS. Early testing of these acrylic dispersions by Dennis Fenn at Chaco Culture National Historic Park (1978) revealed that they caused little or no change in color to the soils used in mortars.[7] The low compressive strength imparted on acrylic-amended earthen mortars eliminated the issue of preferential damage to original masonry. The capillary potential of acrylic-amended mortars was found to exceed that of most masonry stone, which effectively dealt with the problems of the transfer of water from stabilization material onto original material.[8] These advantages are counterbalanced by the high cost of the acrylic admixtures in addition to observed performance failures of earthen mortars amended with them (see

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[5] *Ibid.*
[6] *Ibid.*
[7] *Ibid.*
[8] *Ibid.*

Robert Hartzler's report *Acrylic-Modified Earthen Mortar* for results of laboratory testing on this type of amended soil mortar).[9]

Polyvinyl acetate, also an ingredient of latex paint, is used in preservation of wood and wood products (paper and cloth). Water-insolubility is the property of polyvinyl acetate, a synthetic additive for concrete flooring, that could suggest its further use in soil-cement mortar formulations to achieve high-durability against moisture erosion. However, the hydrophobic properties of PVA that make it an effective sealing agent in paints, poses potential problems in the case of amended soil mortars for transport of water out of wall structures. PVA has also demonstrated the property of thermoplasticity (softening upon heating), suggesting that temperature changes may compromise the strength and durability of such polyvinyl acetate mortar formulations.

The increase in popularity of acrylic amendments, which lacked the benefit of long-term testing for stabilization applications, gives cause for reconsideration of the use of Portland cement. Portland cement was used with varying results, both good and bad, as an amendment to earthen mortars at numerous sites for over 80 years, indicating that at least some benefits validated its continued use. Though field testing has been performed at length on soil-cement formulations in conjunction with observation of the performance of these mortars in use, soil-cement has not been subject to the laboratory testing it requires in order to observe and quantify its properties with soil systems. The hypothesis of this research is that the performance of soil-cement mortars is based primarily on the

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[9] Robert Hartzler (1996).

type and composition of the soil used in the mortar formulation. Through observation of the critical properties of different mortar formulations, the capabilities that varying quantities of Portland cement lend to soil-cement mortars can be understood and controlled to reflect the needs of each site for stabilization mortars.

The critical properties that are tested in this research were selected to indicate the potential compatibility of the mortars with wall systems into which they would be introduced. The complexities of wall structures in ancient Pueblos necessitate that the walls be considered systems. The addition of new material to an operating system must be managed and observed carefully to assure that the system is not thrown out of balance as a result. Many structures at archaeological sites retain original bedding mortars that have not been exposed and, thus, are not deteriorated. However, if the loss of surface finishes or pointing mortars on these walls necessitates the application of stabilization mortars as replacements, original materials can still be susceptible to damage.

Deterioration to remaining original material in a stabilized wall can occur in a number of ways, but the most common cause of this is water. Water enters a wall structure by capillary absorption or as vapor that permeates the outer membrane of the structure. A simple wall consisting of a single wythe of masonry units bedded in and pointed with earthen mortar can be expected to contain some form of water (vapor or liquid) in each of these components at virtually all times. A surviving system constructed of these original materials will preferentially release this water through the most expedient route, usually through the earthen mortar, which, in most cases, will be the most permeable constituent of the system. If a new material, such as an amended pointing mortar, is introduced into the system, however, some problems can occur with this release. If original earthen mortar remains the most permeable building material in this structure, then the remaining routes of escape for entrained water are though the stone masonry or through the amended pointing mortar. Both of these materials will be permeable, but if their permeability is significantly lower than that of the encased bedding mortar the release of the water in the system will occur slowly, effectively trapping water within the system and destabilizing original mortar.

Larger rubble-core walls can be susceptible to this as well. Rubble cores consist of conglomerations of stone and mortar and are surrounded by coursed, bedded masonry membranes. When an amended pointing mortar with low permeability comprises a part of the outer membrane of one of these walls, the interior can become a humidified chamber. The deterioration of the core of this type of wall can significantly diminish the stability of very massive structures, putting them at risk for collapse.

Following prolonged exposure at some sites, certain walls are effectively rebuilt through multiple stabilization campaigns. These walls can be more complex, in regards to further stabilization, than walls that are constructed wholly of original building materials. Stabilization mortars should be more susceptible to weathering and deterioration than original construction materials. However continued loss of original material following the stabilization of a structure is not uncommon. Walls may, therefore, contain combinations of original masonry and mortar, amended stabilization mortar (which, in itself, can be regarded as historic, depending on its age), and even straight cement mortar in some cases. These materials in combination can represent a range of permeability, water absorption and desorption capacity, durability, strength, and color. Any material that is considered to be historic cannot be removed, and some pure cement mortars cannot be removed without damaging the substrates to which they are attached. It is also necessary in this scenario that mortars used in further stabilization be similar (in material composition, color, *etc.*) to the already-present stabilization mortars so as not to establish a wall system of materials with varying properties and appearances. A thorough knowledge of past stabilization efforts at a given archaeological site is an important element in determining the optimal critical properties for new stabilization mortars.

The following critical properties formed the basis for observation of mortar performance in this research:

- Setting time
- Color
- Water absorption
- Water vapor transmission
- Strength
- Durability (resistance to freeze/thaw decay, resistance to erosion)

The time of setting has direct bearing on the application of stabilization materials, particularly in regions where stabilization work can be done only at certain times of the year. It also affects the application process as an indication of the workability of fresh mortar with plastic consistency and how long the material can be expected to maintain consistency.

As discussed, color has been a key issue with Portland cement-amended earthen mortars at archaeological sites. The understanding of the nature of color variation affected by the addition of cement to soil mortars is important in devising methods of mitigating the change in color.

Water absorption has been an extremely important critical issue with soil-cements at most NPS sites. Water movement is assumed to occur in any exposed masonry structure. Water should be able to move both into and out of the ancient masonry material at the same gradual and relatively constant rate. Ancient mortars and renders were composed of soil that had a higher capacity than masonry stone to absorb water. However soil mortars amended with cement can have much lower imbibition capacities than building stone in ancient structures. When water moving through stone reaches a mortar joint that is packed with an amended mortar, it is critical that the amended mortar be able to facilitate the continued movement of that water. Otherwise the resulting liquid retention at the joint could lead to eventual decay of the stone through chemical and physical responses.

Water vapor transmission will also indicate the permeability of the stabilization mortars. This is important in a similar sense to the water absorption capacity of the mortar because its permeability is an indication of how well the mortar can facilitate the removal of water vapor from the building system. Poor vapor transmission capabilities can lead to the trapping of water vapor within wall structures. Trapped vapor eventually condenses and can lead to masonry damage at the joint between mortar and masonry or from within the material in the case of trapped vapor condensing within original material. Monitoring of both water absorption and vapor transmission capabilities in various soil-cement mortar formulations should indicate whether these properties can be controlled through variation of cement content.

The strength that Portland cement can impart on mortars is rarely called into question, although mortars with high strength have been linked to damage of adjacent masonry. The property of strength in response to tensile forces is a more useful consideration in the case of pointing mortars, which do not receive the same compressive forces that bedding mortars receive. Portland cement is known to impart a high degree of hardness and compressive strength to mortars, but this equates with a relatively low tensile strength (still far higher than that of an unamended soil mortar). By observing the strength in bending (flexural strength) of soil mortar formulations, cement content can be determined that corresponds with optimal criteria for water vapor transmission and water absorption while still retaining a deferentially diminished strength capacity relative to that of original masonry.

Durability is one of the greatest benefits to be expected from a mortar that contains Portland cement. This is measured through freeze/thaw testing and testing of the erodability of mortars that are exposed to constant water fall. Cement-amended soil mortars are expected to stand up well to these stresses, and their performance will be an indication of the frequency with which the stabilization materials themselves might need to be maintained or replaced. Such measures of endurance are also determined with consideration for the minimum content of cement necessary to maintain this durability in a stabilization mortar while also meeting goals for high water absorption capacity and vapor permeability.

The experimental component of this thesis is the laboratory testing performed on cement-amended earthen mortar samples composed of soils from three sites managed by the National Park Service: Bandelier National Monument, Chaco Culture National Historic Park, and Salinas Pueblo Missions National Monument. Differences among the three sites in the geology of site formation as well as the periods and purposes of the original architectural structures assure both a range of soil properties and a range of requirements for stabilizing the corresponding structures. Though the soils are not taken from on-site locations at any of the parks, the differences among them in content and performance can be taken as representative of typical differences in soils that are found in the same general region, in this case, Northern New Mexico.

Bandelier was established as a National Monument in 1916. Located 30 miles west of Santa Fe New Mexico near the city of Los Alamos, the 30-thousand acre environment of steep canyons and mesas carved by river flow through volcanic plateau formations also includes dense wooded areas in the existing river valley. The archeological remains include ancestral Pueblo ruins of thousands of dwellings in the cliffs and the canyon floors occupied from the 12th to the 16th century. Excavation and preservation efforts have been underway at Bandelier since the early 20th century. Building stone used for Puebloan construction at Bandelier consists of varying types of volcanic tuff, formed from compacted ash. It should be noted that this stone is extremely porous and permeable and, therefore, tends to facilitate vapor transmission and water absorption/desorption.

Chaco Culture National Historic Park is located 80 miles northeast of Gallup New Mexico near the town of Nageezi. The 30-thousand acre site of non-wooded, high-desert sloping terrain contains the architectural remains of dozens of monumental ceremonial Pueblo structures that formed a major regional center of ancient culture and trade between the 9th and 13th centuries. The structures at Chaco represent architectural innovation along with several distinct masonry styles. Excavation and preservation efforts have been underway at Chaco since the early 20th century. Building stone used at Chaco consists of locally quarried sandstone with generally high compressive strength and somewhat variable capillary rise potential. Data on some stone types used at both Chaco and Bandelier are presented in Appendix M.

The Salinas Pueblo Missions, formally established as a National Monument in 1980, is located 50 miles southeast of Albuquerque New Mexico near the town of Mountainair. The 1000-acre environment is dry, juniper-shrub and cactus woodland in the basin of a prehistoric lake. Construction of the missions began in the late 16th century. By this time, the sites that would become the Salinas Pueblo Missions had already been inhabited for centuries by native Puebloan culture.[10] The growth of the mission architecture in the Salinas basin occurred in close proximity to the existing Pueblo locations. Currently the site includes the remains of four mission churches and a partially excavated Pueblo at the Gran Quivira site. The design and construction of the mission buildings of New Mexico were "…a combination of the Spanish architectural tradition of wall and beam construction and the influence of local Indian cultures skilled in the same methods."[11] The Gran Quivira site has a long history of stabilization work with varying formulations of cement-stabilized mortar (described in Chapter 2), though it has not undergone any stabilization work since 1996. The building stone at this site is local limestone appearing in both granular and dense varieties.

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[10] Ivey, (1987).

[11] Ibid.

Chapter 2 – Previous Research

2.1 Stabilization of Architectural Remains

Stabilization of architectural remains is a strategy compatible with founding principles of the NPS: stewardship on behalf of visitors and future generations, and interpretation of natural and historic resources. Nevertheless, effective stabilization that preserves both the character and fabric of archeological architecture requires methods that have been scientifically developed and tested.

The environments in which archaeological sites exist can foster preservation or, in some cases, destruction of architectural remains. Unexcavated structures can potentially survive indefinitely with the benefit of burial, which offers protection from exposure to the elements. Soil fill also provides structural support to architectural elements that have become weak or unstable through loss or displacement over time. Natural deposition of soils (soil fill) at archaeological sites is itself a result of the same weathering forces responsible for deterioration. When excavation occurs, therefore, structures in an already-deteriorated condition can become exposed. Stabilization and structural intervention is often necessary to maintain re-exposed architectural remains. Stabilization intervention incorporating modern construction materials is not uncommon. It is often desirable to use modern construction materials as complements or enhancements to traditional architectural materials and systems in the interest of designing intervention measures to preserve the architectural remains. These notions apply to the formulation of amended soil mortars.

The primary use of stabilization mortars at sites of archaeological ruins is to reinstate both structural integrity and weather proofing in the masonry remains through the use of replacement materials. This practice has been in place since the first excavation/stabilization efforts in the late 19th century at National Park Service (NPS) sites such as Casa Grande and Mesa Verde.

It is desirable for stabilization materials to be visually and functionally compatible with the original materials and systems that are being stabilized. Therefore, traditional materials are considered first for their capacity to assure a measure of performance compatibility between original and replacement materials. Often, however, exposure of masonry joints and the deteriorated condition of the structure calls for more durable materials than those originally used. A mortar stabilization campaign, for example, often proceeds on the assumption that the mortar being replaced was not meant to be exposed and might originally have received sacrificial protective finishes such as plaster or stone veneer for durability. Restoration of these finishes at archeological sites would usually involve considerable interpretative license and the introduction of new materials. Such restoration would generally be considered unacceptable. Stabilization more commonly provides protection to the exposed original fabric without functionally or architecturally completing the structure and without misrepresenting its condition. A stabilization mortar must be sacrificial where the well-being of original material is concerned, but it also must be durable enough to withstand regular weathering for a reasonable period of time. The NPS has adopted the practice of amending earthen materials with Portland cement, acrylic emulsions, and other additives over the last century to increase the strength of earthen building/stabilization materials.

One particular issue affecting the success or failure of stabilized earthen mortars and plasters is the nature of the soil that is used. The use of indigenous soils for stabilization mortars at ancient and historic sites managed by the NPS may not always be the right choice for the formulation of a stabilization mortar. Indigenous soils were used traditionally for stabilization at most sites. Today utilization or any other disturbance of indigenous materials within a national park is considered to be mining, and is thus prohibited. Stabilization must consequently rely on imported soils.

Despite their original use and immediate availability at each site, indigenous soils can also be unsuitable for use in stabilization mortars that employ amendments. High contents of expansive clay in soils lead to drastic shrinking, swelling and cracking of mortars constituted of such soils. Significant amounts of soluble salts in many southwestern soils can be a source of early masonry deterioration as a result of salt crystallization in soil mortars. Uneven particle size distribution (exhibited in very fine soils in particular) can lead to inherent weakness in mortars. Soils vary widely among sites and even within sites, thus challenging the ability to formulate reproducible mixes for stabilization mortars.

The composition of amended mortars can be formulated for compatible use at each site providing that the parameters for compatibility are defined. These parameters include knowledge of the 1) original masonry materials and system of construction, 2) environment including climate, 3) history of past treatment, and 4) current maintenance program.

Susan Einegar documented the stabilization history at the three major historic centers of the Salinas Pueblo Missions National Monument in Mountainair, New Mexico.[12] Past stabilization approaches at Salinas involved stabilization mortars based largely on indigenous soils. Einegar documents a relatively vast array of amendment materials and formulations of soil-cement stabilization mortars used in more than 70 years of field tests at Salinas. The damage to core masonry caused by specific failures of many formulations is also documented in Einegar's report. The approach to stabilization was a seemingly random implementation of materials and mixes, and the corresponding absence of trends in the results is not surprising.

Dennis Fenn has tested the properties of indigenous soils and associated amended mortars using materials from multiple locations at Bandelier National Monument and Chaco Culture National Historic Park in New Mexico.[13] Fenn's data are based on laboratory studies of soil and mortar samples. The scope of Fenn's tests of soil samples provides an opportunity to determine differences in soil properties between the two sites as well as the breadth of properties within a

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[12] Susan Einegar (1998).
[13] Dennis Fenn (1978).

site. The results of Fenn's tests of soil-cement mortar formulations of known composition provides a second opportunity to determine whether systematic trends in the measured properties of stabilization mortars are observable from such tests and whether such trends are large enough to justify further laboratory studies.

This thesis chapter reviews the observations and data recorded by both the Einegar and Fenn studies. It examines the trends that appear in the data from these studies, and summarizes possibilities suggested by these trends for laboratory indicators of future approaches to stabilization mortars.

2.2 Documented Use of Stabilization Mortars at Salinas Pueblo Missions, New Mexico

Local soils and various amendments have been used since 1920 to formulate stabilization mortars at Salinas without the benefit of testing the materials or documenting their characteristics and properties. The general outcome has been a long and varied stabilization history that included repairs to damage caused by the stabilization process itself.

The Salinas Pueblo Missions incorporate three historic centers: Gran Quivira, Abo, and Quarai. Each has a complex stabilization history. Each site has used numerous amendment approaches involving different stabilization mortars. The stabilization history for Gran Quivira extended over the largest time period.

This is detailed in Einegar's report and is summarized in Table 2.1.[14] The process might be viewed as an extensive empirical field experiment, documenting the effects of stabilization using different combinations of newly available and local materials.

Stabilization of the mission architecture at Gran Quivira occurred between 1923 and 1996. Stabilization mortars were used for bedding, capping, and pointing. Many varied mortar amendments were employed in the 70-year stabilization period. Most were abandoned for insufficient strength. Because of improper use or incompatible properties, some stabilization mortars actually caused damage rather than preventing it. Only cement amendments were retained for use throughout the entire period.

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[14] Einegar (1998), pp. 6-11.

Table 2.1. Salinas Pueblo Missions, Stabilization History of Gran Quivira Site
Stabilization Mortars Used with Original Limestone

Park Site	Period	Structures	Mortar Amendments	Mortar Mixes
Gran Quivira	1923-1929	Mission Architecture: San Buenaventura and San Isidro Churches and Convento (north)	1. None/soil (primary) 2. Cement	
	1940	Convento (west)	Cement	arroyo sand
	1942	Convento (repair rain damage in 9 rooms)	Cement	
	1948	San Buenaventura (repair nave	Cement	
	1951	Convento (completing rain repairs)	1. None/soil over cement 2. None/soil 3. Bituminous asphalt	
	1951	House A (plus undocumented work on Buonaventura, convento)	1. None/soil over cement 2. None/soil	
	1962	Buenaventura, Convento, San Isidro, House A, Kiva D	1. Tinted cement 2. None/soil over cement	
	1964	Buonaventura (repair deterioration of 1962 capping)	Tinted cement	
	1965-1968	Mound 7 roomblock (226 rooms, 8 kivas)	Tinted cement	
	1976, 1977	Buenaventura, Convento, Mound 7	None/soil	caliche caliche:sand::5:1 caliche:soil-plus-ash::5:2
	1978	Buenaventura, Convento, Mound 7	calcium aluminate, or $Ca_3(Al_2O_3)_2$ (or Ca-Al)	caliche:ash:Ca-Al::3:1:1

Table 2.1. Salinas Pueblo Missions, Stabilization History of Gran Quivira Site (cont.)
Stabilization Mortars Used with Original Limestone

Park Site	Period	Structures	Mortar Amendments	Mortar Mixes
Gran Quivira	1979	Buenaventura, Convento, Mound 7	calcium aluminate, or $Ca_3(Al_2O_3)_2$ (or Ca-Al)	caliche:ash:Ca-Al::3:1:1 caliche:Ca-Al::3:1
	1980	Buenaventura, Convento, Mound 7	calcium aluminate, or $Ca_3(Al_2O_3)_2$ (or Ca-Al)	caliche:ash:Ca-Al::3:1:1
	1981	Buenaventura, Convento, Mound 7	calcium aluminate, or $Ca_3(Al_2O_3)_2$ (or Ca-Al)	caliche:sand:Ca-Al::3:1:1
	1985	Mound 7 (82 rooms) and east Mounds 15, 16	Cement	caliche:cement::7:2 caliche:cement::7:3
	1988, 1991, 1993, 1995, 1996	Mound 7 (92 rooms); portions of Mounds11, 13 and 15; House A; the corral; Kivas C, E and J; Isidro; Buenaventura; Kivas E and F	Cement	dirt:cement:6:1 dirt:cement::6:2

The following examples of masonry deterioration observed at Gran Quivira are typical types of failure that can occur as a result of incompatibility between original masonry systems and stabilization materials.

Some surface (capping) mortars bonded poorly to masonry cores, resulting in crack separation between the mortar and core. Water entered these cracks and exposed the core to weathering. Alternative mortar formulations from various stabilization efforts have also been used side-by-side within the masonry structures. Differences in density and permeability of these varying formulations have resulted in ongoing water damage extending into core masonry.

The advantages of cement-amended soil mortars noted in the Salinas report include adequate strength, good durability (protection against weathering and moisture), and low cost.[15] Disadvantages with cement-amended mortars include the undesirable color and the entrapment of moisture because of low moisture permeability.

Documented failures of specific mortars and, in some cases, damage to the mission architecture resulted from the use of incompatible stabilization materials and techniques at Salinas. The pure cement stabilization mortars used for capping and for pointing of the San Buenaventura Church at Gran Quivira in 1962 required reapplication only two years later, and it was noted at this time that in the interim, those wall structures that had been stabilized with pure cement mortars had lost veneer and capping materials due to cracking from differential movement of the wall materials. The rubble cores of these walls had also deteriorated in the two-year period, a likely result of the trapping of water and water vapor inside the walls by the non-permeable cement membranes.[16] Conversely, unamended soil mortars used in stabilization efforts in 1976 and 1977 were found to be excessively weak and eroded very quickly.[17] These failures led to the subsequent exploration of soil mortars amended with cement as a potential middle ground between the two failed alternatives.

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[15] *Ibid.*
[16] *Ibid.*, p. 9.
[17] *Ibid.*, p.10.

2.3 Characterization of Soils at NPS Sites

The properties of local soils at ancient and historic sites are often insufficient for stabilization mortars. Significant variations in soil properties within sites further complicate the standardizing of mortar formulations for each site. (Refer to results from Dennis Fenn's research tabulated in Appendix M for testing data on soil-cement stabilization mortars previously used at Bandelier National Monument and Chaco Culture National Historic Park).[18]

Tables 2.2 – 2.5 give an analysis of a subset of the tests performed by Fenn on soil samples to determine their utility in stabilization mortars based on established performance criteria for soluble salt content, composition, granulometry, and clay mineralogy of these soils. The results given for each selected test are the average and standard deviation for the six Chaco samples and seven Bandelier samples tested. The test criterion for suitability of the soil is indicated beneath each table. Comparing the criterion for each test with the average test result determines the suitability of the soil. Comparing the average test result for the Chaco and Bandelier samples indicates the differences between properties of soils at the two NPS sites. The standard deviation in each case indicates the variation in soil properties among the six (Chaco) or seven (Bandelier) different locations within the single NPS site. The comparisons illustrate that the local soils are often (in some cases always) unsuitable for use as stabilization mortars. They show very large differences in soil properties

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[18] Dennis Fenn (1978), pp. 13-67.

between sites and, in some cases, equally large variations in properties from different locations within a site.

Table 2.2. Average Result of the Chemical Analysis of Soluble Salts (Data from D. Fenn 1978)

	BANDELIER 7 sites		CHACO 6 sites	
	Mean	**1s**	**Mean**	**1s**
ppm Soluble Salts	1107	2064	199	195

Criterion: Soluble salt content < 1000 ppm

An excess of soluble salts (>1000 ppm) in soils used for mortars attracts large amounts of moisture to the mortar, which results in cracking as temperatures rise and fall, and can cause staining of masonry and damage to the original core materials.[19] The soluble salts in two of seven Bandelier soils is unacceptable for mortars and is the reason for the very high standard deviation in the Bandelier results. High salt content was not observed in Chaco soils.

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[19] *Ibid*.

Table 2.3. Average Hydrometer Soil Analysis Results (Data from D. Fenn 1978)

	BANDELIER 7 sites		CHACO 6 sites	
	Mean	**1s**	**Mean**	**1s**
% Sand	65	9	75	11
% Silt	8	4	13	7
% Clay	26	9	12	4

Criteria: 20-25% clay, 60-70% sand, 0-10% silt

Sedimentation analysis for particle size determines the relative content of fine sand, clay, and silt. Soil with high silt (above 10%) or low clay (below 20%) content produces mortar that is reduced in strength.[20] Fenn deemed five of six Chaco soils unacceptable for mortars because of high silt and low clay content, while all Bandelier soils were determined to have acceptable particle-size distributions.

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[20] *Ibid*.

Table 2.4. Average Sand Sieve Analysis Results (Data from D. Fenn, 1978)

	BANDELIER **7 sites**		**CHACO** **6 sites**	
	Mean	**1s**	**Mean**	**1s**
% V Coarse	11	4	1	1
% Coarse	26	5	4	2
% Medium	20	3	12	6
% Fine	21	4	61	7
% V Fine	22	9	22	6

Criterion: Predominance of coarse/very-coarse sand

Sieve analysis gives the grain size distribution of the sand fraction of a soil. Soils with predominant fractions of fine/very-fine sand, like silt, are correlated with reduced strength in mortar formulations. Stronger mortars require a high content of well-graded, coarse/very-coarse sand. This assures that sufficient particles of all sizes exist to fill the voids formed within the binder matrix of soil-cements. All Chaco soils tested by Fenn were considered to be unacceptable for mortars because of the very high content of fine/very-fine sand. Only one of seven Bandelier soils was considered to be unacceptable for mortars based on this criterion.

Table 2.5. AVG CLAY ANALYSIS RESULT by X-ray DIFFRACTION
(1 = NONE, 3 = MEDIUM PRESENCE, 5 = DOMINANT)
(Data from D. Fenn, 1978)

	BANDELIER 7 sites		**CHACO 6 sites**	
	Mean	**1s**	**Mean**	**1s**
Montmorillonite	1	1	3	2
Mica (Illite)	3	1	3	0
Vermiculite	2	1	3	0
Chlorite	0	1	1	1
Kaolinite	3	1	3	1
Interstratified	2	1	2	1

Criterion: Absence of "swelling" clays: montmorillonite/vermiculite

Clay mineralogy in soils is measured by X-ray diffraction. Excessive presence of swelling clays in soils used for mortars causes the mortar to crack from uptake and release of water. One half of the Chaco soils and one fifth of the Bandelier soils were considered unacceptable because of excessive swelling clays.

2.4 Some Optimal Properties of Engineered Soil-Cements Relevant to Stabilization Mortars

The properties of cement-amended soil mortars (soil-cements) can be engineered to meet variable needs for stabilization. Fenn used four of the seven

Bandelier soils and the six Chaco soils to make three corresponding test mortars amended with Portland cement. The soil:cement ratio was 4:1, 6:1 and 10:1 for the soil-cement test samples. These correspond to 20%, 14% and 9%, respectively, for cement content (cement/soil-plus-cement) of the three mortar samples for each soil. Complete compilations of Fenn's results for the testing of soil-cement mortars composed of Bandelier and Chaco soils are included in Appendix M.

It was found that both the strength and capillary potential of soil-cement mortars can be optimized to meet the stabilization need. The strength of a mortar can be measured by putting samples of the mortar under compressive or flexural stress. Both of these types of testing can provide expressions of the strength of the mortar under varying conditions in the working environment. Bedding mortars are subject to direct compressive force in masonry systems, and the formulation of these mortars can benefit greatly from compression testing. The compressive strength of a mortar should be as high as possible without exceeding the strength of the building stone (which can also be measured by compression).[21] This requirement maximizes the overall structural strength and, under conditions of severe compression, results in preferential cracking of the mortar, preserving the original core masonry.

The capillary potential (measured by capillary rise of moisture) should exceed that of the building stone.[22] This requirement results in preferential

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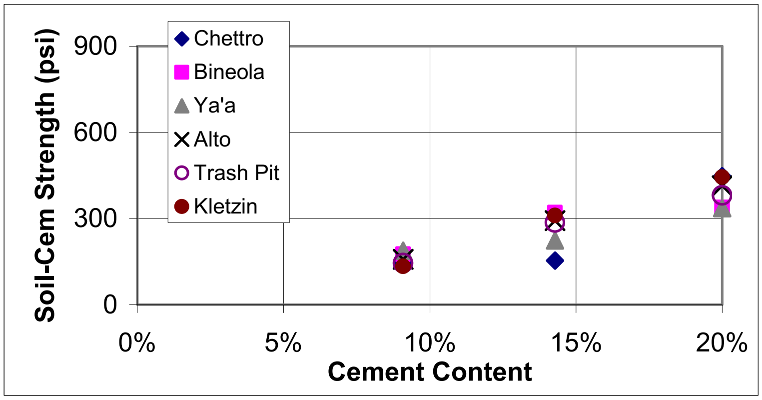
[21] *Ibid*. p. 5.
[22] *Ibid*.

uptake of moisture by the mortar, reducing moisture transport through the core masonry and minimizing the deterioration effects of moisture in the original building stone. Increasing the cement content of a soil-cement mortar increases both its strength and capillary potential, as indicated in Charts 2.1 – 2.4. The further addition of sand (beyond the natural sand content of the soil) reduces strength and capillary potential of the soil-cement mortar as needed.

Charts 2.1 and 2.2 are plots of the compressive strength (in psi) *vs*. cement content of soil-cement mortar samples prepared using soils from the six locations at Chaco Canyon (Chart 2.1) and the four locations at Bandelier (Chart 2.2). Mortar strength increases by a factor of three in the range from 9% to 20% cement content (up to ~450 psi) in the case of the Chaco soil-cement mortars. The corresponding increase for the Bandelier soil-cement mortar samples is a factor of five (up to ~ 800 psi). Higher mortar strength was not considered to be a potential threat to original masonry in this case because the compressive strength varies from 1000 to over 10,000 psi for Chaco stone and from 400 to over 10,000 psi for Bandelier stone.

Chart 2.1. Compressive Strength - Chaco Soil-Cements (Fenn 1978).

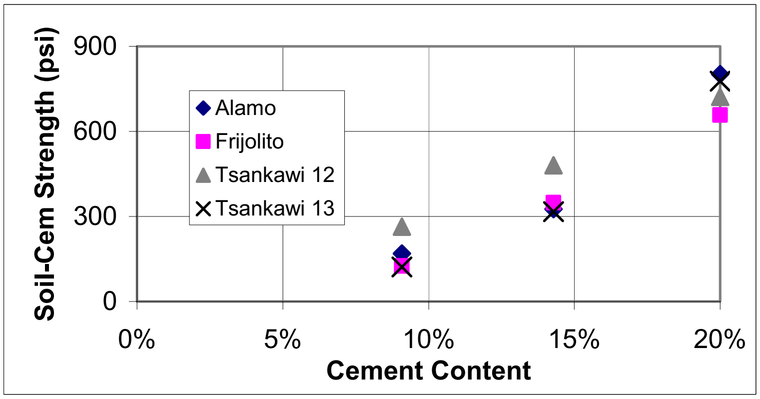
% Cement
20%
14%
9%



Compressive strength of mortars is plotted vs. cement content of soil-cement mortar samples prepared using soils from the six locations at Chaco Canyon.

Chart 2.2. Compressive Strength - Bandelier Soil-Cements (Fenn 1978).

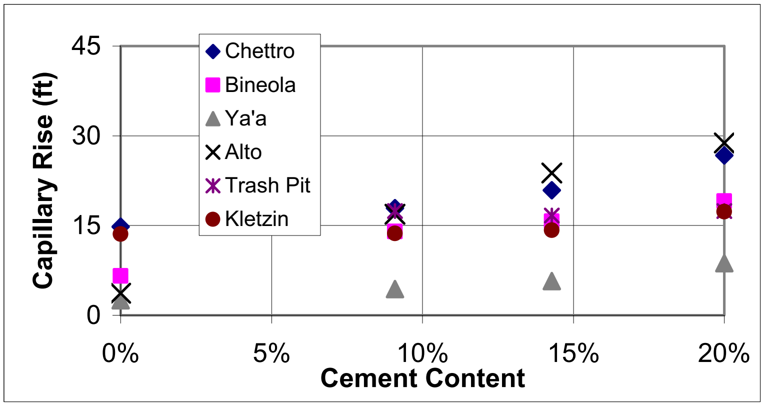
% Cement
20%
14%
9%



Compressive strength of mortars is plotted vs. cement content of soil-cement mortar samples prepared using soils from the four locations at Bandelier.

Chart 2.3. Capillarity - Chaco Soil-Cements (Fenn 1978).

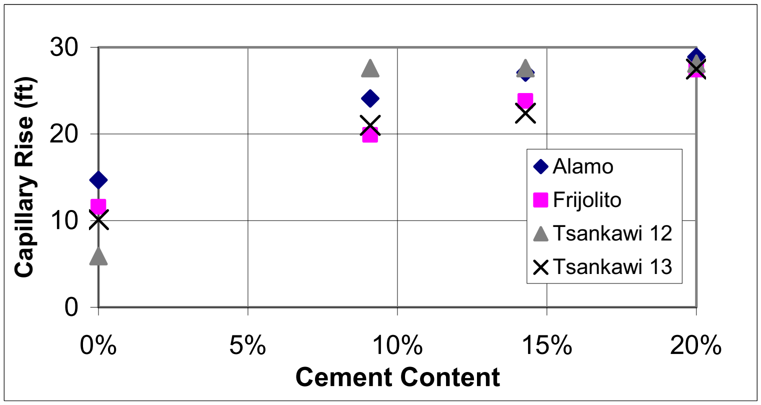
% Cement
0%
9%
14%
20%



Capillary rise of mortars is plotted vs. cement content of soil-cement mortar samples prepared using soils from the six locations at Chaco Canyon.

Chart 2.4. Capillarity - Bandelier Soil-Cements (Fenn 1978).

% Cement
0%
9%
14%
20%



Capillary rise of mortars is plotted vs. cement content of soil-cement mortar samples prepared using soils from the four locations at Bandelier.

Charts 2.3 and 2.4 are plots of the measured capillary rise (in ft) *vs*. cement content (%) of soil-cement mortar samples prepared using soils from the six locations at Chaco Canyon and the four locations at Bandelier, respectively. Measurements of capillary rise were also performed on un-amended mortar samples (0% cement). Capillary rise increases by a factor of three in the range from 0% to 20% cement content (up to ~30 ft) using both Chaco and Bandelier soils.

The previous research on soil cement-mortars indicates that the use of amended soils as replacement bedding, capping and pointing mortars at archaeological sites can provide effective solutions to stabilization and maintenance of historic and ancient structures. Successful soil-cement formulations must be based on tested properties of soil mixtures and on measured characteristics determined by geological parameters at each site. Optimization studies are required to determine the ideal soil-cement mix for stabilization mortars at each site. Such studies will also serve to document site characteristics (soil and stone properties), which will help to avoid future damage from poorly matched mortar/stone materials.

Chapter 3 – Characterization, Testing, and Materials

3.1 Soil Characterization

Where possible, all tests selected for soil characterization were conducted according to standards established by the American Society for Testing and Materials (ASTM). Certain soil properties such as microstructure, soluble salt content, acid-soluble content, and mineralogy that are not specified by American testing standards were also tested.

Each of the soils used in the mortars were characterized according to the following parameters:

- Color
- Particle size distribution
- Soil particle description (and soil texture)
- Atterberg limits (liquid limit, plastic limit, and plasticity index)
- Soil density
- Qualitative soluble salt analysis
- Qualitative organic content analysis
- Carbonate (acid-soluble) content
- pH

Each soil was also analyzed by X-ray diffraction for clay mineralogy.

3.1.1 Soil Characterization Description

Color - Soil color was measured in accordance with ASTM D1535-97, *Standard Practice for Specifying Color by the Munsell System*[23]. Soil colors were specified according to three criteria; hue, value and chroma. The hue notation establishes a soil color in reference to its closeness to the colors red and yellow. The value indicates the lightness of the soil. Chroma is meant to indicate the strength or neutrality of the soil color for its given lightness.[24]

Soils and sieved fractions were viewed under north-facing, indirect daylight illumination in comparison to the standard Munsell soil-color reference set. Establishing the color of each soil relative to the color standards of the Munsell System is a typical measure of soil characterization. The initial color characterization of the soils is an important point of comparison when color characterization is performed on the finished mortar samples created from those same soils by the addition of Portland cement.

Particle Size Distribution - Analysis of soil particle size distribution was performed according to ASTM D422-63, *Standard Test method for Particle-Size Analysis of Soils*. Also referenced is the ASTM C136-01, *Standard Test Method*

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[23] "D1535-97, Standard Test Method for Specifying Color by the Munsell System", (Philadelphia: ASTM, 1998).

[24] *Munsell Soil Color Charts* (1988).

for Sieve Analysis of Fine and Coarse Aggregates. Particle size designations established by ASTM were followed in this characterization.[25]

Gravel	76.2 mm – 4.75 mm
Coarse Sand	4.75 mm – 0.075 mm
Fine Sand	0.075 mm – 0.02mm
Silt	0.02 mm – 0.002 mm
Clay	<0.002 mm

Individual soil characterizations included in Appendix A illustrate the distribution of the soil fractions based on these designations for each type of soil used. The test method utilizes numbered sieves to collect particles larger than 75 µm (gravel and sand) and sedimentation with a hydrometer to account for particles smaller than 75 µm (silt and clay).

Figure 3.1. ASTM sieve stack and mechanical sieve shaker.

Samples of the oven-dried soils were soaked overnight in a 4% sodium hexametaphosphate solution. This acted as a dispersing agent for the clays in the soils, which clump together when wet, to assure a complete separation of clay particles in suspension. Following the overnight soaking, the samples and solution were agitated for 15 minutes with magnetic stirring bars and then sieved wet through a 75 µm (0.075 mm) sieve. The liquid suspensions containing the >75 µm soil fractions that had passed through the

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[25] “D653, Standard Terminology relating to Soil, Rock, and Contained Fluids”, (Philadelphia: ASTM, 1998).

sieve were poured into 1000 ml glass sedimentation cylinders. The fractions of the samples retained on the sieve were oven dried and then mechanically sieved through a set of soil sieves. The fine fractions of the samples (those fractions that passed the 75-µm sieve) were added to the sedimentation cylinders. Deionized water was added to the cylinders to bring the level of the suspension to 1000 ml. The cylinders were then capped and agitated in order to bring all settled particles into suspension. Hydrometers were inserted into the suspensions and readings were taken at regular intervals over the following 96 hours.

Figure 3.2. Soil sedimentation cylinders with control cylinder on left.

The sedimentation procedure is theoretically based on Stokes' Law, the premise of which is that the square of the diameter of approximately spherical particles is proportional to the particles' terminal velocity, i.e., the constant speed that a falling particle reaches when upward drag or, in this case, fluid resistance matches the force of gravity, halting acceleration. While clay particles are not spherical, Stokes' law can be applied to their fall through liquid to approximate the various sizes of the particles in the clay fraction of a soil.[26] Sedimentation can, therefore, be a fairly accurate method of determining size distribution among clays.

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[26] Jeanne Marie Teutonico (1988), p. 83.

As another standard component of soil characterization, particle size distribution can indicate, to a degree, the suitability of soil or aggregate for use in mortar. The test method yields quantitative data that can be expressed as ratios of one particle size to another. A well-graded soil or aggregate, one that contains equal proportions of multiple particle sizes, is well suited for use in a mortar because naturally occurring voids between larger particles may be occupied by smaller particles, ensuring a more homogenous and consistent mortar. The sedimentation procedure for particles smaller that 75 μm can aid in the determination of the presence and quantity of clays in soils, as clay particles are in the smaller ranges of size.

Soil Particle Description - The soil particle description is a qualitative method of soil characterization that can provide a good general overview of the physical characteristics of the soil. The soil samples in sieved fractions were viewed under reflected light with a Nikon SMZ1 stereoscopic microscope. Particles in the soil fractions were rated on the bases of particle size, Munsell Color, sphericity, roundness, and sorting (how well or poorly graded each fraction appeared). The presence or absence of visible organic content was also noted.

Atterberg Limits - The Atterberg, or liquid and plastic, limits of the soils were determined according to ASTM D4318-00, *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. The determination of the liquid and plastic limits of the soils is a particularly important step in the soil characterization. The two properties serve as indicators of a soil's ability to retain water. The liquid limit of the soil will indicate the point at which a soil, when mixed with water, has physical qualities closer to those of a liquid than a solid. The plastic limit test uses soil samples that have been mixed with water until they have reached plastic consistency and assesses the point at which, through loss of water into the surrounding environment, the samples lose plasticity. These data can then be used to calculate the plasticity indices of the soils. The plasticity index of a soil is an expression of water content in soil mixtures with plastic qualities and is calculated by subtracting liquid limit value from plastic limit value of a soil.[27]

Figure 3.3. Casagrande device with grooving tool.

In testing for liquid limits, soil samples were mixed with enough water to form a paste of plastic consistency. A portion of this paste was then applied to a Casagrande device. The paste was spread across the lower half of the bowl of the device and a groove was scored over the width of the spread, from front to back. The bowl of the device was then repeatedly dropped against the base by turning the crank located at the back of the apparatus, causing the two halves of the spread to move together until the groove closed over a length of 13 mm. A portion of the spread was then removed from the bowl, weighed, and dried. The procedure was then repeated three times

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[27] "D4318-00, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils", (Philadelphia: ASTM, 2000).

with the remainder of the soil paste, with water being added to the soil during each repetition. The water content of the sample taken for drying after each trial was based on the difference between the dry and wet weights of the sample and was calculated as a percent of the dry weight of the sample. The water contents for all trials were then plotted semi-logarithmically against the number of drops required to close the groove for each trial. A best-fit straight line was drawn through the plotted points. The moisture content at intersection of this line, also called the “flow curve”, with an ordinate of 25 drops was established as the liquid limit for the soil.[28]

In testing for the plastic limits, soil samples were mixed with water until their plasticity became sufficient for a portion of a sample to be hand-rolled into a round ellipsoidal mass without sticking to the palm. This mass was then rolled against a flat surface into a thread with a rough diameter of 1/8 of an inch. The thread was then compacted and reformed into the ellipsoidal shape. This rolling process was repeated until the soil thread crumbled before reaching 1/8” in diameter due to evaporation of water from the mass. At this point the sample was weighed and dried. The test was repeated three times afterward for each soil. The plastic limit was then calculated (and expressed as a percent) for the soil mass tested in each trial as the mass of water lost divided by the dry weight of the soil. The plastic limits for all trials were averaged to yield the plastic limit for the soil.

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[28] Jeanne Marie Teutonico, (1988), p. 107.

The plasticity index of each soil was calculated by subtracting the soil's plastic limit from its liquid limit. Soils for which either the liquid limit or the plastic limit (or both) cannot be calculated are regarded as non-plastic. The plasticity index of a soil is largely relative to the clay content in the soil, and a higher plasticity index (indicating high clay content) is indicative of greater strength capabilities in the soil.[29] This information can aid in the knowledge of which soils are suitable as building materials. The liquid and plastic limits of soils can also be significant in determining the amount of water necessary to mix with the soil/cement mixtures when creating mortar samples. The results of these tests can also be used in expressing the relative consistency of the soils and in determining, to an extent, the weathering characteristics of some clay soils.


Figure 3.4. Soil slurries during deairation.

Soil Density - The density of the soils was determined according to ASTM D854-00, *Standard Test Methods for Specific Gravity of Soils by Water Pycnometer*. The calculation of density requires a fairly precise knowledge of the volume of a volumetric flask or equivalent container. Soil was added to this container along with deionized water and agitated to form a slurry. This was boiled for a period of two hours to remove air from the mixture. Following the boiling period the container was filled with deaired water that was boiled prior to the test to remove entrained air bubbles in

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[29] *Ibid*, p. 106.

order to ascribe to it an accurate mass density for a given calibration temperature. A data table containing expressions of the mass densities of deaired water at various temperatures can be found in ASTM D854.[30] After cooling to room temperature, the soil and water mixture was put in a closed chamber overnight to attain thermal equilibrium. The container was then weighed and the density of the soil calculated based on the weight of the soil/water mixture at the thermal equilibrium temperature, the weight of the same container filled with only deaired water at the equilibrium temperature, and the weight of the oven-dried soil sample. The density of the soils is used in the calculation of soil particle size distribution as specified in ASTM D 422-63.

Qualitative Soluble Salt Analysis - The presence of soluble salts in the soils was tested for using ion test strips. The species of salts tested for were chlorides and sulfates as these are aggressive salts that are commonly found in saline southwestern soils. Merck - Merckoquant Sulfat test strips were used to test for the presence of sulfate (SO_4^{-2}) ions. Hach – Titrators for Chloride were used to test for the presence of chloride (Cl^-) ions. Samples of each soil (10 g) were soaked for three hours in 10 ml. of deionized water to bring any soluble salts into solution. Test strips for chloride and sulfate ions were then immersed in the solutions and observed for color changes in the indicators on the strips. Specific changes in the color of the indicators are correlated to varying ranges of

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[30] "D854-00, Standard Test Methods for Specific Gravity of Soils by Water Pycnometer", (Philadelphia: ASTM, 2000).

ion species concentration in the solutions represented in parts per million. Because the colors of the test strips only indicate ranges in which ion concentrations fall, this method does not provide a full quantitative analysis, but noticeable amounts of significant salts in the solutions can be suggestive of important soil characteristics such as ion exchange capacity. The presence of high amounts of salts in soils used for repair mortars can also result in premature deterioration of the building material due to salt crystallization.

Organic Content - The organic content of the soils was determined according to ASTM C40-99, *Standard Test Method for Organic Impurities in Fine Aggregates for Concrete*. The express purpose of this test is to examine fine aggregates to be used in concrete for the presence of organic material in amounts that might affect the setting capabilities, strength and overall performance of concrete. The application of this test to soils intended for use in mortars was considered since most local soils selected for stabilization mortars will contain a certain amount of organic impurities that might make them unsuitable for use. Because all soils contain some organic content, eliminating soils on the basis of organic impurity is impractical. The results of this test, therefore, are meant to serve as an indication or as explanatory evidence for certain performance characteristics exhibited by mortars that utilize these soils.

Samples of the three soil types were submerged in a 3% sodium hydroxide (NaOH) solution to suspend organic material present in the samples in the supernatant liquid above the soil in the flasks. The color of the supernatant liquid was compared to a standard color solution of reagent grade potassium dichromate ($K_2Cr_2O_7$) dissolved in concentrated sulfuric acid at the rate of 0.25 grams $K_2Cr_2O_7$ per 100 ml of acid. A color lighter than that of the standard solution indicates a negligible amount of organic material present in the soil sample while degrees of color in the supernatant liquid that are darker than the standard solution indicate the presence of significant organic content in the soil.

Carbonate (Acid – Soluble) Content - The carbonate content of the soil samples was tested using digestion by acid (15% hydrochloric acid solution). This is an adaptation of a standard gravimetric mortar analysis procedure. Expansive clays, smectite in particular, are rich is calcium, (usually present as carbonate). Many non-expansive clays such as chlorite, illite, and kaolinite also contain calcite (calcium carbonate), though in minor amounts. Smectite and mixed layer illite/smectite are common components of many Southwestern soils.[31]

Spot tests were performed on the soil samples to determine if they had any noticeable carbonate content. A few drops of acid solution were combined with a small quantity of soil. If effervescence (indicating production of CO_2 gas) was observed, a full acid digestion was then performed on the sample as follows. The soil samples were dried to constant mass, weighed, and submerged in 15% HCl. The mixtures were agitated overnight with magnetic stirring bars, then diluted with deionized water and filtered. The filtered samples were then dried

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[31] George S. Austin (1990), p. 419.

and weighed, and the reduction in mass due to the dissolution of carbonate material and emission of CO_2 was expressed as a percent of the original sample weight.

The presence or absence of a significant carbonate fraction in any of the soils can partially suggest the environmental response of the soil when used in mortar, particularly in and acid environment. The presence of natural calcite in many southwestern soils makes the test for carbonate content fairly important. Naturally occurring calcite (also known as caliche) is thought to act as a binder in many soils used for making adobe. The presence of this mineral in the tested soil samples can potentially foretell some of the performance characteristics to be observed in the mortars.

pH - Soil pH was measured in accordance with ASTM D4972-95a, *Standard Test Method for pH of Soils*. The analysis of soil pH can help to determine the content of soluble minerals in soils as well as the degree of ion mobility in the soils. The test was conducted using an Omega PHH-60 ms/ PHH 60 TDS pH conductivity meter on soil samples suspended in deionized water and in a 0.01 M calcium chloride ($CaCl_2$) solution. A phosphate buffer solution was used to determine a known pH for purposes of comparison with those of the soil samples measured in water and $CaCl_2$. Suspension of the soil samples in both media was required to fully characterize the soils' pH. Because pH testing on water-based solutions can result in dilution, $CaCl_2$ solution test was required for comparison and yielded lower pH values for each solution because aluminum ions (common in most clays), when bound to chlorine, react with water molecules to form an acidic, rather than neutral solution (hydrolysis).[32]

X-ray Diffraction - X-ray diffraction (XRD) is a useful analytical technique for determining the mineralogy of clays in the soil. Other methods of analysis such as scanning electron microscopy (SEM) and thermal analysis have applications in this context, but XRD is probably best suited to soil analysis because of the clay content of the soils. Clay minerals are crystalline in nature. The inter-molecular spaces within the crystal grains are nearly the same as X-ray wavelengths. By directing X rays through a prepared soil sample and monitoring the diffraction of the rays, the patterns of diffraction observed can be cross-checked with those of known minerals and the clay minerals thus identified.

3.2 Mortar Formulation and Sample Preparation

The mortars prepared for this research program consisted of two different formulations (with variable cement components) for each soil being tested. The following table contains the mortar formulations in volumetric proportion:

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[32] "D4972-95a, Standard Test Method for pH of Soils", (Philadelphia: ASTM, 1995).

Table 3.1 - Cement-Amended Earthen Mortar Formulations

Sample (soil) Designation	White Portland Cement (by volume)	Soil (by volume)
Bandelier 1 (B1)	1	3
Bandelier 2 (B2)	1	6
Chaco 1 (C1)	1	3
Chaco 2 (C2)	1	6
Salinas 1 (S1)	1	3
Salinas 2 (S2)	1	6

3.2.1 Mixing and Curing of Mortars

The mixing of stabilization mortars in the field seldom adheres to standard procedure. In addition to the varying preferences of masonry personnel for mortar consistency, the varying behavior and capacity for water-absorption of soils used for stabilization mortars makes attempting standard procedure somewhat impractical. In the same regard, the mixing of the mortar formulations for this testing program was, to an extent, a matter of trial and error. While standard practice was followed for the actual mechanical mixing of the mortars, determination of the appropriate water content for each soil-cement mixture was ultimately a matter of the expectations for the workability of the mortars, once they were mixed. The optimal working properties decided upon for laboratory use were that the mortars be wet enough to have a thoroughly plastic consistency, yet without having elastic properties that would cause them to resist being molded with planar surfaces. Overly wet mortars tend to bulge outward, or slump, when molded and appear to have a high surface tension that makes flattening the exposed surfaces difficult.

The high clay contents of the Chaco Canyon BLM Quarry soil and the Mountainair local quarry soil used by Salinas Pueblo Missions assured that these mortars would have appropriate adhesive capabilities when mixed to plastic consistency. Therefore the common practice of judging a mortar’s optimal consistency by its ability to stick to the inverted surface of a putty knife or trowel was not applied to mortars formulated with these soils. The comparatively low clay content and well-graded aggregate of the Garcia Landscape Materials Blend currently used at Bandelier for stabilization allowed for the mortars formulated with this soil to have many properties similar to those of non-soil-based mortars. The fresh mortars mixed with this soil were far less paste-like in consistency than those mixed with soils from the other two parks, and so the optimal consistency of these mortars was best determined through observation of their adhesion to an inverted putty knife in addition to their plasticity and non-elasticity.

Test batches of each formulation were mechanically mixed with deionized water added incrementally until the mortars were judged to have optimal consistency. The additive volumes were recorded for use in the sample batches of each mortar. The mortars were machine mixed, molded, and cured according to ASTM D1632-96, *Standard Practice for Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory* and ASTM C305-99, *Standard practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency*.

The mortars were mixed using a Hobart C-100, 3-speed mechanical mixer. Deionized water was first introduced into the mixing bowl, and the binder (Lehigh White Portland Cement Type 1) was added to it. The combination of water and cement was mixed at slow speed for 30 seconds. Soil was then added to the bowl over the next 30 seconds, still mixing at slow speed. The mixer was then stopped and reset to medium speed and mixing resumed for another thirty seconds. The mixer was stopped again, the sides quickly scraped with a rubber spatula and the bowl covered with plastic for of 1

Figure 3.5. Hobart C-100 mechanical mixer.

½ minutes after which mixing at medium speed was resumed for 1 final minute.[33] The wet mortar was immediately molded after mixing. The molded samples were placed in a tented baker's rack between pans of water where the relative humidity was maintained at or near 90%. Molded samples were removed from their molds one week after being placed in the tented rack and allowed to cure in the tent for the remainder of a 28-day period.

3.3 Tests on Earthen Mortars

Laboratory testing of prepared mortar samples was performed in accordance with American testing standards (ASTM) as well as with Italian (NORMAL), and International (RILEM) standards. One test for the erodability of the finished mortar samples was taken from CRATerre, the International Center of Earth Construction. Testing protocols for ASTM standards have been arranged specifically for the testing of soil-cement mixtures in many cases. This is not true in all cases, however. Where testing standards designed specifically for the testing of soil-cement mixtures do not exist, other standards – usually those for the testing of hydraulic cement mortar properties – will suffice, though some adjustments may be made to ensure their suitability to the testing of soil cement formulations. Table 3.2 lists standard test methods signifying the critical properties desired from stabilized mortars and specifies the samples used.

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[33] "C305-99, Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency", (Philadelphia: ASTM, 1999).

Table 3.2 - Mold and Sample Schedule for Cement-Stabilized Earth Mortars

Test	Standard	Mold Shape	Mold Size	Number of Samples per Formulation	Total Number of Samples
Setting Time	ASTM C191-99	Vicat (Conical)	70 mm base diameter, 60 mm top diameter, 40 mm depth	3 samples for each of 6 formulations	18
Modulus of Rupture	ASTM D1635-00 (modified) ASTM C192-00 (prism)	Prism	1’ x 1” x 4”	3 samples for each of 6 formulations	18
Splitting Tensile Strength	ASTM C496-96	Cylinder	2” diameter x 4” depth	3 samples for each of 6 formulations	18
Water Vapor Transmission	ASTM E96	Cylinder	1 ½ ” diameter x ½” depth	3 samples for each of 6 formulations	18
Water Absorption/	NORMAL 7/81	Cube	2”	3 samples for each of 6 formulations	18
Drying Index	NORMAL 29/88	Cube	2”	3 samples for each of 6 formulations	18
Frost Resistance	RILEM V3	Cube	2”	3 samples for each of 6 formulations	18
Erodability	CRATerre Drop test	Cube	2”	3 samples for each of 6 formulations	18

3.3.1 Earthen Mortar Tests

The following tested properties were deemed to be critical to field performance of earthen stabilization mortars:

- Setting time
- Water absorption capacity
- Drying behavior
- Freeze/thaw sensitivity
- Water vapor transmission
- Erodability (mechanical resistance to falling water)
- Modulus of rupture
- Resistance to shear forces (splitting tensile strength)

In addition to these properties, Munsell color ratings were ascribed to each formulation so that color change caused the addition of white Portland cement could be noted. The setting time for each formulation was also tested as the information is important in the consideration of the working properties of the mortars.

Time of Setting - The determination of the time of setting for the mortars proceeded according to ASTM C191-99, *Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle*. This test is used to determine a nominal time period after which hydraulic cement mixtures can be expected to harden and, in this case, to establish a comparison between the hardening times required by each soil-cement formulation being tested.

Figure 3.6. Vicat Apparatus with ring mold and sample.

To prepare the samples for this analysis, three samples of each mortar formulation were prepared. Each sample was formed into a loose ball and tossed from one hand to the other six times, then pressed into a ring mold without being compacted. The conical ring mold has a base diameter of 70 mm and a rim diameter of 60mm. Molded samples were set on Plexiglas bases and tented in the baker's rack for 30 minutes at a prescribed relative humidity (RH) of 90%.[34] Following this initial period, samples were set beneath a Vicat apparatus. This device consists of a 1 mm needle attached to a penetrometer able to indicate the extent of the needle's penetration into the sample to a depth of 40 mm (the depth of the ring mold). The Vicat needle is used to vertically pierce the sample at regular time intervals until the setting of the mortar impedes the depth of the needle's

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[34] "C191-92, Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle", (Philadelphia: ASTM, 1999).

penetration. Following the 30-minute tenting period, samples were tested every 15 minutes for penetration depth until the needle could not penetrate the surface of the sample. The application of this information can be very useful in laboratory testing and in field work. Knowledge of the set time for any mortar can indicate to lab or field workers how long the mortar can be expected to maintain plastic consistency and workability. The knowledge of what set properties to expect from a mortar can influence how it is applied in the field, which may include situations where climatic conditions or other variables require mortars that harden quickly.

Color - The color of the set mortars is determined in accordance with ASTM D1535-97, Standard Practice for Specifying Color by the Munsell System. The reapplication of the Munsell-System-based color test to the mortar samples provides for comparison with the results of the color analysis done on the component soils used to make the mortars. The addition of grey and white Portland cement to soil mortars can alter the color of the soils significantly. This color alteration can be important in the context of the stabilization of Puebloan structures, where visual uniformity between original and stabilization materials is often desired. In determining the appropriate mortar to use for particular stabilization needs, one factor is always the matching of mortar color to some standard material. While this research will not attempt to perform color matching by the use of additive colorants for mortar mixes, comparing colors of soils to those of the mortars made from them and to the materials selected by each of the national parks for color matching can provide good information as to what changes in color can be expected from a given combination of soil and cement and what steps, if any, are necessary to obtain a desired mortar coloration.

Water Absorption - The sensitivity of the mortars to the exposure to water was tested according to NORMAL 7/81, *Water Absorption by Total Immersion*. The test for water absorption is designed to simulate the effect over time of repeated exposure of mortars to liquid water. The test was performed on hardened, molded soil-cement specimens. The molds used for the test samples were wooden 2-inch cube molds treated with mineral oil prior to the molding of samples.

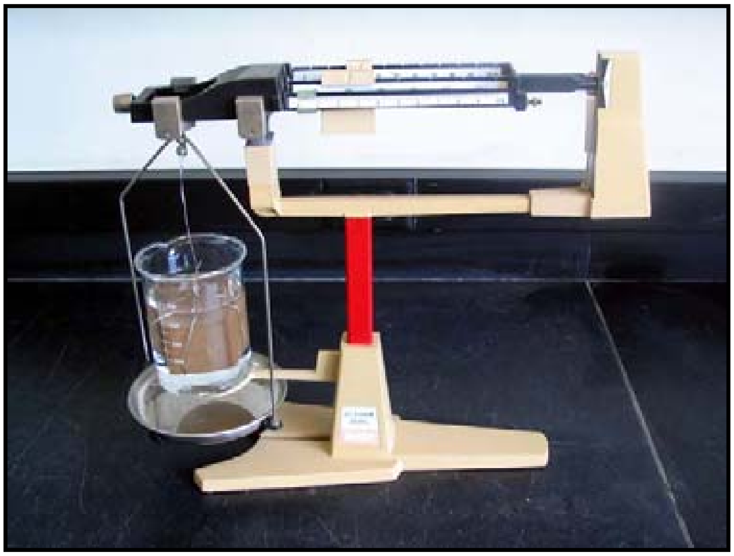

Figure 3.7. Triple-beam balance for hydrostatic weighing of samples.

Three samples for each mortar formulation were oven-dried to constant mass and then submerged in room-temperature deionized water. The wet samples were quickly surface-dried and weighed at intervals, until their changes in mass due to water absorption became asymptotic, that is, the weight change between two 24-hour readings was less than or equal to 1% of the weight of the sample. The samples were then hydrostatically weighed by suspending them from a wire in a beaker of deionized water. The beaker rested on a fixed pedestal and the wire hung from a triple-beam balance.

The hydrostatic weight allowed for a calculation of the apparent porosity of the samples.

The addition of the cement amendment to the mortars should, theoretically, impart a degree of hardness to them that will result in added resistance to the degradation caused by wetting and drying. The ultimate goal of the test is to identify a formulation that is resistant to this type of weathering but whose strength does not exceed that of the particular adobe or stone used with the mortar. As in most cases with these tests, a mortar that fails to resist the weathering effects of this test can still give an indication of what proportions of cement content might be necessary to achieve acceptable resistance to water. Another important application of this data is in the determination of the absorptive capacity of each formulation.

Drying Index - The test complementary to that of water absorption by total immersion follows NORMAL 29/88, *Measurement of the Drying Index*. The drying index is an expression of the time required by the saturated samples to become dry in air. After becoming saturated from total immersion, the samples were dried of standing surface water, placed in a climate controlled chamber at relative humidity of 50% and ambient temperature ranging from 25^{o} to 30^{o} C, and weighed at intervals similar to those followed in the total immersion test until their change (loss) in weight fit the following equation:

$$1.0 \geq [(M_0 - M_{i-1}) / (M_0 - M_i)] \geq 0.90$$

where M_0 = weight at time t_0, M_{i-1} = weight at time t_{i-1} and M_i = weight at time t_i.

The samples were then placed in a drying oven set at 60°C and dried until the weight change between two consecutive readings was less than or equal to 0.01% of the dry weight of the sample.

The drying index will indicate the ability of the formulations to release absorbed water, thereby removing the water from contact with original materials in building systems. It also indirectly describes wall durability as wet walls can be subject to collapse from plasticized mortars.

Figure 3.8. Climate-controlled chamber containing drying index samples.

Frost Sensitivity - The sensitivity of the mortars to freezing and thawing is determined according to RILEM standard V.3, *Frost Resistance*. This test is a means for evaluating the resistance of the mortars to particular environmental stresses. The method employs rapid freeze/thaw cycling to simulate potential field conditions that may occur over a longer period of time. The test was performed on hardened, molded soil-cement specimens cured for 28 days in the moist tent. Again, the molds used for the test samples were wooden, 2-inch cube molds pre-treated with mineral oil.

Figure 3.9. Frost resistance specimens in raised-bottom tray.

Three specimens of each mortar formulation were placed in plastic trays with a raised, perforated grid on the bottom, allowing for both easy drainage and for full exposure of all sample surfaces. The samples were submerged in room-temperature deionized water and allowed to absorb water for an initial period of six hours. The samples were then placed in a freezing cabinet for a fixed period of no less than six hours after which they are subjected to repeat cycling between the freezing cabinet and the room-temperature bath, the temperature of which fluctuated between 20^{o} and 30^{o}C. This cycle was repeated 15 times with both hydrostatic and in-air weights being taken during the thawing portions of the 4th, 8th, 12th and 15th cycles. The difference between the in-air and hydrostatic weights of the samples represents the samples' bulk volume. The final bulk volume of each sample expressed as a percentage of the sample's original bulk volume is regarded as a measure of the ability of the mortar formulation to resist degradation from freeze/thaw cycling. This test has applications similar to those of the water absorption test in determining the amount of cement necessary to impart resistance to weathering on the mortar.

Water Vapor Transmission - The permeability of the mortars to water vapor was determined according to ASTM E96-00, *Standard Test Method~~s~~ for Water Vapor Transmission of Materials*. The test allows for the determination of water vapor permeability as the amount of water as vapor that can pass through a certain distance of a mortar (or other material) over a set time as differing pressures on both sides of the material attempt to achieve equilibrium. The actual rate of water vapor transmission describes the constant rate of movement of water through a material with parallel surfaces within fixed climatological conditions. The mortar samples effectively act as a barriers sealed around the rims of a plastic beakers of water. As the water moves from the inside toward the outside of the container in response to changes in interior water vapor pressure, it must travel through the mortar samples. The transmission of water causes the beaker apparatus to change weight over time and these differences in the weight of the apparatus indicate the rate of transmission of the vapor.

Samples for this test were molded in sections of PVC pipe 1.5 inches in diameter and 0.5 inches in depth. The molds were treated with petroleum jelly prior to the molding of the samples to assure the release of the mortar coupons from the molds when setting was complete. Samples were cured in the moist tent for 28 days. Three samples of each formulation were tested.

Each sample was sealed around its outer diameter with electrical tape with both parallel surfaces left fully exposed. Tri-corner plastic beakers were filled with deionized water to a level no closer to the beaker rim than 0.75 inches.[35] Cotton lint was added to the water to deter the formation of water droplets on the exposed inner surface of the mortar samples, which would result in a spike in the rate of water vapor transmission. The mortar samples were then rested on the rims of the beakers and sealed around their edges with paraffin wax, creating an airtight chamber in the interior of the beaker. The assemblies were put inside a climate-controlled chamber wherein the relative humidity was maintained between 46% and 50% and the temperature varied from 28° to 33°C. The assemblies were weighed initially before entering the chamber and then subsequently once every 24 hours for 10 days.


Figure 3.10. Climate-controlled chamber with vapor transmission assemblies.

The results of this test serve as an indication of the potential compatibility of each mortar with the masonry systems for which it has been designed. Considering the propensity of any masonry system to be vulnerable at some point to the entry of water, it is essential that any materials added to the system

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[35] "E96-00, Standard Test Methods for Water Vapor Transmission of Materials", (Philadelphia: ASTM, 2000).

for stabilization or repair do not impede the egress of that water. The vapor permeability of each mortar type can suggest whether it is suitable for use.

Erodability of Mortar - The erodability of the mortars was tested according to the CRATerre water drop test originally developed to determine the effects of impacting water on the surfaces of compressed earthen blocks.[36] Adapting this test for evaluation of earthen mortars can similarly indicate the resistance of a mortar formulation to erosion and leakage when exposed to the direct impact of falling water. Although no published standard for this test method exists, the procedure has been described in detail in previous laboratory testing programs arranged for material testing at the University of Pennsylvania and is easily adapted to this program.

The molds for the samples used in this test were 2-inch, wooden cube molds pre-treated with mineral oil. Three samples of each formulation were tested in this procedure as well as three unamended samples (molded to the same dimension) of each soil. The results of this test are primarily qualitative in nature, because they are based on visual observation of the damage done to the specimens over the course of their exposure to the falling water. It was, therefore, imperative to have one set of specimens for each soil that would almost certainly sustain significant damage to use as a basis of comparison in the rating of the resilience of each formulation to impacting water fall.

Three laboratory ring stands were outfitted with burette clamps and three-prong extension clamps. The extension clamp on each stand held a Plexiglas

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[36] A. Douline (1990).

plate. A water bottle with a spigot at the base was set on each of the plates and a length of flexible rubber tubing attached to the spigot. A burette stopcock was fitted to the output end of the tube and fed into the barrel of the burette held to the stand by the clamp. The assemblies were then placed on a tall cabinet and the burettes adjusted to the recommended height of 2.5 meters above the floor.

Samples were arranged at the floor level in groups of three beneath the overhanging burettes (Figure 3.12). Each sample was supported by a test-tube rack nested inside of a bucket to catch runoff water. The bottles in the assemblies were then filled with deionized water and both stopcocks in each assembly were adjusted to distribute one drop of water per second. The burettes were thus filled at the same rate as they drained. The samples were exposed to the falling water across an approximately 1 inch area in the center of their exposed surfaces at the rate of one drop per second for a period of one hour (approximately 3600 drops), after which time the maximum


Figure 3.11. CRATerre Water Drop test array.

depth of erosion was recorded with a digital caliper accurate to 0.01 cm. The samples were photographed after the hour of exposure. The depths of erosion for the three samples of each unamended soil and soil-cement formulation were averaged and divided by the amount of elapsed time in minutes to determine the rate of erosion in cm/minute. While mortars used for pointing are not generally subject to receiving direct water fall, the knowledge of the resistance of any mortar to this type of deterioration is useful in evaluating the strength of the mortar via its endurance against one of the more damaging types of water-exposure. Because of the erosive capabilities of falling water, this test is also useful in the determination of minimal cement quantities required for amended mortars to effectively resist erosion.

Figure 3.12. CRATerre Water Drop Erosion test array in operation in the Architectural Conservation Laboratory

Modulus of Rupture – The modulus of rupture, or flexural strength, of the six mortar formulations was tested according to ASTM D1635-00, *Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third-Point Loading*. Sample sizes used were based on ASTM D192-00, *Standard Practice* *for Making and Curing Concrete Test Specimens in the Laboratory*, which specified a rectangular prism of 4 inches in length, 1 inch in width and 1 inch in depth. Samples for this test were molded in wooden molds pre-treated with mineral oil. Samples were cured in the moist tent for 28 days. Three samples of each mortar formulation were tested.

This test calls for the placement of the mortar test specimen in a machine-mounted bending apparatus. The specimen's width and depth were measured at the center of each specimen prior to the test. The beam-shaped samples were placed with each end on one of two raised seating points. The space between the points was 3 inches (specified as three times the depth of the sample).[37] Pressure was then applied through a blunted fulcrum from above the specimen at its middle continually and with increasing load strength. The loading was recorded at the specimen's breaking point as was the maximum deflection of the sample before breaking. The test is intended to determine the flexibility of a mortar as well as its resistance to bending. The test was conducted at the Laboratory for Research on

Figure 3.13. Instron Model 4206 set for three-point bending.

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[37] "D1635-00, Standard Test Method for Flexural Strength of Soil-Cement Using Simple Beam with Third Point Loading", (Philadelphia: ASTM, 2000).

the Structure of Matter (LRSM) at the University of Pennsylvania using an Instron testing machine model 4206 (electromechanical testing machine).

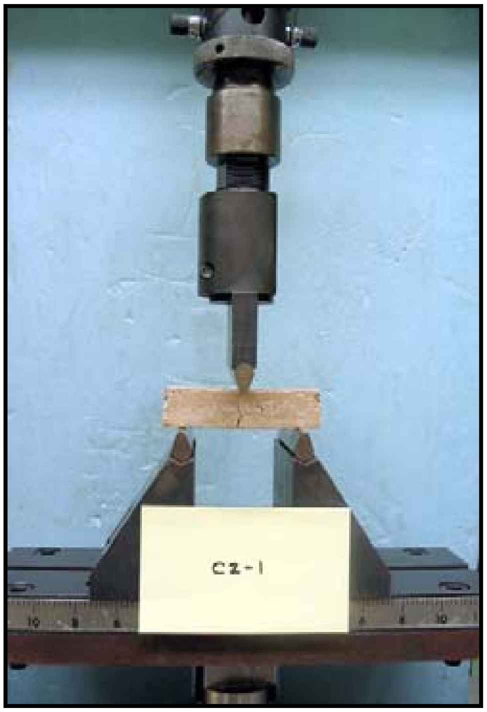

Figure 3.14. Sample failing under three-point bending.

Splitting Tensile Strength - The resistance of the finished mortars to shear forces was determined according to ASTM C496-96, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. ASTM C192, *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory* was consulted for the dimension of the samples. This test is designed for concrete but is adapted in this case for soil mortars. There is no real difference in the execution of the method but only in the materials used for the specimens. In response to the express desire on the part of the three Parks participating in this study, the nominal use intended for the mortars is as pointing mortars. Rather than a test for compressive strength alone, it was judged that an expression of splitting tensile strength of the mortars might more accurately reflect the stress that pointing mortars receive in use, as it is bedding mortars that come under direct compression. The samples used for the splitting tensile strength test are cylindrical, not cubical as are samples used to test for compressive strength. Though both tests put samples under compression, testing on cylindrical specimens induces tensile stress upon the plane in the specimen that bears the applied load.[38]

Cylindrical samples having a diameter equal to ½ of the samples' length were specified.[39] Sample dimensions of 2 inches for diameter and 4 inches for length were selected. Samples were molded in 4-inch sections of 2-inch diameter PVC pipe. The pipe molds were treated with petroleum jelly prior to the molding of the samples to insure easy removal of set specimens. The samples were cured for 28 days. Three Samples of each formulation were tested.

Figure 3.12. Instron Model 4206 set for compression.

Perpendicular diametrical lines were drawn on both ends of each sample. The diameter of each sample was measured to the nearest 0.01 inch at either end and at the middle, and these values were averaged. Two length measurements were made to the nearest 0.1 inch, and these were averaged as well. These

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[38] "C496, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", (Philadelphia: ASTM, 1996).

[39] "C192, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory", (Philadelphia: ASTM, 2000).

values are used in the calculation of splitting tensile strength. Two wooden bearing strips, having dimensions of 4 ½ inches for length, 7/8 inch for width and 1/8 inch for thickness, were cut for each sample. These bearing strips were placed on the top and bottom of each specimen, which was then positioned between the bearing block and compression cell of the compression testing machine. The sample was then oriented with the diametrical markings on both ends centered on and perpendicular to the bearing strips.[40] The test calls for the application of a continuous and increasing load to a cylindrical specimen until the specimen splits at which point the maximum load is recorded. This test was also conducted at the LRSM using the Instron 4206 testing machine.


Figure 3.13. Sample failing under compression.

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[40] "C496-96, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", (Philadelphia: ASTM, 1996).

3.4 Mortar Formulation Materials

The term soil-cement suggests a simple mixture of materials. However, the basis for the variability in performance of cement-stabilized earth mortars is the complex composition of their earthen components, which consist of numerous typologies all categorized under a blanket heading as soils. Additionally, cement is available in different varieties, most of which are commercially available. Thus it is necessary to discuss the basis for the selection of the materials used to formulate the mortars tested in this research.

3.4.1 Cement

The Type 1 White Portland cement used for testing is a fine white powder produced by Lehigh Cement Company. It was purchased in November 2004 at George F. Kempf Building Material Supply in Philadelphia. Type 1 specifications correspond to the requirements of ASTM C150 Standard Specification for Portland Cement. Type 1 Portland cement is “for use when the special properties specified for any other type are not required.”[41]

3.4.2 Soil

Loosely defined, soils are naturally occurring blends of sand, silt, clay, and (organic) plant litter. They comprise the particulate surface material found in any non-aquatic location on the earth. Numerous factors affect the exact composition

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[41] “C150-00 Standard Specification for Portland Cement,” (Philadelphia: ASTM, 2001).

of the soils in any particular region. These determining factors include local geology, climate, local vegetation, and land use.[42] The American Society of Testing and Materials (ASTM) has defined particle size classes which identify the major particle components of soils. They are gravel (76.2 mm – 4.75 mm), coarse sand (4.75 mm – 0.075 mm), fine sand (0.075 mm – 0.02 mm), silt (0.02 mm – 0.002 mm), and clay (<0.002 mm).[43] None of the soils used in this testing program contain notable fractions of the gravel-size category, and those found were removed prior to soil characterization and mortar testing.

Quartz is the dominant mineral component in the sand fractions of soils. Sand grains occur in varying degrees of roundness and sphericity depending upon fracturing and weathering. For use in mortars, soils with angular grains are considered to be optimal because the irregular sizes and shapes of the particles result in an interlocking effect within the matrix formed by the binder material. By contrast, rounded, evenly-sized grains, are less suitable as their surfaces can be prone to slipping when in contact with each other, resulting in weaker mortars overall.[44]

Silt and clay particles are typically grouped within the classification of "fines", being the smallest types of particles to be found in soils. Silt particles are primarily composed of weathered and/or fragmented quartz. Clays comprise the smallest particles found in soils. The basic components of most clays are aluminum silicates, and differentiation between clay types is determined by the

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[42] Ferguson (1992), p. 1.

[43] "D422, Standard Test Method for Particle-Size Analysis of Soils," (Philadelphia: ASTM, 1963).

[44] Ferguson, (1992), p. 2.

presence of additional minerals such as iron oxides, magnesium, sodium, and potassium, which cause variation in the electrochemical activity capacities of clay minerals.[45]

Three of the most common clay types are kaolinite, illite, and smectite. These occur in varying proportion (and often in combination) in the majority of soils. Of the three, kaolinite displays the greatest dimensional stability, with a low capacity for adsorption and cohesion as well as a low general plasticity in comparison to the other two types. Smectite displays the highest rate of dimensional variability and chemical activity of the three.[46]

The proportions and types of the different particles found in soils are determining factors, to an extent, of the stability that the soil can maintain under loading. Some of the characteristics that bear on this capability follow: Internal friction in a compacted soil mixture is

> …the internal resistance to sliding of one particle against another. Internal friction tends to be high in gravel and sand no matter what the moisture content. Internal friction tends to be low in clay but can vary greatly with the moisture content.[47]

Cohesion is an expression of the tendency for the particles in a soil to bind to each other because of “mutual attraction due to molecular forces and the presence of tensile moisture films.”[48] Quartz particles in soils are typically inert, and thus sandy soils tend to exhibit low cohesion. This can be true for certain

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[45] *Ibid*.
[46] *Ibid*.
[47] *Ibid*., p. 3.
[48] *Ibid*.

types of clay, however shrinking and swelling clays (particularly smectite) whose particles exhibit a high ionic exchange capacity, take and bind to water molecules readily as well as to each other in the presence of water. Soils containing this type of clay can be very cohesive, and their particles will remain tightly bonded even after the removal of water.

Plasticity is another important defining factor in the stability of a soil. This is the tendency of the soil as a wet mass to deform without crumbling and has bearing on soil-cement mortar application because the plastic texture of a soil will be suggestive of the consistency to expect from a freshly mixed mortar consisting of that soil. The amount of fine particles (silt and especially clay) in a soil is the determinant of the plasticity. The presence of dominant sand or gravel fractions in a soil tends to negate the plasticity as a result of interspersing a small amount of minute particles with a larger amount of inert grains.

The grading, or particle size distribution, of a soil is a key determinant of the soil's potential as a mortar component. Soils with a good distribution of particle sizes in the range of coarse sand as well as adequate proportions of both silt and clay are generally regarded as being well-graded, providing good potential plasticity and cohesion when wet, with enough inert particulate composition (sand and gravel) to control any shrinkage of clay fractions and provide internal stability to the binder matrix. Poorly-graded soils tend to display concentrations of certain, single-particle sizes/types. The general lack of variability in particle size in a poorly-graded soil results in mortars that have the positive working characteristics associated with the predominant particle fraction but not the complementary strengths imparted by other fractions. Such soils breed in weakness through overspecialization. A soil that is predominantly fine sand, silt, and clay, for example, might display good plasticity and cohesion as a mortar but it would probably also display low internal friction. The homogeneity in a binder matrix that formed in a mortar composed of this type of soil would render it weak in comparison with the more varied matrix that would form in a well-graded soil's mortar. It should be noted that the problems associated with poorly-graded soils can typically be remedied in the formulation of mortars through the addition of appropriate quantities of commercially available or naturally occurring aggregate.

The soils used in the mortar formulations that were tested in this research are those currently in use at each of the parks that participated in the project. The Bandelier soil is a mixture of three components purchased from Garcia Landscape Materials in Espanola, New Mexico. The proprietary classifications of the two soil components are "dirt" (67.5% sand, 17.5% silt, and 15.0% clay) and "clay" (90% sand, 5.0% silt, and 5.0% clay). The final component is a standard washed masonry sand. These three components are mixed in the volumetric ratio of 3:1:1, respectively, for testing purposes. The Chaco soil is a locally quarried soil taken from a Bureau of Land Management (BLM) quarry near the park site. The Salinas soil is also a local soil quarried in Mountainair, New Mexico. The particle size distribution curves for each of the soils are shown below in Charts 3.1-3.3. These can also be found in Appendix A.

The three soils all have distinct similarities in their profiles but they differ in their respective (and often crucial) particle size fractions. All three are potentially good candidates for use as mortars with cement amendments. The aforementioned differences in particle size distribution represent a range of soil properties that can directly affect strength, durability, permeability and plasticity of soil-cement mortars. Unamended, the durability of any one of the three soils as a mortar would be highly questionable. Due to the presence of clay and silt in all of the soils, the particle sizes of the smaller soil fractions fall outside of the parameters designated by ASTM C144 *Standard Specification for Aggregate for Masonry Mortar*. This is to be expected of natural soils, which are selected for use in stabilizing archaeological sites to maintain some measure of homogeneity with the sites' original construction materials.

Chart 3.1 Particle Size Distribution

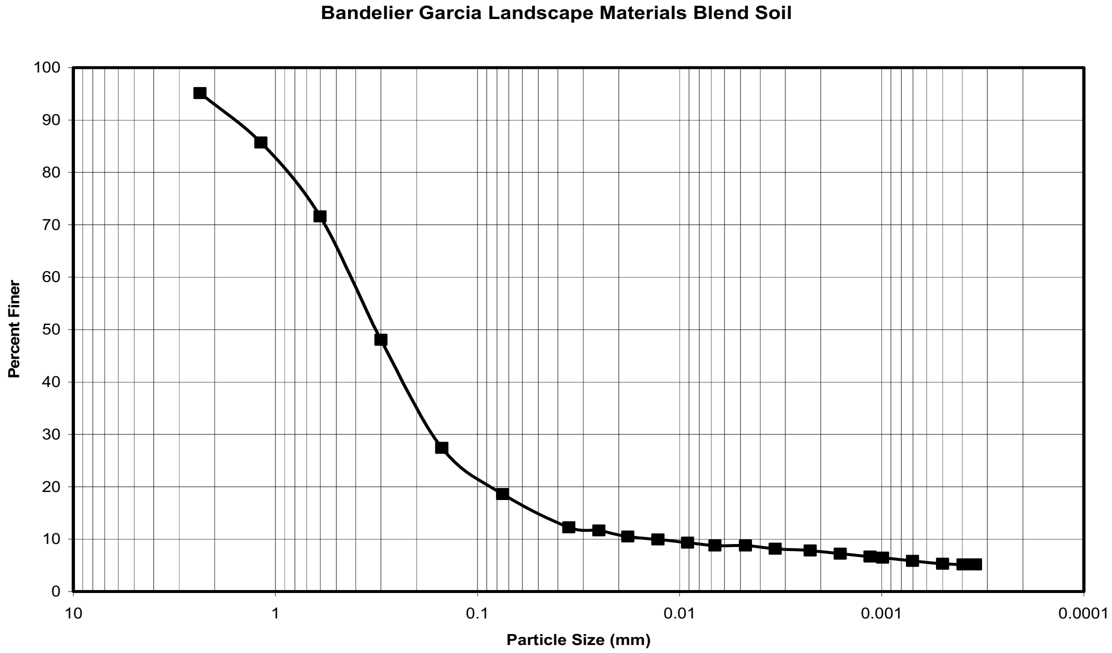


Chart 3.2 Particle Size Distribution

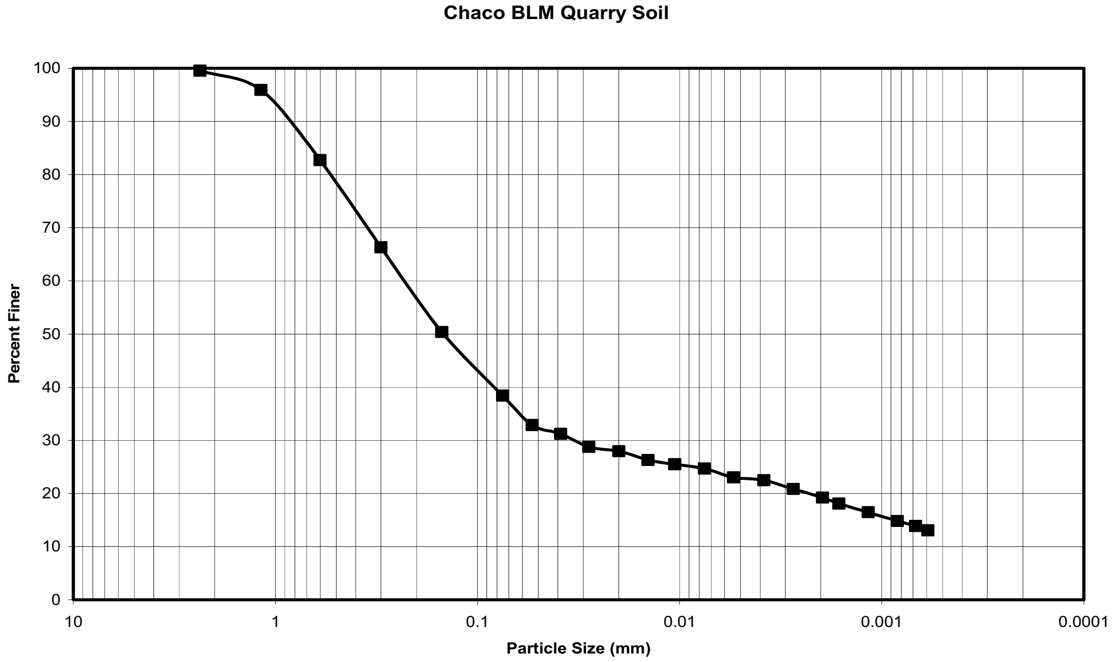
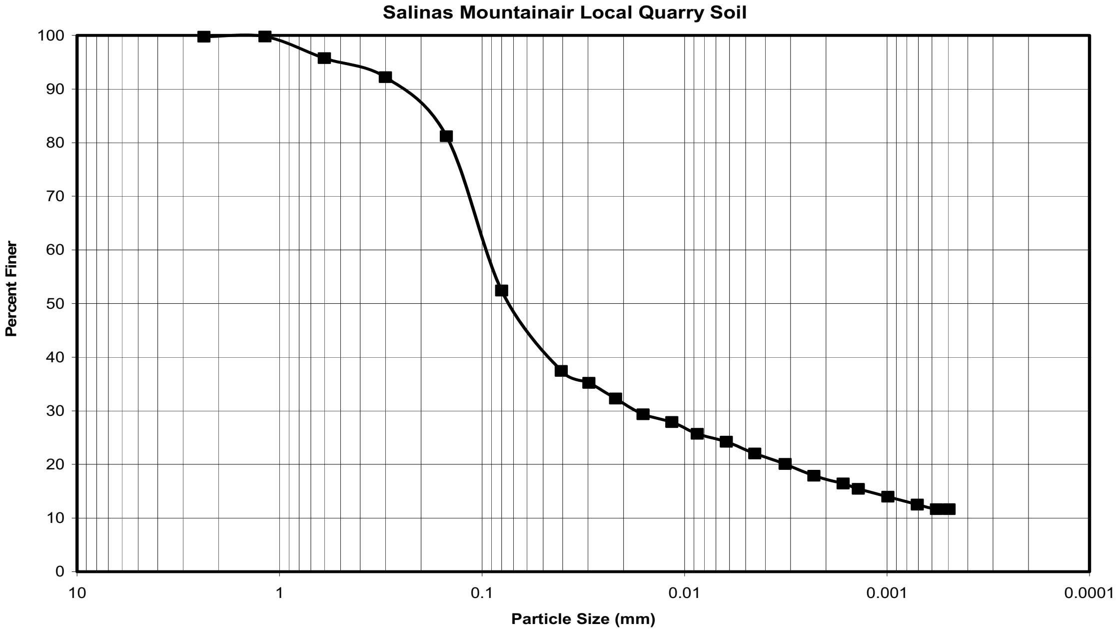


Chart 3.3 Particle Size Distribution



Chapter 4 – Test Results

4.1 Soil Characterization

Soil characterization summaries are presented as data sheets in Appendix A. These summaries combine pertinent information on the properties of each soil. This includes particle size distribution data presented in two formats. The first format is a semi-logarithmic chart with grain/sieve sizes plotted as ordinate against percent of the sample passing each sieve as abscissa. The second format for grain size distribution data is pie charts comparing grain size groupings by percent and using the ASTM particle size classifications of coarse sand, fine sand, silt and clay. Also presented on each characterization sheet are the soil's Atterberg limits (liquid limit, plastic limit and plasticity index), pH in water and in calcium chloride solution, Munsell color, percent carbonate (acid-soluble) content, soluble salt concentration, and density. Finally, each sheet includes a general descriptive notation of soil particles having greater size than 0.075 mm. The descriptive categories are particle size, shape and color. The format of the soil characterization data sheets follows that established by Robert Hartzler in his study of acrylic-modified earthen mortar.[49] Appendix B includes soil characterization data tabulated by characteristic.

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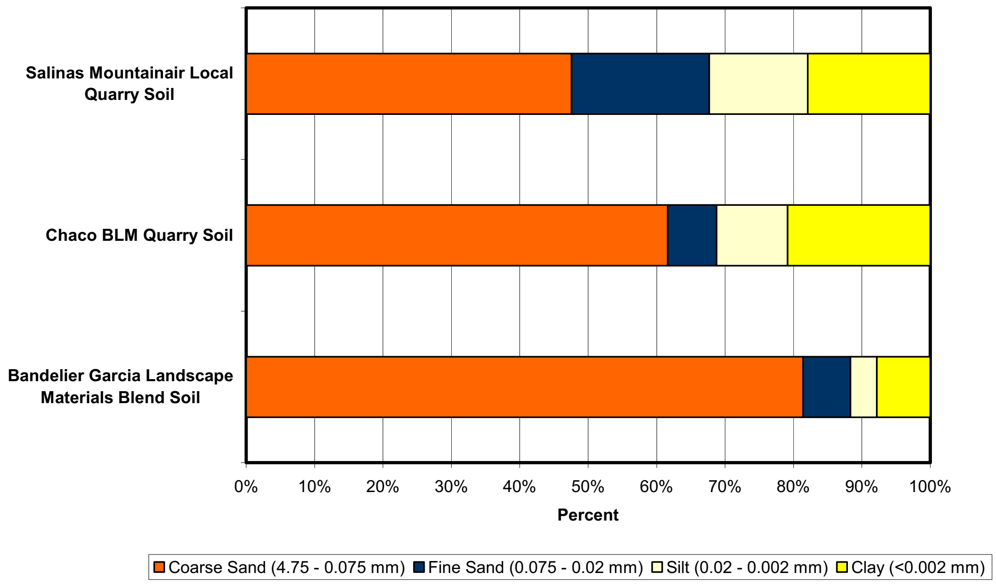
[49] Robert Hartzler (1996), pp. 79-95.

Color – The Bandelier Garcia Landscape Materials blend was brown with a Munsell rating of 7.5YR 5/4. The Chaco BLM Quarry soil was a light yellowish brown with a Munsell color rating of 2.5Y 6/3. The Salinas Mountainair local quarry soil was brown with a Munsell color rating of 7.5YR 4/4. The presence of quartz-grains in the Bandelier soil may have contributed to a general lightness in its value designation. The higher carbonate content in this soil was also a likely contributor to its lightness. The Salinas soil, by comparison was both darker in value and stronger in chroma than the Bandelier. It contained few large grains of any kind and had lower carbonate content than the Bandelier soil did, though the ratings for both soils fell within the Munsell range classified as brown.

Particle Size Distribution – Sieving and soil sedimentation confirmed the visual suggestion that both Chaco BLM Quarry soil and Salinas Mountainair local quarry soil had higher clay contents than Bandelier Garcia Landscape Materials blend soil. Coarse sand (4.75 – 0.75 mm) was noted in greatest proportion in the Bandelier soil, followed by Chaco, and Salinas lastly. This also confirmed earlier impressions of the soils based on their respective textures. The proportions of particles in each of the four main ASTM grain size categories for each soil are located below in Chart 4.1.

Chart 4.1. Particle Size Distribution



Soil Particle Description – Observation of the sieved fractions larger than 0.075 mm in each soil yielded general information about particle size distribution, roundness, sphericity, and color.

The Bandelier Garcia Landscape Materials blend soil contained a large amount of sand particles. Its components were two varieties of building soil (Garcia “clay”, G1, and Garcia “dirt”, G2) distributed by Garcia Landscape Materials in Espanola, New Mexico, blended with washed masonry sand in the volumetric proportion of 1 part G1 (“clay” – composed of 90% sand, 5% silt, 5% clay), 3 parts G2 (“dirt” – composed of 67.5% sand, 17.5% silt, 15% clay), and 1 part washed masonry sand. The particles of the blended soil were well distributed within the range of coarse-sand particle sizes (4.75 - 0.075 mm).

Coarse sand comprised 81% of this soil, 7% was fine sand, 4% was silt and 8% was clay. The particles were predominantly sub-rounded and sub-angular with notable angular components evident within some of the sieved fractions of the soil. Sphericity was medium to high in the particles of this size range. The color of many particles was white from quartz grains. Colors of the sieved fractions were predominantly brown and reddish gray resulting in a light brown color with a slightly reddish hue for the bulk soil.

The Chaco BLM Quarry soil particle size distribution was rated fair to poor among individual sieved fractions. Overall, particles in the soil were distributed fairly well in the four main size classifications, however the coarse sand fraction of this soil consisted predominantly of smaller particles with proportionately low amounts of coarse aggregate. The coarse sand component of this soil comprised 62% of the bulk sample. Fine sand made up 7% of the soil while 10% was silt, and 21% clay. Particles in sieved fractions of this soil ranged from well-rounded to sub-rounded with a generally high sphericity. Coloration of the sieved fractions was brownish gray and yellowish brown, giving the soil an overall light yellowish brown coloration.

The Salinas Mountainair local quarry soil had a generally poor particle size distribution among the coarse sand fractions. The soil contained virtually no coarse aggregate with the vast majority of coarse-sand particles being of the smaller diameters in the range of 0.15 – 0.08mm. The coarse sand component of this soil comprised 48% of the whole. Fine sand was 20%, and silt and clay were 14% and 18%, respectively. Particle sphericity was generally medium to high.

Coloration of all fractions was brown resulting in a strong brown overall coloration for the soil.

Tabulated notes on each sieved fraction of each soil are included in Appendix B.

Atterberg Limits – One of the three soils used in the earthen mortars, the Bandelier Garcia Landscape Materials blend, was designated as non-plastic. This soil did not contain enough clay for it to achieve a plastic consistency when wet, and thus neither a liquid limit nor a plastic limit could be calculated for it. The comparatively high clay contents in the other two soils allowed for the determination of both values for each. The following table lists these values and the plasticity indices of the soils. The table is also included in Appendix B.

Table 4.1. Atterberg Limits

Soil	Plastic Limit	Liquid Limit	Plasticity Index
Bandelier - Garcia Landscape Materials Blend	Indeterminate	Indeterminate	Non-Plastic
Chaco - BLM Quarry Soil	19.3	22.5	3.2
Salinas - Mountainair Local Quarry Soil	21.7	24.6	2.9

Soil Density – The densities of the soils used in the mortars tested were calculated as follows: Bandelier Garcia Landscape Materials blend soil was 4.20 g/cm^3, Chaco BLM Quarry soil was 2.68 g/cm^3, Salinas Mountainair local quarry soil was 3.25 g/cm^3. These values are reiterated in a table in Appendix B.

Qualitative Analysis for Soluble Salts – Analysis of soil/deionized water slurries with ion test strips showed no measurable concentrations of chloride or sulfate ions in any of the three soils tested.

Figure 4.1 Soil samples submerged in 3% sodium hydroxide solution.

Qualitative Analysis for Organic Content – Immersion of samples of the three soils in a 3% solution of sodium hydroxide (NaOH) revealed notable amounts of organic mater in both the Chaco BLM Quarry soil and in the Salinas Mountainair local quarry soil. This was indicated by the extremely dark and opaque color of the supernatant suspension above the soil level in the flasks containing these samples. The Bandelier Garcia Landscape Materials appeared to contain negligible amounts of organic material judging from the light, transparent coloration of the supernatant liquid in the flask.

The liquid in all three flasks was compared to the color standard solution which confirmed these findings. In comparison to the color of the color standard solution, supernatant liquids with lighter coloration than the standard are judged to have insignificant organic content while those with varying degrees of darker coloration are judged to have more than trace amounts.

Carbonate (Acid-Soluble) Content – Low to moderate effervescence observed during spot testing on all three of the soils confirmed the presence of some amount of carbonate material in each. Standard gravimetric analysis was performed on 25 g of each soil and revealed the following results, tabulated below:

Table 4.2. Carbonate Content

Soil	% Acid-Soluble
Bandelier - Garcia Landscape Materials Blend	5.60
Chaco - BLM Quarry Soil	2.40
Salinas - Mountainair Local Quarry	2.48

This data table is included in Appendix B along with sample weights prior to, and following acid-digestion.

Soil pH – All three soils were found to have relatively neutral pH yet also tending toward alkalinity. It was thought that soils quarried from areas with local deciduous plant growth might have been more acidic because plant litter from such vegetation has a tendency to acidify soils and numerous varieties of pine trees account for much of the indigenous plant growth in Northern New Mexico. If it is the case that any of these soils was quarried in proximity to such vegetation, however, there has not been any apparent acidification of the soils as a result.

Table 4.3. Soil pH

Soil	pH in Water	pH in $CaCl_2$
Bandelier - Garcia Landscape Materials Blend	7.5	7.4
Chaco - BLM Quarry Soil	8.1	7.7
Salinas - Local Quarry Soil	7.3	7.2

X-ray Diffraction Analysis – Analysis of the three soils by X-ray diffraction yielded the following results: The Chaco BLM Quarry soil and the Salinas Mountainair local quarry soil produced spectra that were identical, suggesting that these soils contain similar clays and their associated mineralogical parent materials. Both were very high in quartz (silicon dioxide, SiO_2). Also in high concentration was the clay mineral albite (sodium aluminum silicate, $Na(AlSi_3O_8)$), suggesting that the dominant clay in these two soils is kaolinite. Kaolinite is one of the most common clay minerals in soils, and its particles exhibit fairly high dimensional stability. Microcline (potassium aluminum silicate, $K(AlSi_3O_8)$), and muscovite (potassium aluminum silicate hydroxide,

$KAl_2(Si_3Al)O_{10}(OH)_2$) were also noted in the Chaco and Salinas soils in lesser quantities. These minerals suggest the presence of illite, a moderately dimensionally stable clay, in the two soils.

The Bandelier Garcia Landscape Materials blend soil also contained quartz as the dominant mineral. Albite (and, thus, kaolinite) appeared in the Bandelier soil as well in small quantities. This is consistent with the lower clay content observed in this soil compared to those of the Chaco and Salinas soils.

4.2 Earthen Mortar Testing

Results for earthen mortar tests are presented in terms of comparison between the two formulations tested for each soil. Since all formulations with the number 1 designation were mixed in volumetric ratios of 3 parts soil to 1 part white Portland cement, and all formulations with the number 2 designation were mixed in ratios of 6 parts soil to 1 part cement, results are also compared among the three number one formulations and among the three number two formulations.

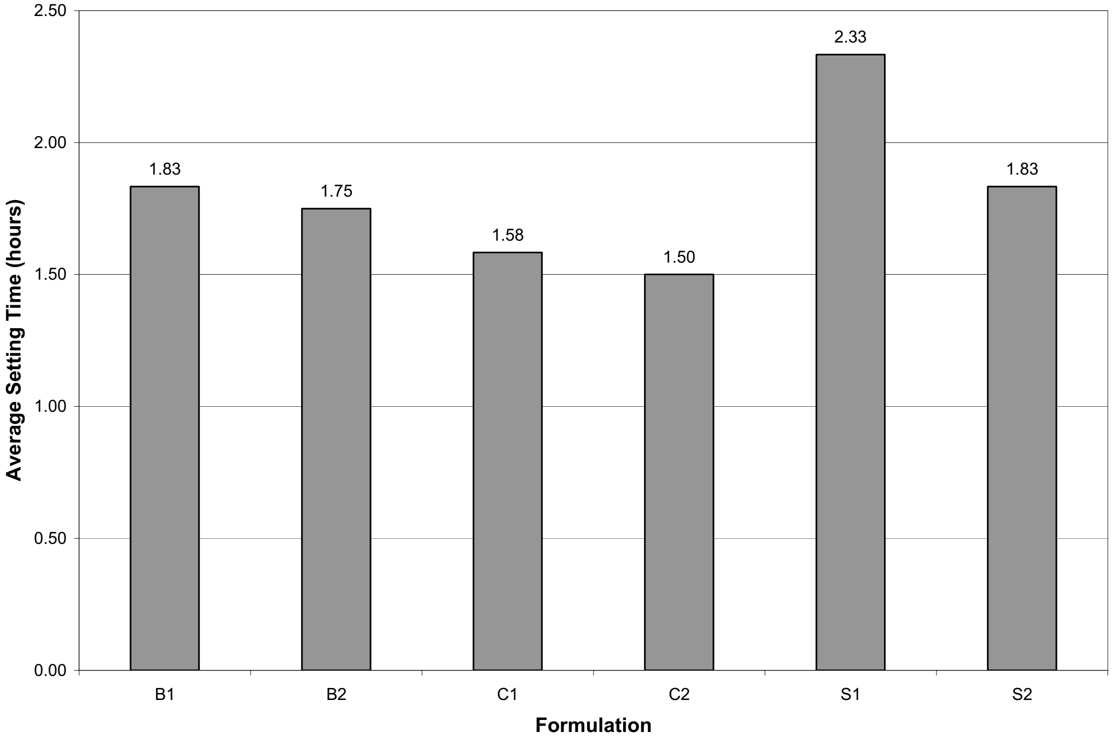
Table 4.4. Key to Samples/Mortar Formulations

B1	3 parts Bandelier Garcia Landscape Materials Blend Soil : 1 part Type 1 White Portland Cement
B2	6 parts Bandelier Garcia Landscape Materials Blend Soil : 1 part Type 1 White Portland Cement
C1	3 parts Chaco BLM Quarry Soil : 1 part Type 1 White Portland Cement
C2	6 parts Chaco BLM Quarry Soil : 1 part Type 1 White Portland Cement
S1	3 parts Salinas Mountainair Local Quarry Soil : 1 part Type 1 White Portland Cement
S2	6 parts Salinas Mountainair Local Quarry Soil : 1 Part Type 1 White Portland Cement

Setting Time – Average setting time was under 2.5 hours for all earthen mortar formulations. For every soil type, the number 1 formulations had a longer average time of setting than the number 2 formulations did, although the differences were not significant. B2 formulation samples set in 95.6% of the time taken by B1 formulation samples. C2 formulation samples set in 94.9% of the time taken by C1 formulation samples. The greatest disparity between two formulations containing the same soil was in the case of the Salinas Mountainair local quarry soil mortars. S2 formulation samples set in 78.5% of the time taken by S1 formulation samples.

Among the number 1 formulations, C1 samples had the shortest average time of setting at 1.58 hours, followed by 1.83 hours for B1 samples and 2.33 hours for S1 samples. The same trend applied to the number 2 formulations. The C2 samples had the shortest average time of setting at 1.50 hours, followed by B2 samples at 1.75 hours and S2 at 1.83 hours. Chart 4.2 illustrates the average setting time for each of the sample formulations. The data and plots for the time of setting for each sample group are presented in Appendix C.

Chart 4.2. Average Setting Time



Color – Each of the soils experienced a decrease in value (lightness) and chroma (strength) due to the addition of white Portland cement. None of the soils experienced a variation in hue, however, indicating that the addition of cement left the basic color of the soils unchanged. The appearance of the Salinas Mountainair local quarry soil was altered the most of the three soils, going from a strong, deep brown in the unamended state to a pinkish grey after the addition of cement. The Chaco and Bandelier soils had less strong colors to begin with, and so the amended mortars formulated from these soils did not exhibit the more extreme qualitative color change that the Salinas soil did. The Munsell color ratings and descriptions for each of the cured mortar formulations are shown in Table 4.5, along with the color values of each of the component soils. This information is also included in Appendix D.

Table 4.5. Cured Mortar Color Ratings

Formulation	Munsell Color Designation (unamended soil)	Munsell Color Designation (mortar)
B1	7.5YR 5/4 Brown	7.5YR 7/2 Light Gray
B2	7.5YR 5/4 Brown	7.5YR 7/2 Light Gray
C1	2.5Y 6/3 Light Yellowish Brown	2.5Y 7/1 Light Gray
C2	2.5Y 6/3 Light Yellowish Brown	2.5Y 6/2 Light Brownish Gray
S1	7.5YR 4/4 Brown	7.5YR 7/2 Pinkish Gray
S2	7.5YR 4/4 Brown	7.5YR 7/2 Pinkish Gray

Water Absorption by Total Immersion – Samples were allowed to absorb water until their weight gain became asymptotic, i.e., the change in mass between two consecutive measurements was less than or equal to 1% of the dry weight of each sample. The time taken by samples of each formulation to reach this state was variable. Formulations B1 and B2 took 8 and 6 days, respectively. Formulations C1 and C2 took 7 and 5 days. Formulations S1 and S2 took 5 and

9 days. The S formulations were the only case in which the weaker formulation (S2, 6 soil : 1 cement) took longer than the stronger formulation to reach the asymptotic state.

Chart 4.3 illustrates the average water absorption curves for all soil-cement formulations. As shown in the chart, the Salinas soil mortars absorbed the highest amount of water followed by the Chaco soil mortars and, finally, the Bandelier soil mortars. The weaker number 2 formulations (6 soil : 1 cement) absorbed more water than the number 1 formulations (3 soil : 1 cement) in all cases.

Chart 4.3. Average Water Absorption Curves

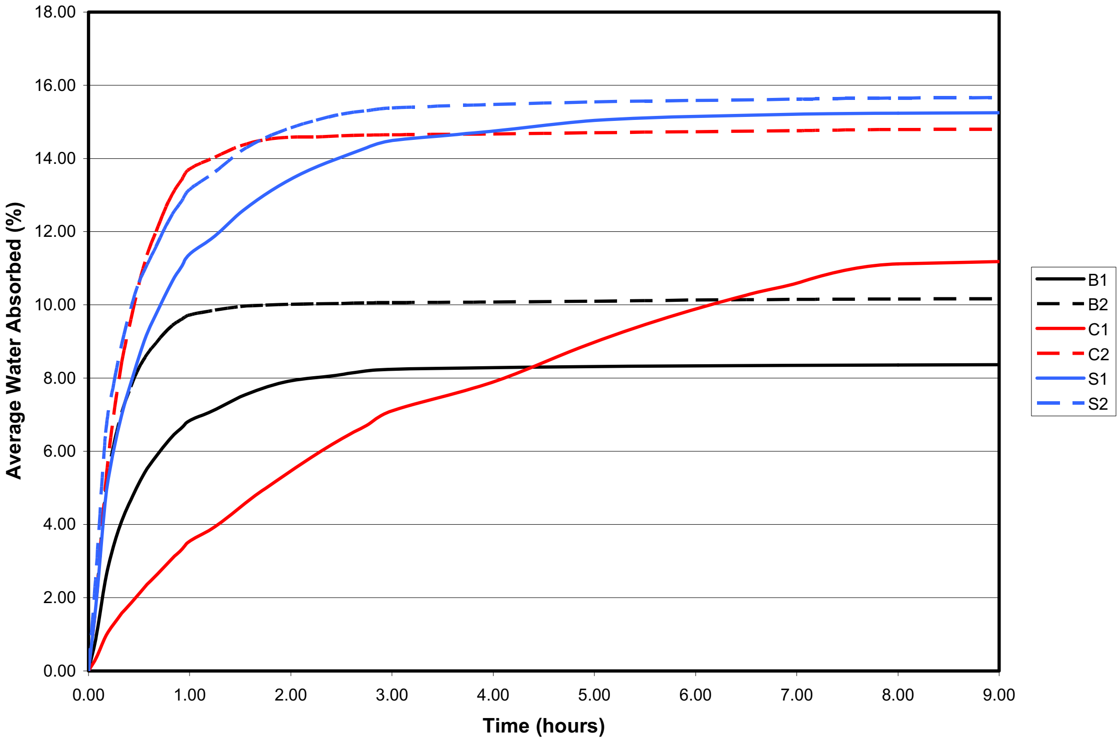


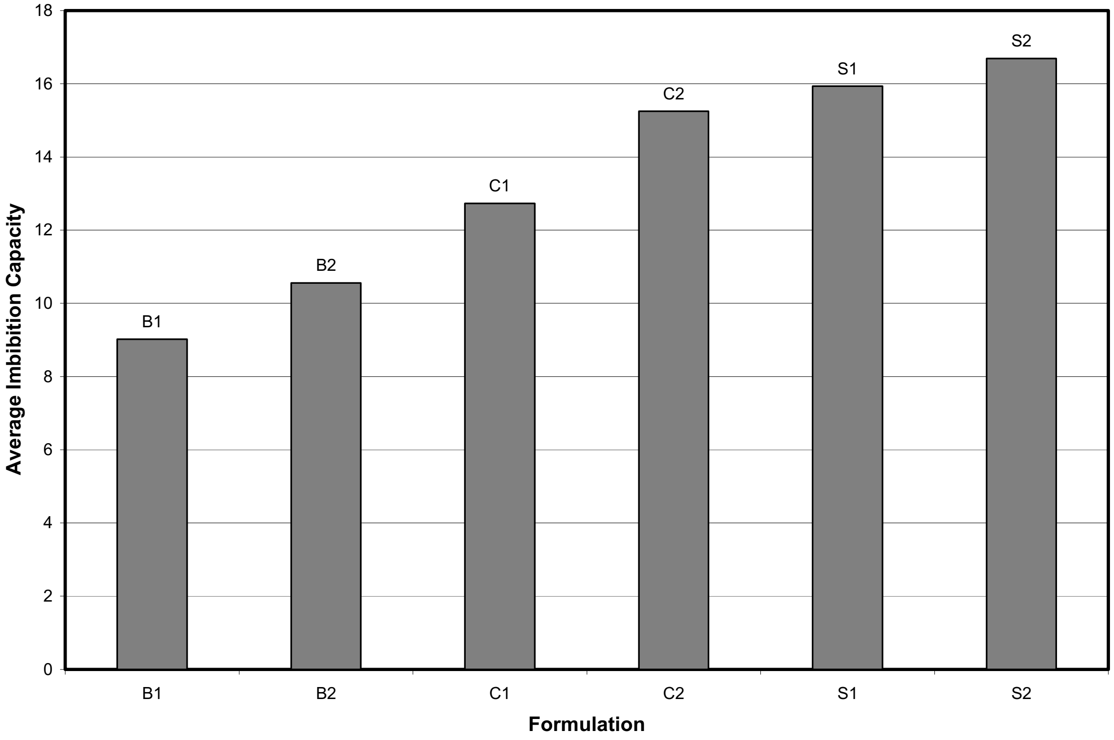
Table 4.6 includes the average imbibition capacities and apparent porosities for each soil mortar formulation as averages of the calculated imbibition capacities and apparent porosities of each of the samples tested. The two values are correlated in that a higher capacity to imbibe water suggests a higher porosity. This correlation is confirmed by the data in Table 4.6. Chart 4.4 compares the average imbibition capacities of each of the six formulations. As the chart illustrates, the number 2 formulations of every soil type show higher capacities for water absorption than the number 1 formulations. The formulation with the lowest imbibition capacity (and lowest apparent porosity) is B1 (3 parts Bandelier Garcia Landscape Materials blend soil : 1 part cement). The formulation with the highest imbibition capacity is S2 (6 parts Salinas Mountainair local quarry soil : 1 part cement). This formulation should also have the highest average apparent porosity, which Table 4.6 confirms. The data for the water absorption measurements as well as water absorption curves for each of the samples tested is collected in Appendix E.

Table 4.6. Imbibibition Capacity and Apparent Porosity

Sample	Final weight of water absorption	Hydrostatic weight	Final dry weight	Imbibition capacity %	Average imbibition capacity %	Apparent porosity %	Average apparent porosity %
B1-1	286.70	158.10	262.84	9.08	9.02	18.55	18.47
B1-2	290.58	160.35	266.38	9.08		18.58	
B1-3	291.32	160.95	267.51	8.90		18.26	
B2-1	287.62	155.50	260.23	10.53	10.56	20.73	20.76
B2-2	279.12	150.60	252.34	10.61		20.84	
B2-3	282.79	152.50	255.81	10.55		20.71	
C1-1	275.43	143.30	244.17	12.80	12.73	23.66	23.56
C1-2	267.12	138.90	236.17	13.10		24.14	
C1-3	275.28	143.60	245.16	12.29		22.87	
C2-1	268.69	137.40	233.08	15.28	15.25	27.12	27.15
C2-2	266.57	136.40	231.25	15.27		27.13	
C2-3	268.55	138.15	233.09	15.21		27.19	
S1-1	251.37	124.20	216.99	15.84	15.93	27.03	27.17
S1-2	252.23	124.25	217.27	16.09		27.32	
S1-3	253.56	125.70	218.84	15.87		27.15	
S2-1	256.15	127.45	219.37	16.77	16.69	28.58	28.46
S2-2	252.15	125.35	216.15	16.66		28.39	
S2-3	255.75	127.30	219.26	16.64		28.41	

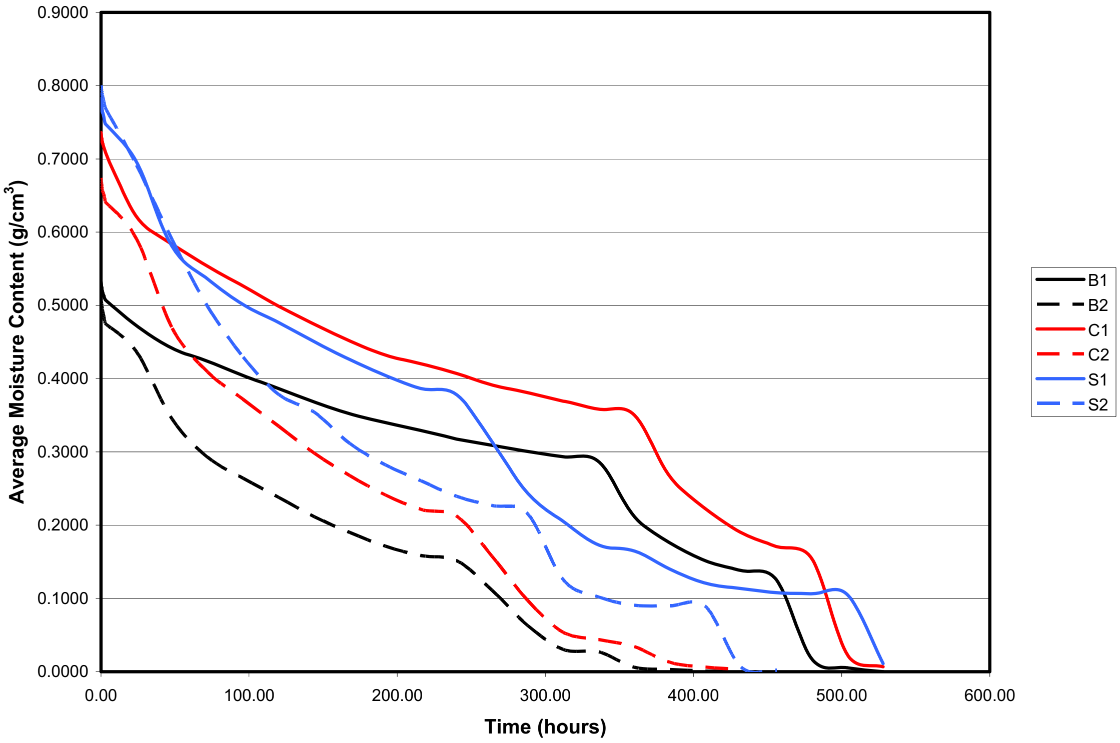
Key to Samples/Mortar Formulations	
B1	3 soil : 1 cement
B2	6 soil : 1 cement
C1	3 soil : 1 cement
C2	6 soil : 1 cement
S1	3 soil : 1 cement
S2	6 soil : 1 cement

Chart 4.4. Average Percent Imbibition Capacity



Drying Rate – The rate of drying varied frequently during the period of measurement, though general trends about the drying behavior of each of the formulations were revealed. All of the weaker number 2 formulations dried more quickly than did any of the number 1 formulations. In the cases of both number 1 and number 2 formulations, Bandelier soil mortars were the first to reach the asymptotic state for weight change, defined as a difference between two successive weight measurements of less than 0.01% of the dry weight of the sample. The Bandelier mortars were followed by Chaco soil mortars and lastly, Salinas soil mortars. Even the fastest-drying samples (formulation B2) did not reach the asymptotic state until nineteen days after drying had begun. The formulation S1 samples, which were the last to reach the asymptotic state, did not do so until twenty-five days after drying had begun. Chart 4.5 shows the average drying rate curves for each of the formulations. As each of the curves indicates, there was a steep drop in the moisture content of all formulations when samples were switched from atmospheric drying conditions in a dessicator to the drying oven. Four of the six curves also illustrate secondary drop-off points that occurred when the temperature of the drying oven was increased. These drops in moisture content in response to temperature increases indicate that the mortars are capable of retaining water at length in dry atmospheric conditions. The measured data for the drying of the samples is tabulated in Appendix F along with plots of the drying rates of all samples tested.

Chart 4.5. Average Moisture Content During Drying



Frost Resistance – All of the soil-cement mortar samples tested survived fifteen cycles of freeze/thaw cycling. Any damage that occurred was minimal. The S2 formulation (6 parts Salinas Mountainair local quarry soil : 1 part cement) was the only group that visually exhibited deterioration following the fifteenth cycle of testing. The surfaces of all three S2 samples of this soil-cement mortar showed clear patches of delamination, but there was no indication of more profound damage to any of the three.

The bulk volume of the samples is the expression of the material retained over the duration of the test. The bulk volume was calculated for each of the mortar samples at the beginning of the procedure and then at the end of the 4th, 8th, 12th and 15th freeze/thaw cycles by subtracting the hydrostatic weight of each sample from the weight of the sample in air. This yields the weight of the water remaining in the sample. The loss of material from the sample will decrease the amount of water that it can hold, and thus the bulk volume will decrease. Assuming that material is lost from the sample, dividing the final bulk volume by the initial the amount gives remaining material expressed as a percent of the original sample. A mortar is regarded as being more resistant to freeze/thaw deterioration the higher the percent of its retained bulk volume. Table 4.7 shows the average bulk volume for each of the six mortar formulations tested, derived from the initial and final bulk volumes of the samples. Complete data taken during the freeze/thaw cycling along with images of the tested samples at the first and fifteenth cycles are presented in Appendix H. As the data in Table 4.7 shows, the average bulk volume for the S2 formulation is the only instance of decrease (albeit a minor one) among the formulations tested. This decrease is consistent with the visual evidence of material loss from S2 observed at the end of the fifteenth cycle. The average bulk volumes of all other formulations actually increased, which could be due to slight hydric expansion and a subsequent increase in the samples' capacity to hold water.

Table 4.7. Bulk Volume Retained Through Freeze/Thaw Cycling

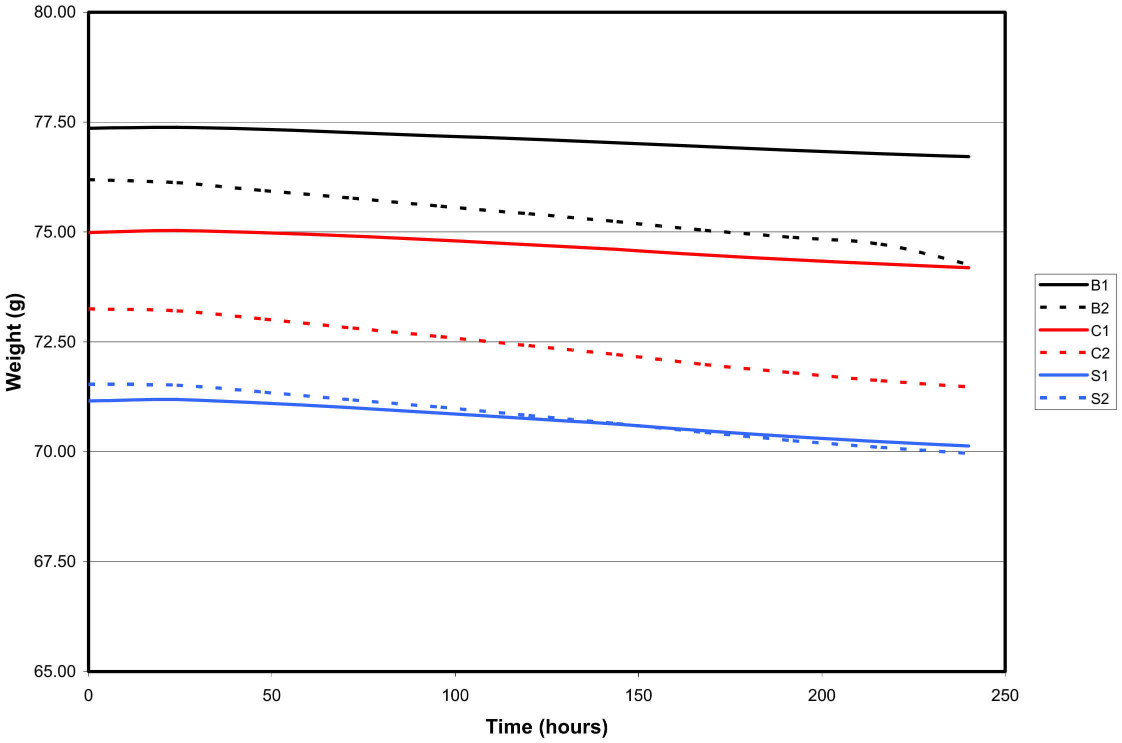
Sample	Initial Bulk Volume (g)	Final Bulk Volume (g)	Bulk Volume Retained (%)	Average Bulk Volume Retained
B1-1	128.15	128.52	100.29	100.34
B1-2	126.04	126.55	100.40	
B1-3	126.91	127.34	100.34	
B2-1	127.87	128.41	100.42	100.40
B2-2	124.28	124.93	100.52	
B2-3	127.84	128.18	100.27	
C1-1	124.79	126.38	101.27	101.72
C1-2	123.63	125.98	101.90	
C1-3	122.84	125.27	101.98	
C2-1	124.46	124.99	100.43	100.44
C2-2	123.40	124.14	100.60	
C2-3	128.35	128.73	100.30	
S1-1	127.27	128.47	100.94	100.86
S1-2	124.86	125.82	100.77	
S1-3	129.09	130.20	100.86	
S2-1	125.58	125.48	99.92	99.60
S2-2	121.20	120.84	99.70	
S2-3	126.79	125.76	99.19	

Key to Samples/Mortar Formulations	
B1	3 soil : 1 cement
B2	6 soil : 1 cement
C1	3 soil : 1 cement
C2	6 soil : 1 cement
S1	3 soil : 1 cement
S2	6 soil : 1 cement

Water Vapor Transmission – Over the 10-day test period for water vapor transmission, all samples tested achieved a relatively constant rate of vapor transmission, at which a minimum of six measurements could be taken that would appear as evenly-spaced points on a vapor transmission curve (as dictated by ASTM E96-00). Following a brief period during the beginning of the procedure in which nearly all sample assemblies experienced a slight weight gain, all samples of each formulation tested began to lose weight constantly for the remainder of the testing period. Samples of the number 1 formulations (B1, C1 and S1) all lost roughly 0.10 g per day between the 2nd and 10th days of testing while samples of the number 2 formulations generally lost between 0.15 g and 0.20 g per day between the 1st and 10th days of testing. Data collected during the test period is tabulated in Appendix G along with water vapor transmission curves for all samples tested.

Chart 4.6 illustrates the average change in weight of the vapor transmission assemblies for each mortar formulation over the elapsed time. As the chart indicates, all number 2 formulations quickly achieved a constant rate of transmission that was higher than that of their counterparts of the number 1 formulations. The difference between the transmission rates of the numbers 1 and 2 formulations is not particularly extreme, however, especially in the case of the Salinas soil mortars. Nevertheless, a connection can be observed here between higher cement content and lower water vapor transmission rates. The inverse of this is also true. This is seen as a positive indication that a stronger soil-cement formulation is not necessarily an impediment to vapor transmission.

Chart 4.6. Average Water Vapor Transmission Curves



Water vapor transmission, WVT, was calculated in metric units as follows:

$$WVT = G/tA = (G/t)/A$$

where:

G = weight change (from straight line), g,

t = time, h,

G/t = slope of the straight line, g/h,

A = test area (sample area), m^2,

and

WVT = water vapor transmission, $g/h \cdot m^2$.

Permeance was calculated in metric units as follows:

$$\text{Permeance} = WVT/S(R_1 - R_2)$$

where:

S = saturation vapor pressure at test temperature, Pa (1mm Hg = 133.3 Pa)

R_1 = relative humidity at the source expressed as a fraction (in the dish for water method),

and

R_2 = relative humidity at vapor sink expressed as a fraction (in the chamber for water method).

Average Permeability (metric perm·cm) was calculated as follows:

$$\text{Average Permeability} = \text{Permeance} \times \text{thickness}.$$

All mortar samples tested had a test area of 0.013 m^2 and a thickness of 1.3 cm. The average test temperature was established to be 31°C at which the saturation vapor pressure was determined to be 33.72 mm Hg (4495 Pa). The relative humidity within the vapor transmission assemblies was 100%, and the average relative humidity in the dessication chamber was 49%. Table 4.8 includes the

Average Permeance and Permeability calculations for each formulation as well as the average water vapor transmission figures. This data is also included in Appendix G. The following comparisons can be made based on the data found in Table 4.8. Formulation B2 of the Bandelier soil-cement mortars (6 soil : 1 cement) showed an average water vapor transmission rate that was 3 times greater than that of formulation B1 (3 soil : 1 cement). The average permeance and average permeability of formulation B2 were also roughly 3 times greater than the values determined for formulation B1. The average water vapor transmission, permeance, and permeability of the Chaco soil-cement formulation C2 were roughly 2 times higher than the respective values determined for formulation C1. The Salinas soil-cement formulation S2 showed an average water vapor transmission rate, permeance, and permeability that were 1.5 times higher than the respective values for formulation S1. Lower cement content correlated with better capabilities of water vapor transmission, permeance, and permeability in every case. However, the magnitudes of these increases were not the same for each soil, indicating that soil composition is a variable determinant of water vapor transmission capabilities for each soil-cement mortar formulation.

Table 4.8. Water Vapor Transmission, Permeance and Permeability

Sample	WVT ($g/h \cdot m^2$)	Average WVT	Permeance ($g/Pa \cdot s \cdot m^2$ or perm)	Average Permeance	Permeability (perm·cm)	Average Permeability
B1-1	0.19	0.21	2.38E-08	2.55E-08	3.09E-08	3.31E-08
B1-2	0.22		2.73E-08		3.55E-08	
B1-3	0.21		2.54E-08		3.30E-08	
B2-1	0.51	0.62	6.30E-08	7.63E-08	8.19E-08	9.92E-08
B2-2	0.52		6.42E-08		8.34E-08	
B2-3	0.82		1.02E-07		1.32E-07	
C1-1	0.25	0.26	3.13E-08	3.17E-08	4.07E-08	4.12E-08
C1-2	0.28		3.41E-08		4.43E-08	
C1-3	0.24		2.97E-08		3.86E-08	
C2-1	0.55	0.57	6.81E-08	7.04E-08	8.86E-08	9.15E-08
C2-2	0.59		7.33E-08		9.53E-08	
C2-3	0.56		6.97E-08		9.06E-08	
S1-1	0.36	0.33	4.40E-08	4.07E-08	5.72E-08	5.29E-08
S1-2	0.32		4.00E-08		5.20E-08	
S1-3	0.31		3.80E-08		4.94E-08	
S2-1	0.54	0.50	6.62E-08	6.14E-08	8.60E-08	7.99E-08
S2-2	0.46		5.68E-08		7.38E-08	
S2-3	0.50		6.14E-08		7.98E-08	

Key to Samples/Mortar Formulations	
B1	3 soil : 1 cement
B2	6 soil : 1 cement
C1	3 soil : 1 cement
C2	6 soil : 1 cement
S1	3 soil : 1 cement
S2	6 soil : 1 cement

Water Drop Erosion – All samples tested in this procedure were exposed over an area of about 1 in^2 to a steady and direct water fall at the rate of 1 drop per second (from a standard burette) over a distance of 2.5 m (8.20 ft.) for a period of one hour. Table 4.9 includes all depths of penetration for each sample tested as well as the average depth of penetration for each sample group. The information in the table is also included in Appendix I along with images of all samples tested taken following their respective exposures to the water fall.

Every amended soil mortar tested in this procedure exhibited excellent resistance to erosion as opposed to the unamended soils. No visual or measurable damage to the soil-cement samples was detectable. The successful resistance of the soil-cement formulations to deterioration was underscored by the rapid failure of all specimens of the unamended soils that were tested. Of these samples, the Bandelier Garcia Landscape Materials Blend soil proved to be the most susceptible to erosion, averaging a depth of 20.61 mm penetration. The Chaco BLM Quarry soil samples fared slightly better, averaging 15.04 mm depth of penetration. The unamended Salinas Mountainair local quarry soil samples were the most resistant of the three soil types to erosion, averaging 8.75 mm penetration depth. These samples, however, were also the most absorptive and, though the cubes did not lose their basic shape during their exposure to water fall, they were far more malleable following exposure than the samples composed of the other two soils.

Table 4.9. Penetrative Damage from Falling Water

Sample	Depth of Penetration (mm)	Average Depth of Penetration (mm)
B1-1	0.00	0.00
B1-2	0.00	
B1-3	0.00	
B2-1	0.00	0.00
B2-2	0.00	
B2-3	0.00	
BU-1	22.73	20.61
BU-2	20.42	
BU-3	18.69	
C1-1	0.00	0.00
C1-2	0.00	
C1-3	0.00	
C2-1	0.00	0.00
C2-2	0.00	
C2-3	0.00	
CU-1	14.08	15.04
CU-2	13.42	
CU-3	17.62	
S1-1	0.00	0.00
S1-2	0.00	
S1-3	0.00	
S2-1	0.00	0.00
S2-2	0.00	
S2-3	0.00	
SU-1	7.68	8.75
SU-2	10.11	
SU-3	8.47	

Key to Samples/Mortar Formulations	
B1	3 soil : 1 cement
B2	6 soil : 1 cement
BU	unamended Bandelier Garcia Landscape Materials blend soil
C1	3 soil : 1 cement
C2	6 soil : 1 cement
CU	unamended Chaco BLM Quarry soil
S1	3 soil : 1 cement
S2	6 soil : 1 cement
SU	unamended Salinas Mountainair local quarry soil

Modulus of Rupture – The modulus of rupture is an expression of the maximum load-carrying capacity of the soil-cement mortar samples in bending. It is proportional to maximum load (moment) borne by each sample and is a representation of the tensile strength of the mortars. During testing, all samples were seated atop two blunt-edged bearing blocks (mounted on the Instron 4206 testing machine) with a 3-inch span between them. Force was applied to each sample from above via a blunted knife blade until the sample broke. Samples were stored in a moist environment, as dictated by ASTM D1635-00, prior to testing, after being cured in a moist tent for 28 days.

The modulus of rupture was calculated for each specimen in relation to the maximum recorded load as follows:

$$R = PL / bd^2$$

where:

R = modulus of rupture, psi (lb/in^2),

P = maximum load applied at the time of breaking, lbf,

L = span length (between supports), in.,

b = width of sample tested, in.,

and

d = depth of sample tested, in.

Table 4.10 includes the calculations of the modulus of rupture for each sample tested, as well as the average modulus of rupture for each formulation. The data table, along with the load curves for each of the samples tested is located in Appendix J. One sample of the number 2 Salinas soil formulation (designated S2-2) cracked prior to testing. The sample was subjected to three-point bending, but no maximum load could be determined from the data collected and thus it was excluded from the calculation of average modulus of rupture for the S2 formulation.

As expected, all number 1 formulations (3 soil : 1 cement) showed superior strength to number 2 formulations (6 soil : 1 cement). Of the number 1 formulations, the B1 samples displayed the highest strength in bending, with an average modulus of rupture of 1130.11 psi. This was followed by the formulation C1 samples and finally the S1 samples. Of the number 2 formulations the S2 samples showed the highest strength in bending with an average modulus of rupture of 485.48 psi. These were followed by formulation C2 and B2 lastly.

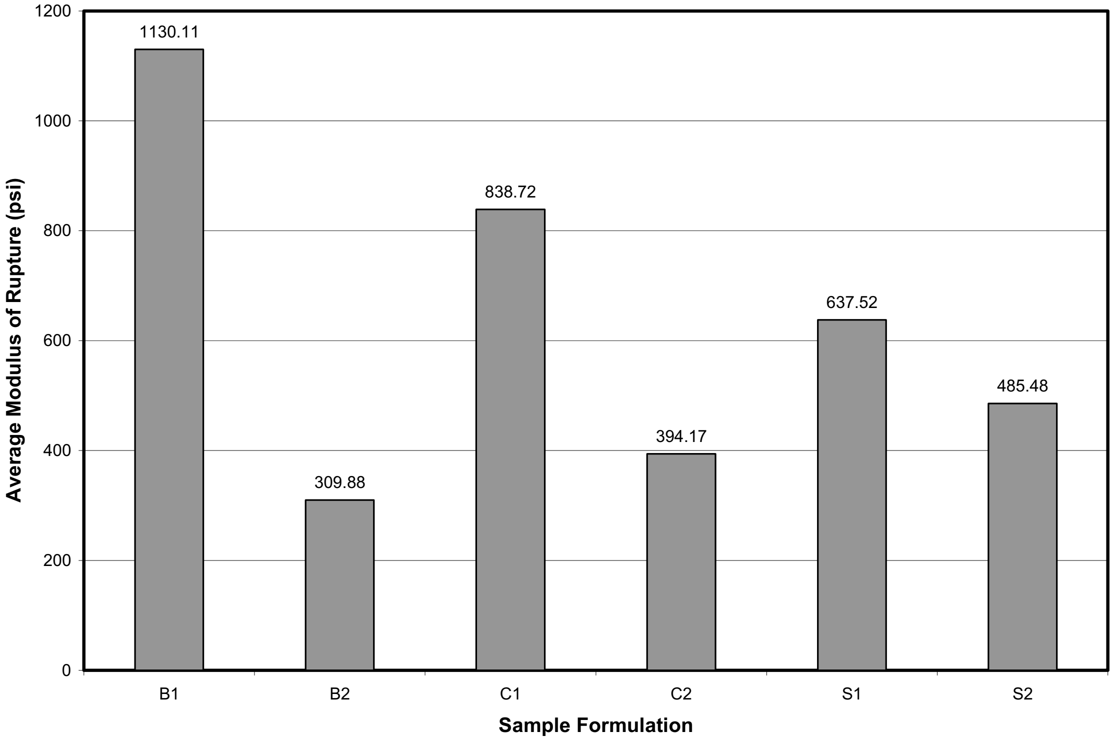
Formulation B1 showed an average modulus of rupture that was 3.5 times higher than that of formulation B2. The average modulus of rupture for formulation C1 was 2 times higher than that of C2, and formulation S1 (the weakest of the number 1 formulations) showed an average modulus of rupture that was 1.5 times higher than that of formulation S2 (the strongest of the number 2 formulations). Chart 4.7 compares the average moduli of rupture calculated for each soil-cement mortar formulation.

Table 4.10. Calculation of the Average Modulus of Rupture

Sample	Maximum Applied Load, P (lbf)	Span Length, L (in)	Specimen Width, *b* (in)	Specimen Depth, *d* (in)	Modulus of Rupture, R (psi)	Average Modulus of Rupture (psi)
B1-1	396	3.0	1.008	0.978	1222.41	1130.11
B1-2	391	3.0	1.032	0.985	1135.18	
B1-3	349	3.0	1.015	0.992	1032.74	
B2-1	81	3.0	1.038	0.989	230.58	309.88
B2-2	66	3.0	1.026	0.985	193.86	
B2-3	170	3.0	1.019	0.986	505.21	
C1-1	293	3.0	1.013	0.979	893.73	838.72
C1-2	244	3.0	1.024	0.976	732.84	
C1-3	307	3.0	1.033	0.985	889.58	
C2-1	120	3.0	1.014	0.970	372.12	394.17
C2-2	142	3.0	1.009	0.963	451.21	
C2-3	118	3.0	1.012	0.981	359.17	
S1-1	161	3.0	1.030	0.986	468.29	637.52
S1-2	210	3.0	1.022	0.995	609.25	
S1-3	269	3.0	0.991	0.992	835.03	
S2-1	161	3.0	1.001	0.984	497.84	485.48
S2-2	----	3.0	1.019	0.975	----	
S2-3	145	3.0	1.003	0.956	473.12	

Key to Samples/Mortar Formulations	
B1	3 soil : 1 cement
B2	6 soil : 1 cement
C1	3 soil : 1 cement
C2	6 soil : 1 cement
S1	3 soil : 1 cement
S2	6 soil : 1 cement

Chart 4.7. Average Modulus of Rupture for Soil-Cement Formulations



Splitting Tensile Strength – All of the cylindrical soil-cement samples tested were in this procedure subjected to a compressive force applied along their length by the Instron 4206 testing machine. Samples were positioned to receive force along their diametric planes between wooden bearing strips that evenly distributed the force applied by the load cell from above along the bearing plane.

The splitting tensile strength was calculated for each specimen in relation to the maximum recorded load as follows:

$$T = 2P / \pi L d$$

where:

T = splitting tensile strength, psi,

P = maximum load applied at the time of breaking, lbf,

L = sample length, in.,

and

d = sample diameter, in.

Table 4.11 includes the calculations of the splitting tensile strength for each sample tested as well as the average splitting tensile strength for each formulation. The data table and the load curves for each of the samples tested are located in Appendix K.

All number 1 formulations displayed higher strength under compression than did the number 2 formulations. Repeating the trend observed for modulus of rupture of number 1 formulations, Table 4.11 indicates that formulation B1 mortar samples exhibited the highest splitting tensile strength among the mortars of the number 1 formulations, followed by the C1 samples and finally the S1 samples. The inverse was true in the case of the number 2 formulations, with the Salinas formulation S2 samples exhibiting the highest splitting tensile strength followed by Chaco formulation C2 and Bandelier formulation B2.

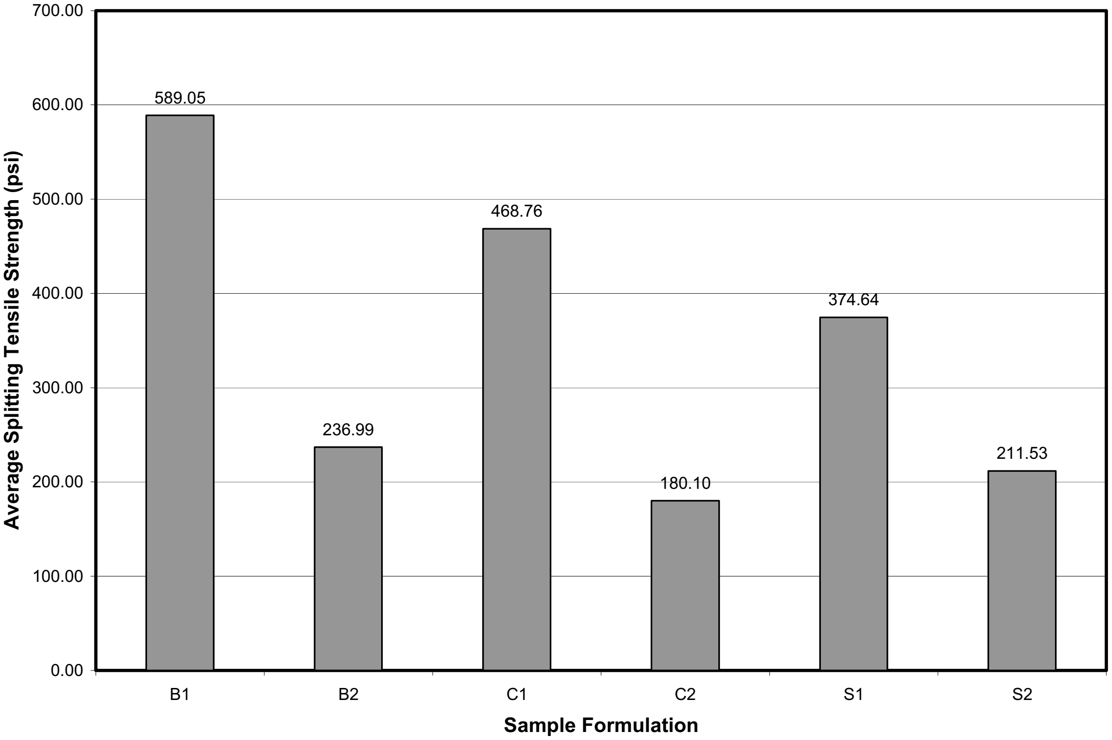
Differences in strength correlated with cement content between the numbers 1 and 2 formulations for each soil were observed as follows. The average splitting tensile strength determined for formulation B1 was 2.5 times higher than that of formulation B2. Formulation C1 also showed an average splitting tensile strength that was 2.5 times higher than that of formulation C2. The average splitting tensile strength of formulation S1 was 2 times higher than that of formulation S2. These numbers represent a somewhat more consistent dependence of strength on cement content than is shown for modulus of rupture. Chart 4.8 comparatively illustrates the average splitting tensile strength for each of the soil-cement formulations.

Table 4.11. Calculation of Average Splitting Tensile Strength

Sample	Maximum Applied Load, P (lb)	Specimen Length, L (in)	Specimen Diameter, *d* (in)	Splitting Tensile Strength, T (psi)	Average Splitting Tensile Strength, (psi)
B1-1	7485	4.023	2.066	573.31	589.05
B1-2	7899	4.050	2.062	602.16	
B1-3	7831	4.049	2.081	591.67	
B2-1	2850	4.042	2.059	218.01	236.99
B2-2	3360	4.058	2.064	255.39	
B2-3	3102	4.037	2.059	237.58	
C1-1	5832	4.047	2.057	446.00	468.76
C1-2	6725	4.017	2.062	516.87	
C1-3	5804	4.047	2.059	443.42	
C2-1	2301	4.040	2.042	177.57	180.10
C2-2	2690	4.031	2.065	205.73	
C2-3	2038	4.025	2.053	157.01	
S1-1	3876	3.998	2.040	302.55	374.64
S1-2	5600	4.023	2.045	433.34	
S1-3	5032	4.031	2.048	388.04	
S2-1	2808	4.002	2.037	219.29	211.53
S2-2	2528	4.025	2.042	195.81	
S2-3	2796	3.999	2.028	219.48	

Key to Samples/Mortar Formulations	
B1	3 soil : 1 cement
B2	6 soil : 1 cement
C1	3 soil : 1 cement
C2	6 soil : 1 cement
S1	3 soil : 1 cement
S2	6 soil : 1 cement

Chart 4.8. Average Splitting Tensile Strength for Soil-Cement Formulations



Chapter 5 – Discussion and Conclusions

The goal of the testing of earthen mortars amended with Portland cement was to explore how Type 1 Portland cement affects identified critical properties of soil mortars when mixed in varying proportions. The results of this testing have indicated that, in general, the performance of soil-cement mortars can be predicted in advance of their application. This prediction does depend on the quantity of cement included in a mortar formulation but, more importantly, it depends on the nature and character of the soil being used as the primary component of the mortar. In particular, the grain size distribution of the soil component of a soil-cement mortar seems to bear directly on the performance of the mortar in laboratory testing. That is, soil-cement mortars formulated with the same soil/cement ratio but containing different soils exhibit different physical properties. This can be seen particularly in the properties of permeability, resistance to freeze/thaw cycling, modulus of rupture, and splitting tensile strength, as the data presented in Chapter 4 indicates. This section presents an analysis of the soil properties that give rise to these variations. By properly characterizing the soils that are selected for use in stabilization, particularly in mortars used for pointing, soil-cement mortars that exhibit both adequate durability and compatibility with original building materials can be formulated to suit the needs of individual sites.

5.1 Soil and Fresh Mortar

The three soils used in formulating the mortars that were tested in this research were subjected to most of the standard measures of soil characterization. Table 5.1 briefly summarizes the critical characteristics of each of the soils.

Table 5.1. Soil Characteristics Summary

Characteristic	Bandelier Garcia Landscape Materials Blend Soil	Chaco BLM Quarry Soil	Salinas Mountainair Local Quarry Soil
Munsell Color	7.5YR/5/4 Brown	2.5Y/6/3 Light yellowish brown	7.5YR/4/4 Brown
Particle Size Distribution (%): Coarse Sand : Fine Sand : Silt : Clay	81 : 7 : 4 : 8	62 : 7 : 10 : 21	48 : 20 : 14 : 18
Liquid Limit	Indeterminate	23.4	25.4
Plastic Limit	Indeterminate	19.3	21.7
Plasticity Index	Non-Plastic	4.1	3.7
Density (g/cm^3)	4.20	2.68	3.25
Carbonate Content (%)	5.60	2.40	2.48
pH (water/$CaCl_2$)	7.5/7.4	8.1/7.7	7.3/7.2

Unlike sands and coarse aggregates commonly used in modern construction, the physical and chemical properties of soils cannot be manufactured. Soils have an almost unlimited capacity for chemical variation in their components, and while soils may be ascribed type-specific designations, there is no way to logically rate each type for suitability as an architectural material because of the potential variability within each typology. However, by characterizing any soil selected for use as a mortar component, a basis can be formed for the determination of appropriate contents of amendment material. The joint analysis of soil characteristics and mortar performance results can often explain behavior of mortars as a function of soil properties, aiding in the prescription of amendment contents that best suit the capacity of the materials.

Soil Color Versus Mortar Color – It was assumed prior to testing that the addition of white Portland cement to soil mortars would alter the colors of the soils to some extent. Grey Portland cement is known to have less of an influence upon the color of mortars, which influenced the decision to use the white variety in order to view the maximum possible alteration of color for the formulations tested. Interestingly, variation of the amount of white Portland cement did not result in significant corresponding variations in mortar color, if any variations occurred at all. While the color designations of the mortar samples differed from those of the component soils in all cases, no consequential difference was observed between the colors of the number 1 and number 2 mortar formulations for each soil. A slight variation was noted between the value and chroma designations of formulation C1 and C2, but the colors of the two formulations remained remarkably similar despite the doubled content of white Portland cement in the number 1 formulations.

The initial color designation of the Bandelier Garcia Landscape Materials blend soil was 7.5YR 5/4, Brown. This is a middling brown soil with a hue that is more red than yellow and with a mid-range value (lightness) and an upper mid-range chroma (strength). By comparison, mortar formulation B1 (3 soil : 1 cement) and formulation B2 (6 soil : 1 cement) both received the same color designation, 7.5YR 7/2, Pinkish Gray. This is a weak gray with no yellow, a low-range value (lightened 2 degrees on the Munsell scale from that of the soil) and low range chroma (weakened 2 degrees from the soil chroma). Qualitatively this difference corresponds with an overall lightening and weakening of the color. The mortar does retain the slight reddish tint that is indicated by the hue designation. Thus hue was more vivid in the soil, and hue only seems reduced because of variation in value and chroma exhibited by the mortars.

The initial color designation of the Chaco BLM Quarry soil was 2.5Y 6/3, Light Yellowish Brown. This is a dull yellow-tinted brown with an upper mid-range value (closer to white than to black) and a lower mid-range chroma (slightly weak). Mortar formulation C1 received a color designation of 2.5Y 7/1, Light Gray, and formulation C2 received a designation of 2.5Y 6/2, Light Brownish Gray. The differences between the value and chroma designations of the two formulations correspond to one degree of lightening in value and one degree of weakening of chroma on the part of formulation C1, whose cement content of 25% was significantly higher than that of C2 (14% cement). Formulation C2, in turn, was one degree weaker in chroma than the soil itself, though both received the same value designation. Each of the two formulations retained the same hue designation as the soil.

The initial color designation of the Salinas Mountainair local quarry soil was 7.5YR 4/4. This is a solid brown with a lower mid-range value (closer to black than white) and an upper mid-range chroma (slightly strong). Mortar formulations S1 and S2 both received the designation 7.5YR 7/2. This is a lightening of three degrees in value and a weakening of two degrees in chroma. These mortars are a far softer brown than the soil, with the most striking visual difference being the weakening in the chroma between the soil and the mortars. These changes in color represent the biggest variation that was observed between the colors of mortar formulations and the colors of their component soils. Again, however, the hue designation did not change.

Based on these observations, it is expected that the addition of white Portland cement to a soil mortar will result in a general lightening and weakening of the soil's natural color but will not necessarily alter the fundamental hue of the soil. Value and chroma reductions can be significant in the context of ruins stabilization because of the potential disparities that may result between the color of original masonry and that of the stabilization material, particularly where highly visible pointing and capping mortars are concerned. Nevertheless the fact that the addition of Portland cement seems to affect change in the quality of soil color rather than its nature suggests that discrepancies between mortar and masonry colors could be corrected by selecting darker soils with hues similar to those of original masonry in stabilized ruins. The addition of colorants to mortars has also been practiced by field personnel with the National Park Service for many years and remains a viable measure of achieving desired coloration for stabilization mortars. The addition of sand to soil-cement mortars can also influence mortar coloration. However, this is not necessarily a consideration if the component soils are determined to have good grain size distribution to begin with, as the addition of coarse sand to such soils might alter the working properties of the soils.

Setting Time – Observation of the setting of the mortar formulations suggested little regarding a link between the type of soil used in each formulation and the time required for the samples to reach final set. The doubled cement content of the number one formulations over the number 2 formulations did not result in a significant corresponding increase in the time of setting. Five of the six formulations subjected to the Vicat test had an average time of setting that fell within the range of 1.5 to 1.8 hours. Formulation S1 (3 soil : 1 cement) was the notable exception, with an average of 2.3 hours. Although this is not uncharacteristically long for a cementitious mortar, formulation S2 also displayed the longest time of setting of the number 2 formulations, averaging 1.83 hours (compared to 1.50 and 1.75 hours for C2 and B2, respectively). It is possible that the comparatively low proportion of coarse sand fractions in the Salinas Mountainair local quarry soil contributed to the increased time of setting for the two Salinas formulations by making it difficult for a binder matrix to form as quickly in the absence of coarse aggregates. If this is the case, future mortars formulated with this particular soil might benefit from the addition of masonry sand to facilitate the formation of the binder matrix.

In all cases the number 1 formulations displayed a slightly longer time of setting than the number 2 formulations did. The plots of the Vicat test results located in Appendix C show the setting time curves of the number 1 formulation samples exhibiting plateaus during their initial setting while the number 2 formulation samples' curves slope almost immediately after the initial penetration of the Vicat needle. This suggests that a slightly shorter window of time is available for application of the weaker mortar formulations before they set. However, there is no substantive advantage for such a small difference in the setting time.

5.2 Set Mortars

5.2.1 Moisture Transport Properties

Water Absorption and Drying – All structures, particularly masonry structures, must have the capacity to cycle liquid water and water vapor out of the building envelope. This is especially important for ancient masonry structures. The majority of extant, above-ground structures at both Chaco and Salinas consist of rubble core masonry walls. Regardless of the status of the masonry (original or rehabilitated), the building materials remain both porous and permeable to water. It is, therefore, essential that no materials be introduced into the systems that alter the overall permeability. Kivas at Chaco, Salinas, and Bandelier are constructed below soil grade, putting them in direct contact with soil and ground water. The kivas, now open where once they were enclosed (or infilled), also face the potential problems of insufficient drainage because of their exposure. Ancient masonry systems were constructed of and maintained with compatible natural materials. Thus the systems themselves could support the constant cycling of moisture to which they were subject. The task of stabilization of the remains of these systems is to continue maintaining this cycling of moisture but also, where possible, to enhance to potential of the building systems to cycle moisture away as quickly as possible in order to avoid prolonged contact of original material with water and the subsequent deterioration that this can involve. The water absorption and drying index tests examine the capability of the mortars to absorb and remove liquid water.

All number 1 formulations showed lower imbibition (water absorption) capacities than the number 2 formulations of the same soils. Of the number 1 formulations B1 had the lowest average imbibition capacity, being lower than C1 by 29% and lower than S1 by 43%. The average water absorbed by each was 9.02% by B1, 12.73% by C1, and 15.93% by S1. Of the number 2 formulations B2 also had the lowest imbibition capacity, being lower than C2 by 31% and lower than S2 by 37%. The average water absorbed by these formulations was 10.56% by B2, 15.25% by C2, and 16.69% by S2. The average imbibition capacity of formulation B1 was lower than that of B2 by 15%. C1 was lower than

C2 by 17%. S1 was lower than S2 by just 5%. All sample formulations, save for C1, reached their saturation water level within 4 hours of immersion. C1 did not reach saturation level until the eighth hour of immersion and exhibited a far more gradual rate of absorption than the other formulations (see Chart 4.3). The reason for this is unclear.

It was expected that higher cement would result in decreased imbibition capacities because of the creation of a denser (less porous) matrix with Portland cement. This expectation was met with the finding that the number 1 formulations for every soil had lower imbibition capacities than the number 2 formulations. The higher values for average imbibition capacity correlate with higher values for average apparent porosity for each of the formulations. The average apparent porosities for B1 and B2 were 18.47% and 20.76% respectively. The average apparent porosity values for the Chaco soil formulations were 23.56% for C1 and 27.15% for C2 and, for the Salinas soil formulations, 27.17% for S1 and 28.46% for S2. The average apparent porosity value for the number 1 formulation for each soil was lower than that for the corresponding number 2 formulation (by 10%, 13%, and 5% for the B, C, and S soils, respectively), similar to the relative results observed for the average imbibation capacities.

One disparate finding is that the average imbibition capacity and the average apparent porosity for formulations S1 and S2 differ by only 5% while the other two soils displayed greater differences (10% - 17%) for the two values for the two values. It is likely that the smaller average particle sizes of the poorly-graded Salinas Mountainair local quarry soil formed slightly more uniform matrices with a large amount of interspacial voids in either formulation. Results of the dry sieve analysis for the Salinas soil (Appendix B) showed that 5/6 of the 48%-coarse-sand fraction of the soil (4.75 – 0.075 mm particle sizes) fell in the size range of 0.15 – 0.075 mm. The remaining 52% of particles fell in the size range below 0.075 mm. In any case, it seems that the less sandy soils (those with greater concentrations of small particles) exhibit the greater imbibition capacities and apparent porosities, as these values were highest for the Salinas formulations (over 90% of Salinas soil particles have sizes smaller than 0.15 mm), followed by the Chaco formulations and, finally, the Bandelier formulations.

Along with a higher absorption capacity, a stabilization mortar should optimally display a higher rate of drying (evaporation) than that of the surrounding original masonry in order to affect faster removal of water from the building system and, hopefully, the preferential passage of that water through the stabilization material. The rate of diffusion is the rate at which moisture, having entered a material through capillary absorption, is able to exit the material via evaporation. The rate of diffusion will depend on both the porosity of the material as well as the size of the pores, and can be affected by the surrounding climate. A higher rate of diffusion is considered positive in the case of stabilization mortars.

A cursory examination of the drying data for all samples tested suggests that each formulation tends to retain water. The number 2 formulations, all of which absorbed more water than their counterparts for each soil, reached the asymptotic state during drying before any of the number 1 formulations did.

Formulation B2, which displayed the lowest imbibition capacity, was the first to reach the asymptotic state at around 400 hours (nearly 7 days) followed by C2 and S2, lastly. Formulation S2 had displayed the highest imbibition capacity. Of the number 1 formulations, B1 was the first to reach the asymptotic state during drying, followed by C1, and S1.

In all cases, average imbibition capacity and average apparent porosity were inversely related to cement content in the tested formulations. Formulations with higher cement content (number 1 formulations) corresponded with lower values in all of these categories while lower cement content (number 2 formulations) corresponded with more optimal values. Imbibition capacity and apparent porosity seem to have been affected by soil type as well, with the well-graded Bandelier Garcia Landscape Materials blend soil formulations exhibiting the lowest values and the poorly-graded but finer Salinas Mountainair local quarry soil exhibiting the highest values. The result suggests that the finer soils can sustain a higher cement content in their mortar formulation while maintaining acceptable moisture transport capabilities. All formulations of the same number designations appeared to have a similar drying rate. Here again the number 2 formulations surpassed the number 1 formulations, exhibiting better diffusion over time and correlating superior drying behavior with lower cement content.

Water Vapor Transmission – Water in vapor form can be found in all masonry building systems. Any imperfect building membrane is permeable to water vapor, and masonry ruins are certainly included in this generalization.

Water can remain in the vapor state inside masonry walls. It can also become liquid by condensation or by means of hygroscopicity (*i.e.*, the ability of a material to absorb and collect moisture from the air). Stabilization mortars with lower vapor permeability than that of the original mortars have the potential to retard the release of water vapor from masonry envelopes, resulting in eventual condensation of trapped water vapor. This can lead to deterioration of masonry and fill material from the inside of a structure and can necessitate replacement of original material. On the other hand, stabilization mortars that display high vapor permeability can facilitate the timely removal of water vapor that inevitably finds its way into a masonry ruin.

The mixing of Portland cement results in the following exothermic chemical reaction:

Tricalcium silicate (Portland cement) + Water--->Calcium silicate tetrahydrate + Calcium hydroxide + heat

or

$$2\ Ca_3SiO_5 + 7\ H_2O \text{ ---> } 3CaO{\bullet}2SiO_2{\bullet}4H_2O + 3\ Ca(OH)_2 + 173.6\text{ kJ}$$

During setting, calcium silicate tetrahydrate forms a crystalline matrix within the voids occupied by water in the wet mortar mix, leading to small pores in the hardened mortar and consequentially low permeability. Therefore it was assumed prior to this test that the water vapor permeability would vary with the amount of Portland cement in the formulations. This hypothesis has been proven accurate. All number one formulations (3 soil : 1 cement) exhibited low average permeability in comparison to the number two formulations. The calculated average permiabilities for B1, C1, and S1 are 3.31 x 10^{-8} perm-cm^2, 4.12 x 10^{-8} perm-cm^2, and 5.29 x 10^{-8} perm-cm^2, respectively (see Chart 4.8). The calculated average permeabilities of the B2, C2, and S2 formulations, in comparison, are significantly larger: 9.92 x 10^{-8} perm-cm^2, 9.15 x 10^{-8} perm-cm^2, and 7.19 x 10^{-8} perm-cm^2, respectively.

The lowest permeability of the number 1 formulations (and of all formulations) was exhibited by formulation B1. This was followed by C1 and S1. The highest was exhibited by B2, followed by C2, and S2. This is an interesting finding, suggesting that the more dilute crystalline binder matrix that forms in the hardening of the weaker number 2 formulation of the well-graded Bandelier Garcia Landscape Materials blend soil leaves a large number of open pores within the mortar. The dilution of the crystalline binder matrix in the S2 formulation also effectively increases permeability compared to the lower value of the S1 formulation. However, it seems as though the uniform small pore size resulting from the poorly graded soil may have compensated for the dilution of the binder matrix by providing a more uniform pore distribution of the binder matrix throughout the hardened volume of the mortar.

Water vapor transmission appears to be unaffected by the clay content of (Chart 4.1), because the fairly well-graded Chaco BLM Quarry soil with slightly higher fractions of the same clay species as the Salinas Mountainair local quarry soil exhibited a permeability comparable to that of the low-clay Bandelier soil in the weaker number 2 formulation.

5.2.2 Durability

Frost Resistance – The testing of the frost resistance of the mortars relies on the simulation of active and intense weathering in a cold and wet environment to induce damage to mortars that is representative of the damage they might incur under field conditions. The fifteen-cycle test consisted of an 8-hour period of thawing and water saturation by immersion of mortar samples in a bath of room-temperature water, followed by an 8-hour freezing period. This is a more rigorous freeze/thaw cycle than field conditions would provide, though, as a measure of compensation for the abbreviated duration of the test compared to the length of exposure that mortars receive in field use.

All mortar formulations tested fared extremely well under the simulated weathering conditions. Only the samples of the S2 formulation (6 soil : 1 cement) experienced deterioration, but this was minimal. The final bulk volume retained by the S2 formulation was 99.60%. All other formulations retained their full bulk volumes. Delamination was observed on the surfaces of the S2 samples, as was some dimensional loss at the corners of all samples. This deterioration in the weaker of the two Salinas soil mortar formulations is the likely result of the combination of the high apparent porosity and imbibation capacity of formulation S2 (as calculated from water absorption data), the uneven particle size distribution of the Salinas soil, and the low cement content. The high porosity and imbibation capacity of this formulation make it likely to absorb relatively large amounts of water during the thawing period. Because of the absence of sand aggregate of any type in the soil there is little potential for variation in the weak binder matrix of the number 2 formulation. Thus the formation of sub-surface ice crystals during the freezing period provided a sufficient strain on the highly crystalline matrix to separate portions of the samples. As both the B2 and C2 formulations fared very well throughout the fifteen cycles, it is probable that the weakness of the S2 formulation could be mitigated by the addition of a small portion of coarse sand of the size range >0.15 mm.

Erodability – The CRATerre water-drop erodability test was designed for the testing of mud bricks, which, as masonry units, are prone to direct exposure to falling water. Pointing mortars are typically covered by masonry and do not normally receive this type of exposure. However, the test does suggest how the mortars will perform under extended exposure to wind-driven rain as well as other erosive conditions.

All mortar formulations as well as 2-inch cubes of the unamended soils were subjected to a constant water fall at the rate of one drop per second falling over a distance of 2.5 meters for the period of one hour. None of the amended formulations exhibited any erosive damage following the period of exposure. The unamended soil samples, however, experienced significant penetration by the water fall. The unamended Bandelier soil samples were scored across an area of roughly 1 in^2 to an average depth of 20.61 mm. The unamended Chaco soil samples were scored over a similar area to and average depth of 15.04 mm. The unamended Salinas samples were scored to an average depth of 8.75 mm. An observation concerning these samples is that depth of penetration seemed to be associated with the coarse sand component of the soils. That is, the greatest depth (scored on the unamended Bandelier soil samples) corresponded to the soil with the highest content of coarse sand. The most minor depth was scored on the unamended Salinas samples. However, the unamended Salinas samples exhibited a greater tendency to deform when handled following the exposure period, followed by the unamended Chaco samples. The unamended Bandelier samples displayed the least tendency to deform. This suggests that a higher coarse sand content renders a very weak unamended soil mortar that is more susceptible to erosion but increases its ability to retain its form under prolonged exposure to precipitation.

Modulus of Rupture – It is not uncommon for masonry ruins to be subjected to significant differential movement in an open environment. Often the loss of building fabric leaves partial remains of these buildings structurally unsound without full foundations or complete enclosures to brace the walls against their own weight. This can result in the application of high tensile strain on the masonry and mortar joints in the structures. Numerous environmental conditions including temperature fluctuation, the presence of liquid water, and water vapor in air can also contribute to expansion and contraction of building stone, putting additional tensile strain on masonry joints. The test result for modulus of rupture uses the maximum load-carrying capacity of the soil-cement mortar samples in bending (the maximum load borne by a sample at the time at the time of breaking) and is a representation of the tensile strength of the mortars. A stabilization mortar's modulus of rupture should be lower than that of the masonry around it in order that tensile strain in the original material be deferred to the sacrificial stabilization material. Optimally the stabilization mortar should also have a high enough modulus of rupture so that it will not crack under tensile strain, although this concern is secondary. The modulus of rupture is an important measure of the durability of a mortar under active use conditions.

It was expected prior to testing that the number 1 formulations would display the highest strength in bending. Cement binder matrices impart high rigidity to mortars, and while rigidity is not normally associated with tensile strength, greater cement quantities in mortars equate to greater resistance to cracking under a three-point load. The expectation of greater strength of the number 1 formulations proved to be accurate. Formulations B1, C1, and S1 all displayed moduli of rupture superior to those of the number 2 formulations. The average calculated value for each was as follows: 1130.11 psi for B1, 838.72 psi for C1, and 637.52 for S1. The strength ratings were inverted by soil for the number 2 formulations with average calculated moduli of rupture of 485.49 psi for S2, 394.17 psi for C2, and 309.88 for B2.

The high overall strength of the B1 samples may be correlated with the good particle size distribution of the Bandelier Garcia Landscape Materials blend soil, which decreases the chance of formation of micro cracks in the sample surfaces. The Chaco and Salinas soils both have a higher clay content and (particularly in the case of the Salinas Mountainair local quarry soil) a poorer particle size distribution within the coarse sand size range. Combined factors promote micro cracks in the surfaces of mortars that are rich in clays and unmitigated by the presence of shrinkage-controlling aggregates. Conversely, the presence of aggregates in a soil such as the Bandelier Garcia Landscape Materials blend soil has the potential to be problematic in weaker formulations because smooth surfaces are harder to mold in samples with more bulk aggregate, resulting in voids and lateral impingements along the corners of the specimens that can compromise bending strength in formulations with lower cement contents. As in other tests performed on these samples, the Chaco soil formulations occupied the mid-range of strength and performance. This trend suggests that optimal performance in a stabilization mortar may be desirable, but with greater strength also comes associated weaknesses in other properties. At times the middle ground can be the best choice.

Splitting Tensile Strength – Stabilization mortars used in pointing are not subject to direct compression from masonry (bedding mortars receive most of this force). The surfaces of pointing mortars are not typically vertical but are usually recessed and display curvature as a result of tooling. Thus any downward load that they do receive from masonry is distributed throughout the concave surfaces and results in a transfer of that compressive load into tensile strain. The test for splitting tensile strength gives the best indication of how pointing mortars will fare under these conditions. By applying a downward force to cylindrical mortar specimens in the test apparatus, tensile failure is induced as a result of triaxial compression.[50] This test method serves mainly as a means for rating the durability of mortars by virtue of their capacity to withstand the tendency to shear off under compression.

The number 1 formulations exhibited the highest average splitting tensile strength with B1 having the highest calculated value at 589.05 psi, followed by C1 at 468.76 psi, and S1 at 374.64. The average calculated splitting tensile strength values for the number 2 formulations was 236.99 psi for B2, 180.10 psi for C2, and 211.53 psi for S2, all reduced by more than half from the results for the corresponding number 1 formulations. While formulation B2 exhibited the highest strength of the number 2 formulations, the average calculated values in this case were fairly similar and, as a group, did not display a trend with the strengths indicated by those calculated for the average modulus of rupture. In contrast the number 1 formulations did fit the pattern of strength displayed by the number 1 formulations in the average modulus of rupture calculations. This trend indicates that the high strength imparted on the number 1 formulations by their 25% cement content allowed failures to occur that better reflected the suitability of each soil as a mortar component. It should be noted that the calculated averages for splitting tensile strength of each formulation are far lower than those calculated for modulus of rupture of each formulation. This indicates the true weakness of cementitious mortars against tensile forces. This demonstrated weakness of the number 2 formulations (with a 14% cement content) acts as a

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[50] "C496-96, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", (Philadelphia: ASTM, 1996).

representation of the limitation of cement as an amendment to stabilization mortars rather than an indicator of mortar strength variations affected by soil type.

5.3 Conclusion

Table 5.2 summarizes the average tested properties of earthen mortars prepared from the Bandelier, Chaco, and Salinas soils amended with Portland cement. Even the weaker cement-amended mortars (14% Portland cement) indicated zero penetration depth in the water drop erosion test and 100% retention of bulk volume following extreme freeze-thaw cycling. Therefore, these two properties of the amended mortars have not been plotted *vs*. percent Portland cement. Amended mortars that are weaker still (less than 14% Portland cement) should demonstrate both substantial resistance to water erosion and essentially full retention of bulk volume under freeze-thaw conditions imposed by the two test methods that establish these mortar properties.

Table 5.2. Sample Averages (A) and the Linear Trends*

Sample	Portland Cement % by Vol. (x)	Splitting Tensile Str. (psi)	Mod. of Rupture (psi)	Penetration Depth (mm)	Water Vapor Permability (perm·cm)	% Bulk Vol. Retained	% Apparent Porosity
B1	**25**	589	1130	0.0	3.31E-08	100.3	18.5
B2	**14**	237	310	0.0	9.92E-08	100.4	20.8
BU	**0**			20.6			
$m_B = B_{slope}$		**32.9**	**76.6**		**-6.17E-09**		**-0.214**
$b_B = B_{intercept}$		**-232.4**	**-783.8**		**1.87E-07**		**23.81**
C1	**25**	469	839	0.0	4.12E-08	101.7	23.6
C2	**14**	180	394	0.0	9.15E-08	100.4	27.2
CU	**0**			15.0			
$m_C = C_{slope}$		**26.9**	**41.5**		**-4.69E-09**		**-0.335**
$b_C = C_{intercept}$		**-204.8**	**-198.6**		**1.59E-07**		**31.94**
S1	**25**	375	638	0.0	5.29E-08	100.9	27.2
S2	**14**	212	485	0.0	7.99E-08	99.6	28.5
SU	**0**			8.8			
$m_S = S_{slope}$		**15.2**	**14.2**		**-2.52E-09**		**-0.120**
$b_S = S_{intercept}$		**-6.0**	**-282.8**		**1.16E-07**		**30.18**

*** Slope and Intercept determined from linear fit to A vs. x (A = mx + b).**

Charts 5.1 through 5.4 are present the average tested properties given in Table 5.1 for splitting tensile strength, modulus of rupture, water vapor permeability, and water porosity (respectively) *vs*. volume-percent of Portland cement for amended mortars of the Bandelier, Chaco and Salinas soils. A linear fit to the pair of results for individual tested properties in two formulations (14% and 25% cement content) of each soil-cement is plotted on each chart as a straight line through the corresponding pair of points. The slope and intercept of each straight-line fit are indicated in Table 5.1. The trends discussed above indicate that these fit parameters are reasonable. The parameters themselves are also useful.

The fit parameters (slope and intercept) are quantitative expressions of two aspects of the systematics discussed above:

1) The quantitative impact of the properties of the individual soil type on the properties of the amended earthen mortars is given by the differences in the slopes (especially) for a given soil property with each of the three soil types.
2) The amendment formulation (% Portland cement) required to achieve a specific result for any of these four soil properties (splitting tensile strength, modulus of rupture, water vapor permeability, and water porosity) can be determined by the corresponding slope and intercept for any of the three soil types.

The most reasonable application of the fitted slopes and intercepts is for earthen mortars with amendments between 14% and 25% Portland-cement amendments. An obvious indication of the invalidity of the linear fit outside this range is that the straight-line fit to the results for splitting tensile strength and modulus of rupture (Charts 5.1 and 5.2) drops below zero for formulations much weaker than 14%-cement. Tests on additional weaker mortar formulations would support a higher-order (quadratic) fit to produce the realistic curvature that would describe the properties of the weaker formulations. Both 10% and 5% formulations are recommended for additional tests based on trends indicated by Fenn’s data (Charts 2.1 and 2.2).

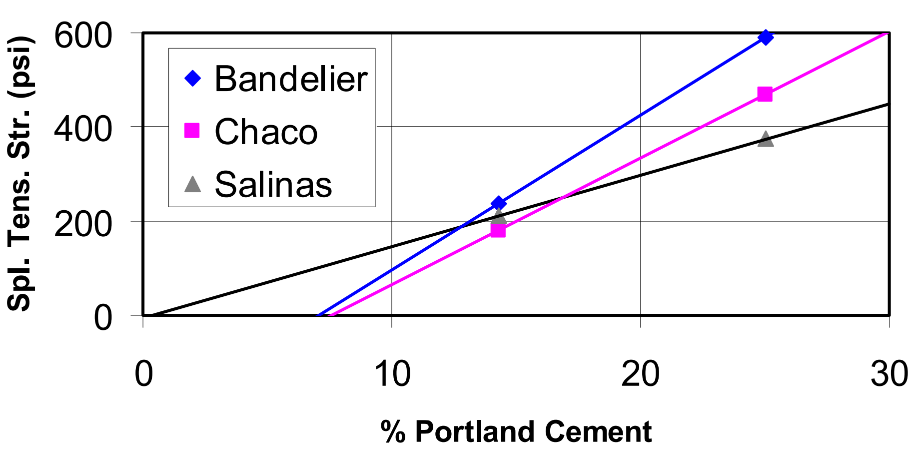

Chart 5.1. Trend for Splitting Tensile Strength

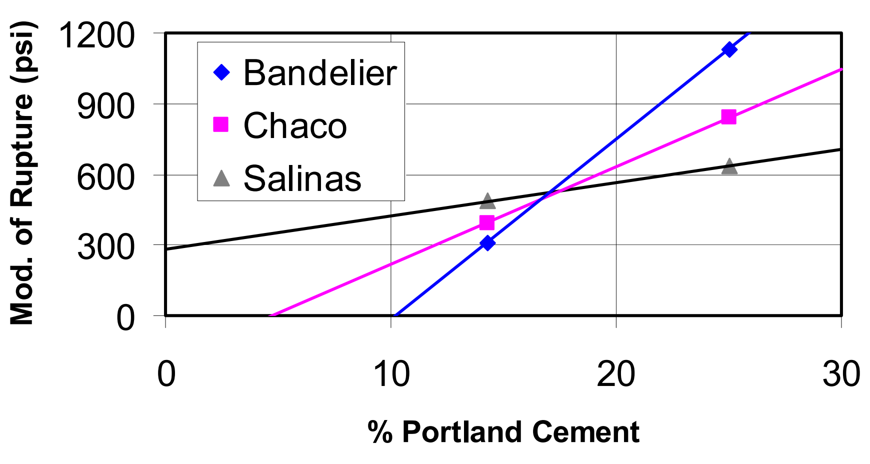

Chart 5.2. Trend for Modulus of Rupture

Certain needs could drive the use of even weaker mortars than the 14%-cement formulation. Zero penetration depth for water erosion and retention of bulk volume in freeze-thaw cycles were invariant properties for the two tested formulations (in all cases but that that of formulation S2, which lost bulk volume during the latter freeze/thaw cycles) suggesting that the durability observed in these formulations is likely to persist with even weaker formulations. The desirable properties of high water vapor permeability and porosity discussed above, whose trends with each cement formulation are indicated in Charts 5.3 and 5.4, may require cement admixtures that are even weaker than 14% for some climates and environments. Knowledge of the splitting tensile strength and modulus of rupture for such weaker cement-amended mortar formulations would be important information in these cases. Therefore, extension of the testing of earthen mortars with amendments below 14% Portland-cement is recommended as beneficial future work in this area.

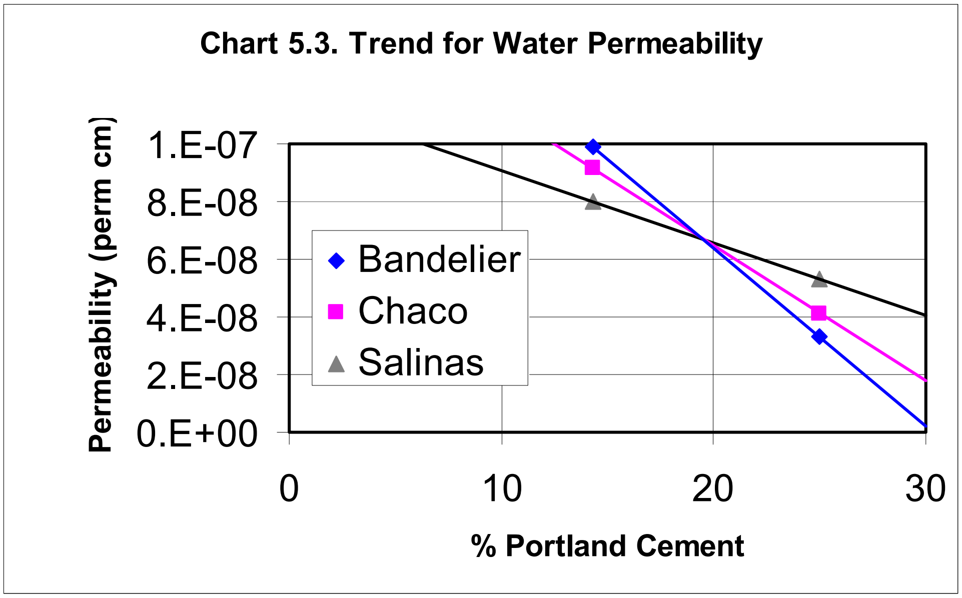
Chart 5.3. Trend for Water Permeability
Permeability (perm cm)
1.E-07
8.E-08
6.E-08
4.E-08
2.E-08
0.E+00
0
10
20
30
% Portland Cement
◆ Bandelier
■ Chaco
▲ Salinas

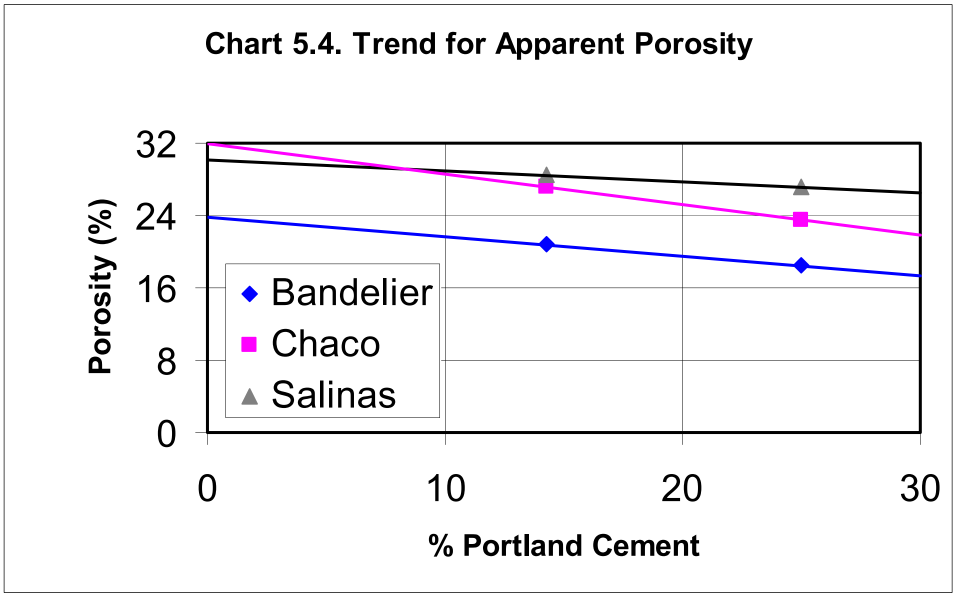
Chart 5.4. Trend for Apparent Porosity
Porosity (%)
32
24
16
8
0
0
10
20
30
% Portland Cement
◆ Bandelier
■ Chaco
▲ Salinas

Extended experimental studies of cement-amended earthen mortars in which specific soil characteristics are varied in a controlled manner is a second area that is recommended for future work. The Bandelier soil may be particularly well suited to such an advanced study because the soil is composed of three specific soil types, each of known formulation. The composition of the Bandelier soil-type mixture described in Section 3.4.2 could be readily varied without altering the three soil-type formulations themselves. Because the Chaco and Salinas soils are quarried, a controlled study of the effects of soil characteristics would be subject to the variations in soil properties within the quarry site and would also require addition of materials (such as coarse sands for bulk) to the quarried soils to achieve specific quantitative variations in the soil composition. Fenn’s characterization of cement-amended mortars from different locations at both Chaco and Bandelier (Chapter 2) illustrate the significant variations in soil properties within a site that must be avoided in a controlled study that examines the quantitative effects of measured soil properties.

Characterizing the various forms of masonry stone used at each site is a third essential experimental effort that must precede long-term implementation. Reiterating requirements related to properties of the stone, stabilization mortars must exhibit maximum durability consistent with lower strength and higher moisture-transport compared to the characteristics of the stone.

5.3.1 General Recommendations for Field Testing of Mortars

A conservative approach to initial field testing of cement-amended stabilization mortars is recommended for NPS implementation at Bandelier, Chaco, and Salinas given the results of the current laboratory testing with formulations as low as 14% cement. The following is a generic overview of suggested test materials, test environments, testing methods, controls, and evaluation criteria. The test plan called out under "Materials" (below) must include a comprehensive specification of: test environments, design of methods, implementation of controls, and evaluation because of the many variables associated with these components of the testing.

Materials – Each site should develop a test plan to implement stabilization mortars with 14%-cement formulations, as these strong formulations show high durability against water erosion and freeze-thaw damage, as well as better moisture transport and a smaller impact on color than the 25%-cement formulations. Use white Portland cement for consistency with the laboratory testing. The three sites should use the same soils utilized in this laboratory thesis study: those that are in current use for stabilization mortars at Bandelier, Chaco, and Salinas as described in Section 3.4.2.

Environments – Choose test locations that offer a range of exposure, high and low, both to moisture and to temperature cycling. The minimum two test locations would include one with the most moisture and greatest exposure to freeze/thaw cycling and a second with the least. Also recommended are two intermediate locations – one of high-moisture and low-freeze/thaw cycling, and the other of low-moisture and high-freeze/thaw cycling – if feasible. Consistent choice of test locations for the cement-amended mortars among parks is not a practical option because of variation in the environments of each park, but compensation is offered by consistency in the monitoring of moisture and temperature/cycling as described next.

Methods – Methods for evaluating durability performance and character-related qualities (such as color) of the test stabilization mortars must be defined in advance of execution of field testing and implemented consistently within each site. Consistent implementation of methods and time intervals for monitoring both moisture and temperature/cycling throughout the test period at each site is essential within each site. The benefit of concerted efforts at the three sites for consistent implementation of methodology among sites would greatly increase the significance of the field-testing data.

Controls – Apply the tests for evaluating durability performance and character-related qualities to other stabilization mortars of known formulations at the test locations when such formulations use soils identical to those specified above under "Materials". Masonry stone used in concurrent testing of stabilization mortars must be the same in order to compare characteristics of test mortars. Concurrent equivalent tests with alternative cement formulations for stabilization mortars are likely options for Bandelier. Concurrent equivalent testing with acrylic-amended stabilization mortars at Chaco where such amendments have been field-tested is also possible. Concurrent equivalent tests with both acrylic-amendment formulations or with alternative cement-amendment formulations for stabilization mortars are likely options for Salinas. Mortars subjected to surface treatment with water repellent chemicals for stabilization should not be considered for the initial field comparisons.

Criteria – Judge performance according to the results for durability of the stabilized mortars tested in the field. Based on the current laboratory data, equal durability performance and equivalent character-related qualities (such as color) would favor the cement over acrylic amendments for greater strength.

5.3.2 Site-Specific Recommendations

Bandelier – The soil currently used for stabilization work at Bandelier National Monument (Garcia Landscape Materials blend) is suitable as a component of soil-cement stabilization mortars. Sieving of the soil should be considered for tests involving pointing mortars to remove some of the larger aggregates (> 2.0 mm), enhancing the strength of weaker soil-cement formulations.

The majority of exposed site structures at Bandelier have undergone some stabilization. Of these, the kiva known as “Big Kiva” is most notable structure to contain significant quantities of cement stabilizing mortars. If the NPS intends to retain the current cement mortars for Big Kiva, then pointing mortars with similar but lower cement content than that of the current cement bedding mortars are recommended for future soil-cement stabilization. This will promote a gradient release of moisture from within enclosed materials. If older cement mortars are removed prior to further stabilization attempts, soil-cement mortars with 14% cement content should be considered as an initial formulation for pointing mortars. Following on-site testing for durability of these mortars and other (possibly weaker) formulations, formulations with lower cement contents than those of new bedding mortars are recommended for pointing to ensure optimal moisture removal from the wall system.

Building stone in this and other structures at Bandelier is regarded as favorably durable in comparison to the weaker soil-cement formulations (see data from Fenn, 1978, Appendix M). The high porosity and permeability of this volcanic stone makes it a good substrate for soil-cement application as the masonry alone presents an expedient route for escape of water from within the wall system.

Chaco – The soil currently used for stabilization mortars at Chaco Culture National Historic Park (BLM Quarry soil) is suitable as a component in soil-cement stabilization mortars. It may be beneficial (at the discretion of masonry personnel) to add small quantities of coarse masonry sand to soil used in pointing mortars. The presence of moderate amounts of small, coarse aggregate was shown to improve permeability of soil-cement mortars in laboratory testing. Because the majority of sites in this park consist of wide, coursed and rubble-core walls, weak soil-cement formulations (14% cement or less) are highly recommended for pointing mortars to expedite water removal from the wall systems. When field-testing soil-cements with 14% cement content, concurrent testing of weaker formulations should be conducted to determine the comparative durability of these weaker formulations. These will inevitably exhibit higher permeability, which will benefit moisture removal from wall systems.

Sandstone masonry at the Chaco sites exhibits high strength (see data from Fenn, 1978, Appendix M) and should not be put at risk for damage by weak soil-cement pointing mortars. Though porous, this stone may exhibit low permeability, and so expedient routes of moisture removal from wall systems should be sought through mortar joints pointed with more permeable soil-cement formulations.

Salinas – The soil used in stabilization mortars at the Gran Quivira site at the Salinas Pueblo Missions National Monument (Mountainair local quarry soil) could benefit from the discretionary addition of coarse masonry sand for use in soil-cement stabilization mortars. This would have the effect of increasing durability to freeze/thaw cycling and increasing the permeability of the mortars to water vapor.

Weak soil cement formulations (14% cement) have been used at this site most recently in 1996. It is recommended that the local soil with a 5-10% addition of coarse masonry sand be field-tested concurrently with unaltered soil, both in a formulation of 14% cement, 86% soil (1 cement : 6 soil), to compare the durability of the two soil-mortar types in similar conditions.

The standing structures at Gran Quivira are thick, rubble-core walls, the majority of which have been reconstructed during multiple previous stabilizations. Kiva structures at this site consist of coursed, previously stabilized masonry.

Field testing of soil-cement pointing mortars with cement contents below 14% is also recommended in the interest of establishing outer membranes in masonry joints that have higher vapor permeability than that of existing cement-amended bedding mortars.

Data on the various types of limestone comprising the masonry at this site was not available for this study. It is recommended that these stones be tested in the future for strength, capillary absorption capacity, and water vapor permeability. Permeability of these stones was assumed to be low based on their apparent density. Therefore site personnel should consider masonry joints as the primary route of exit for moisture within wall structures at Gran Quivira.

5.4 Summary

The experimental work for this thesis has involved quantitative testing of the properties of earthen mortars amended with Portland cement. The work has been successful in

- measuring the critical properties of earthen mortars amended with Portland cement.
- quantifying the effects of variable cement formulations on the tested properties.
- quantifying the effects for a particular cement formulation of specific soil types on the tested properties.

Extending the experimental laboratory work as indicated above to include weaker cement formulations, quantitative soil studies, and characterization of masonry stone will increase confidence in the quantitative applications of the trends derived in this thesis and will extend the range in which such quantitative trends can be applied in the field.

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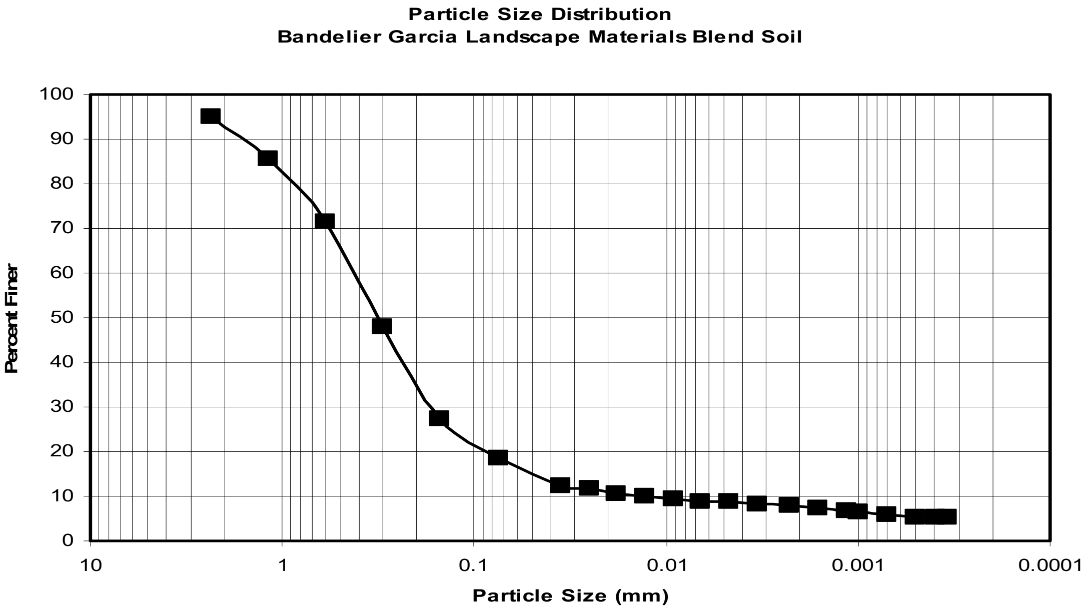
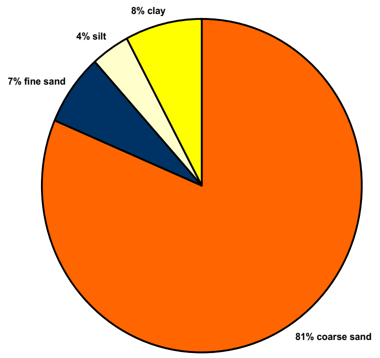
Appendix A: Soil Characterization Data Sheets

SOIL CHARACTERIZATION SHEET	**Bandelier – Garcia Landscape Materials Blend Soil**



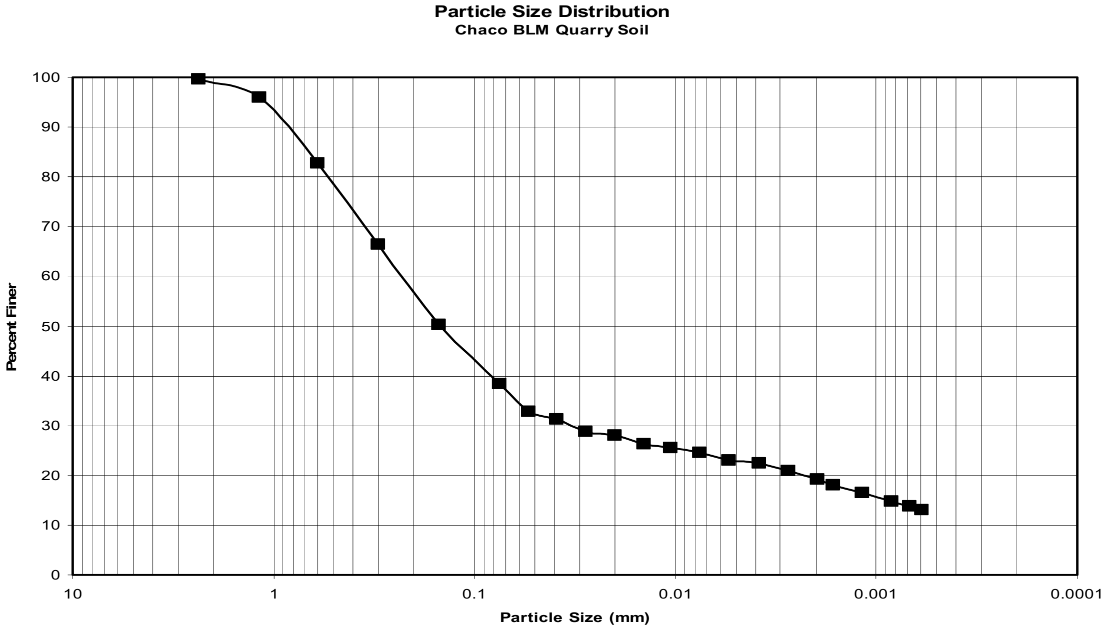
Plastic Limit	Indeterminate
Liquid Limit	Indeterminate
Plasticity Index	Non-plastic
pH in Water	7.5
pH in $CaCl_2$	7.4
Munsell Color	7.5YR 5/3, Brown
Percent Carbonate	5.60%
Soluble Salts	Negligible
Soil Density	4.20 g/cm3



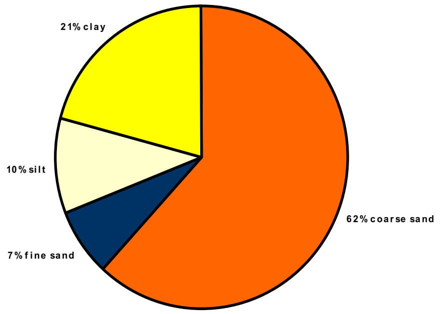
Particle Description	(>0.75 mm)
Particle Size	81% of the grains are coarse sand in the range (4.75 - 0.075 mm)
Particle Shape	good mix of sub-rounded and sub-angular particles
Color	Reddish gray and reddish brown with some light brown, lots of quartz
Notes	Well graded, low clay content, low organic content

Appendix A: Soil Characterization Data Sheets

SOIL CHARACTERIZATION SHEET	Chaco - BLM Quarry Soil



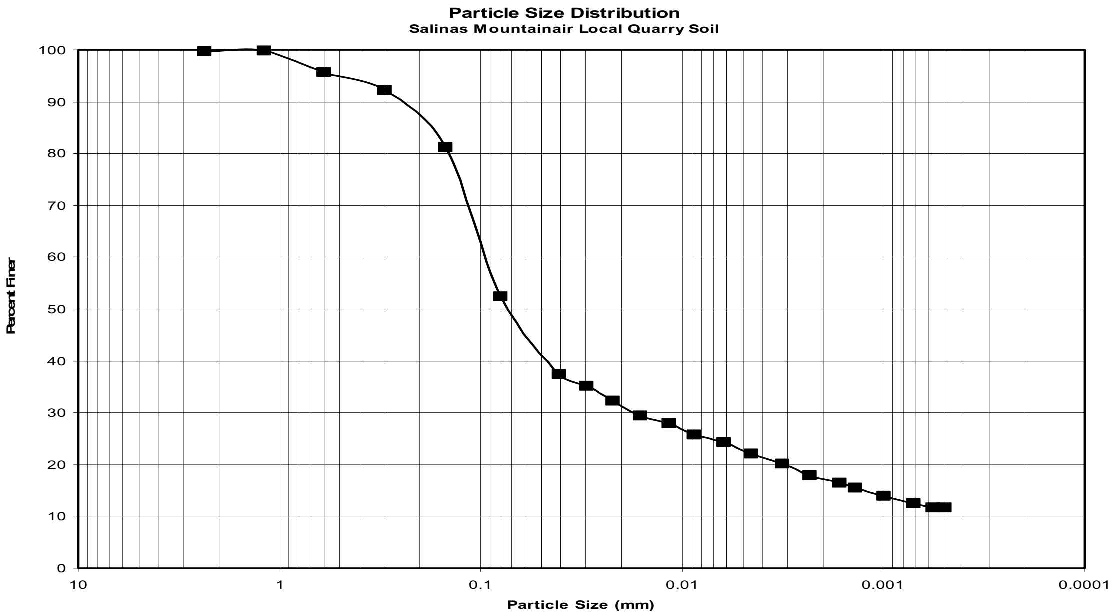
Plastic Limit	19.3
Liquid Limit	23.4
Plasticity Index	4.1
pH in Water	8.1
pH in $CaCl_2$	7.7
Munsell Color	2.5Y 6/3, Light Yellowish Brown
Percent Carbonate	2.40%
Soluble Salts	Negligible
Soil Density	2.68 g/cm^3



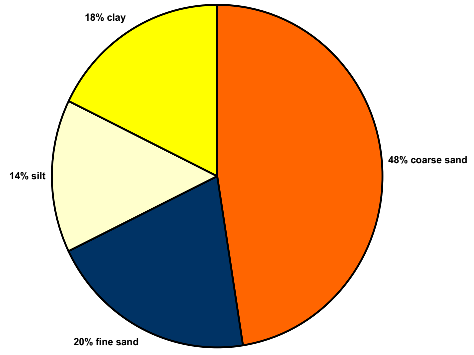
Particle Description	(>0.75 mm)
Particle Size	62% of the grains are in the coarse sand range (4.75-0.75 mm), these are fairly well-graded
Particle Shape	roughly even mix of rounded and sub-rounded particles
Color	yellowish brown and brownish gray
Notes	soil is on the finer side but is well-graded overall

Appendix A: Soil Characterization Data Sheets

SOIL CHARACTERIZATION SHEET	**Salinas – Mountainair Local Quarry Soil**



Plastic Limit	21.7
Liquid Limit	25.4
Plasticity Index	3.7
pH in Water	7.3
pH in $CaCl_2$	7.2
Munsell Color	7.5YR 4/4, Brown
Percent Carbonate	2.48%
Soluble Salts	Negligible
Soil Density	3.25 g/cm3



Particle Description	(>0.75 mm)
Particle Size	48% of the grains are in the course sand range (4.75-0.75 mm), these tend to be poorly graded
Particle Shape	Predominantly sub-angular with a notable quantity of rounded particles
Color	brown overall
Notes	a very fine soil with noticable amounts of organic content.

Appendix B: Soil Characterization Summary Data

Sieve Analysis and Soil Particle Descriptions

Bandelier – Garcia Landscape Materials Blend

ASTM Sieve Number	Screen Size (mm)	Mass of container (g)	Mass of sample & container (g)	Mass retained (g)	Percent mass retained	Percent on or above	Percent Passing
8	2.36	1.94	7.72	5.78	4.87	4.87	95.13
16	1.18	1.91	13.08	11.17	9.41	14.28	85.72
30	0.60	1.93	18.72	16.79	14.14	28.42	71.58
50	0.30	1.90	29.84	27.94	23.53	51.95	48.05
100	0.15	1.88	26.36	24.48	20.62	72.57	27.43
200	0.075	1.91	12.42	10.51	8.85	81.42	18.58
Pan	0.001	1.82	23.88	22.06	18.58	100.00	0.00

Total mass of sample = 118.73g

Sieve Number	Particle Size	Color (Munsell)	Sphericity	Roundness	Sorting	Magnification
8	Granules	7.5YR/7/2 pinkish gray	High	Sub-rounded	Very good	7x
16	Very Coarse	7.5YR/5/2 brown	Medium	Sub-rounded	Good	7x
30	Coarse	5YR/5/2 light reddish gray	High	Sub-angular	Good	9x
50	Medium	7.5YR/6/3 light brown	High	Sub-rounded	Good	20x
100	Fine	5YR/5/4 reddish brown	High	Sub-angular	Fair	30x
200	Very Fine	7.5YR/6/3 light brown	High	Sub-angular	Fair	30x
Pan	Clay/Silt	7.5YR/6/3 light brown	---	---	---	---

Munsell Color of Un-sieved Soil : 7.5YR/5/3 Brown

Appendix B: Soil Characterization Summary Data

Sieve Analysis and Soil Particle Descriptions

Chaco – BLM Quarry Soil

ASTM Sieve Number	Screen Size (mm)	Mass of container (g)	Mass of sample & container (g)	Mass retained (g)	Percent mass retained	Percent on or above	Percent Passing
8	2.36	1.92	2.49	0.57	0.47	0.47	99.53
16	1.18	1.89	6.27	4.38	3.61	4.08	95.92
30	0.60	1.92	17.94	16.02	13.19	17.27	82.73
50	0.30	1.89	21.81	19.92	16.40	33.67	66.33
100	0.15	1.95	21.34	19.39	15.97	49.63	50.37
200	0.08	1.86	16.39	14.53	11.96	61.60	38.40
Pan	0.00	1.97	48.61	46.64	38.40	100.00	0.00

Total mass of sample = 121.45g

Sieve Number	Particle Size	Color (Munsell)	Sphericity	Roundness	Sorting	Magnification
8	Granules	2.5Y/6/3 light yellowish brown	High	Rounded	Poor	7x
16	Very Coarse	2.5Y/6/2 light brownish gray	High	Rounded	Fair	7x
30	Coarse	2.5Y/6/2 light brownish gray	High	Well-rounded	Fair	20x
50	Medium	2.5Y/6/2 light brownish gray	High	Sub-rounded	Poor	30x
100	Fine	2.5Y/6/3 light yellowish brown	High	Sub-rounded	Poor	30x
200	Very Fine	2.5Y/6/2 light brownish gray	High	Sub-angular	Poor	30x
Pan	Clay/Silt	2.5Y/6/3 light yellowish brown	---	---	---	---

Munsell Color of Un-sieved Soil : 2.5Y/6/3 Light yellowish brown

Appendix B: Soil Characterization Summary Data

Sieve Analysis and Soil Particle Descriptions

Salinas – Mountainair Local Quarry Soil

ASTM Sieve Number	Screen Size (mm)	Mass of container (g)	Mass of sample & container (g)	Mass retained (g)	Percent mass retained	Percent on or above	Percent Passing
8	2.36	1.92	2.21	0.29	0.24	0.24	99.76
16	1.18	1.91	4.03	2.12	1.77	2.01	97.99
30	0.60	1.93	4.62	2.69	2.24	4.25	95.75
50	0.30	1.89	6.15	4.26	3.55	7.79	92.21
100	0.15	1.86	15.09	13.23	11.01	18.81	81.19
200	0.08	1.87	36.42	34.55	28.77	47.57	52.43
Pan	0.00	1.88	64.85	62.97	52.43	100.00	0.00

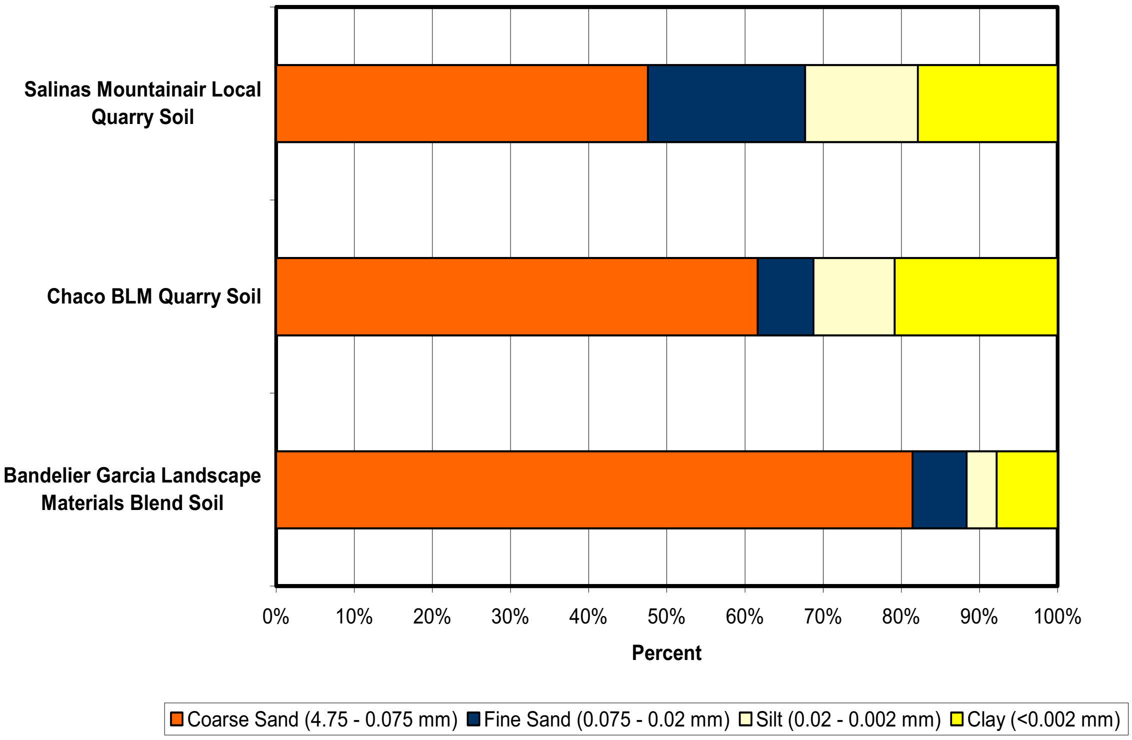
Total mass of sample = 120.11g

Sieve Number	Particle Size	Color (Munsell)	Sphericity	Roundness	Sorting	Magnification
8	Granules	Fraction too small to ascribe overall color rating	High	Sub-rounded	Poor	1x
16	Very Coarse	7.5YR/4/2 brown	Low	Sub-angular	Poor	7x
30	Coarse	7.5YR/4/2 brown	Medium	Rounded	Fair	7x
50	Medium	7.5YR/4/3 brown	Medium	Rounded	Fair	7x
100	Fine	7.5YR/4/3 brown	High	Sub-angular	Good	30x
200	Very Fine	7.5YR/4/4 brown	High	Sub-angular	Poor	30x
Pan	Clay/Silt	7.5YR/4/4 brown	---	---	---	---

Munsell Color of Un-sieved Soil : 7.5YR/4/4 Brown

Appendix B: Soil Characterization Summary Data

ASTM Particle Size Distribution



Appendix B: Soil Characterization Summary Data

Acid Soluble (Carbonate) Fraction

Soil	Dry Sample Mass (g)	Mass after Acid Digestion (g)	Mass of Acid-Soluble Fraction (g)	% Acid-Soluble
Bandelier - Garcia Landscape Materials Blend	25.00	23.60	1.40	5.60
Chaco - BLM Quarry Soil	25.00	24.40	0.60	2.40
Salinas - Local Quarry	25.00	24.38	0.62	2.48

Atterberg Limits

Soil	Plastic Limit	Liquid Limit	Plasticity Index
Bandelier - Garcia Landscape Materials Blend	Indeterminate	Indeterminate	Non-Plastic
Chaco - BLM Quarry Soil	19.3	23.4	4.1
Salinas - Local Quarry Soil	21.7	25.4	3.7

Appendix B: Soil Characterization Summary Data

Soil Density

Soil	Density (g/cm^3)
Bandelier - Garcia Landscape Materials Blend	4.20
Chaco - BLM Quarry Soil	2.68
Salinas - Local Quarry Soil	3.25

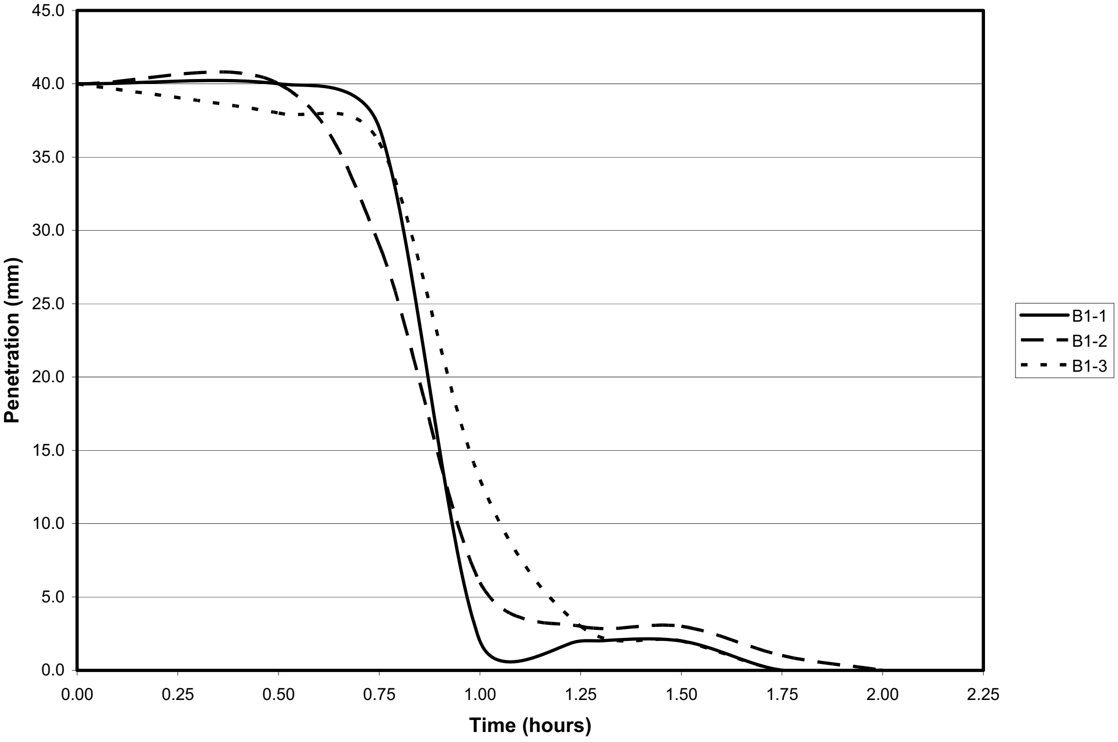
Soil pH

Soil	pH in Water	pH in $CaCl_2$
Bandelier - Garcia Landscape Materials Blend	7.5	7.4
Chaco - BLM Quarry Soil	8.1	7.7
Salinas - Local Quarry Soil	7.3	7.2

APPENDIX C: TIME OF SETTING – ASTM C191-92

Formulation B1 (3 soil: 1cement)

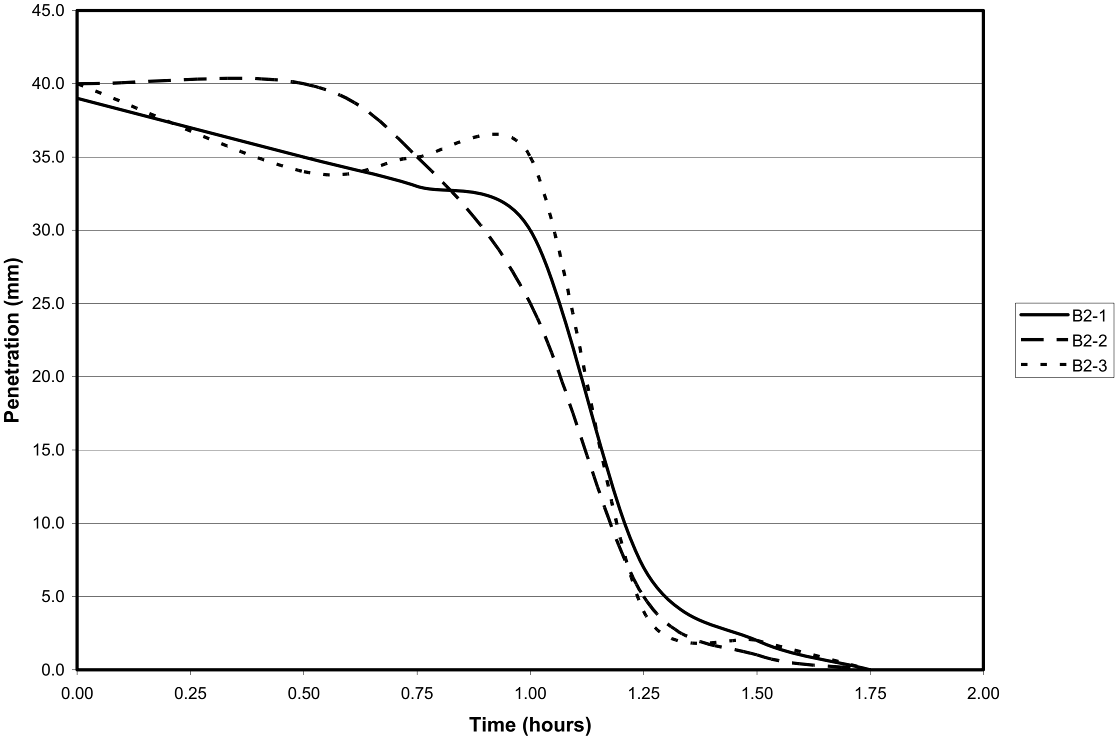
Time Elapsed (hours)	Depth of Penetration (mm)		
	B1-1	B1-2	B1-3
0.00	40	40	40
0.50	40	40	38
0.75	37	29	36
1.00	2	6	13
1.25	2	3	3
1.50	2	3	2
1.75	0	1	0
2.00	0	0	0



APPENDIX C: TIME OF SETTING – ASTM C191-92

Formulation B2 (6 soil: 1cement)

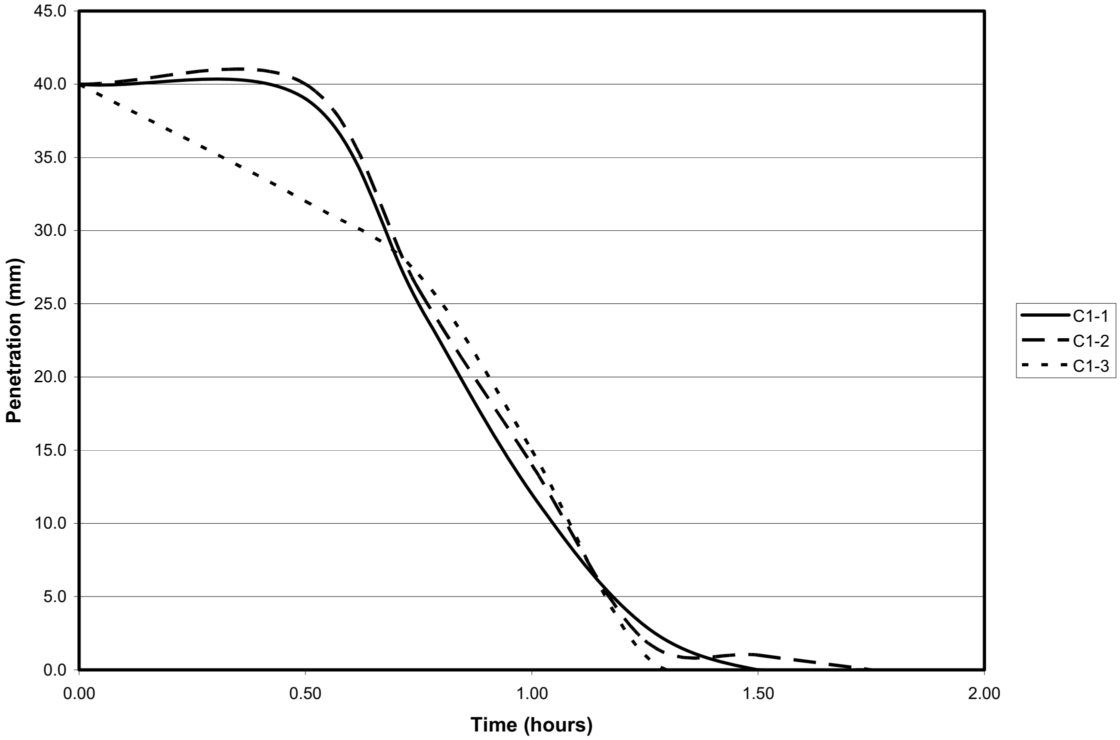
Time Elapsed (hours)	Depth of Penetration (mm)		
	B2-1	B2-2	B2-3
0.00	39	40	40
0.50	35	40	34
0.75	33	35	35
1.00	30	25	35
1.25	7	5	4
1.50	2	1	2
1.75	0	0	0



APPENDIX C: TIME OF SETTING – ASTM C191-92

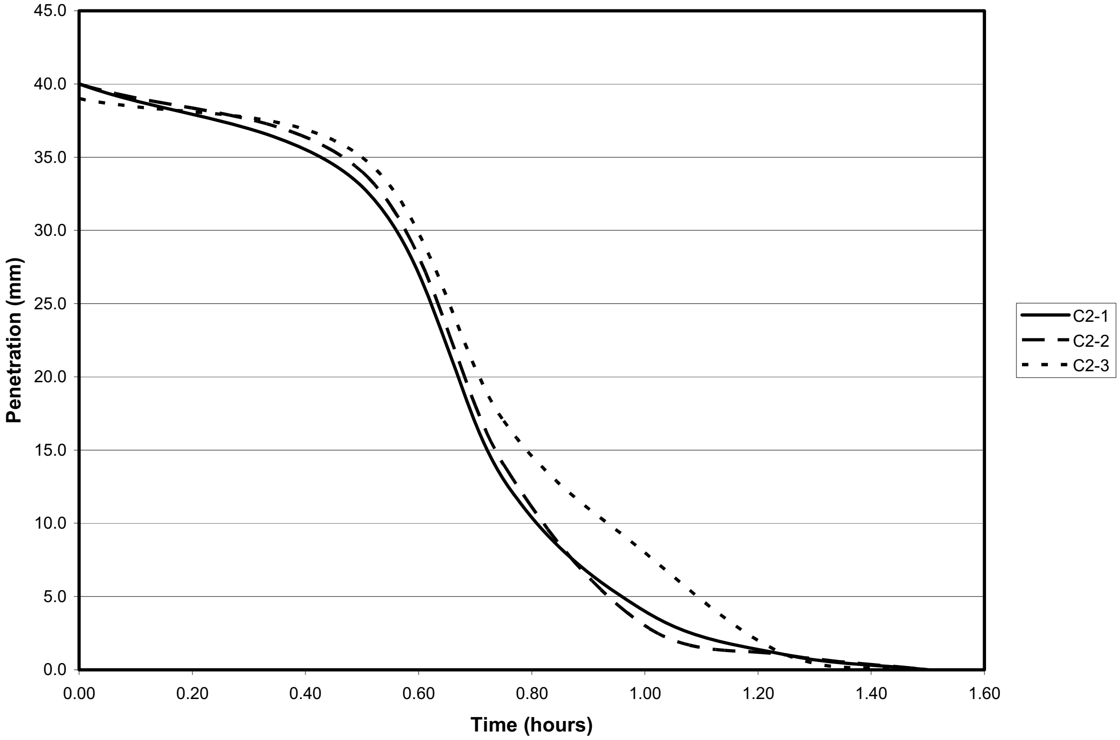
Formulation C1 (3 soil: 1cement)

Time Elapsed (hours)	Depth of Penetration (mm)		
	C1-1	C1-2	C1-3
0.00	40	40	40
0.50	39	40	32
0.75	25	26	27
1.00	12	14	15
1.25	3	2	1
1.50	0	1	0
1.75	0	0	0



APPENDIX C: TIME OF SETTING – ASTM C191-92
Formulation C2 (6 soil: 1cement)

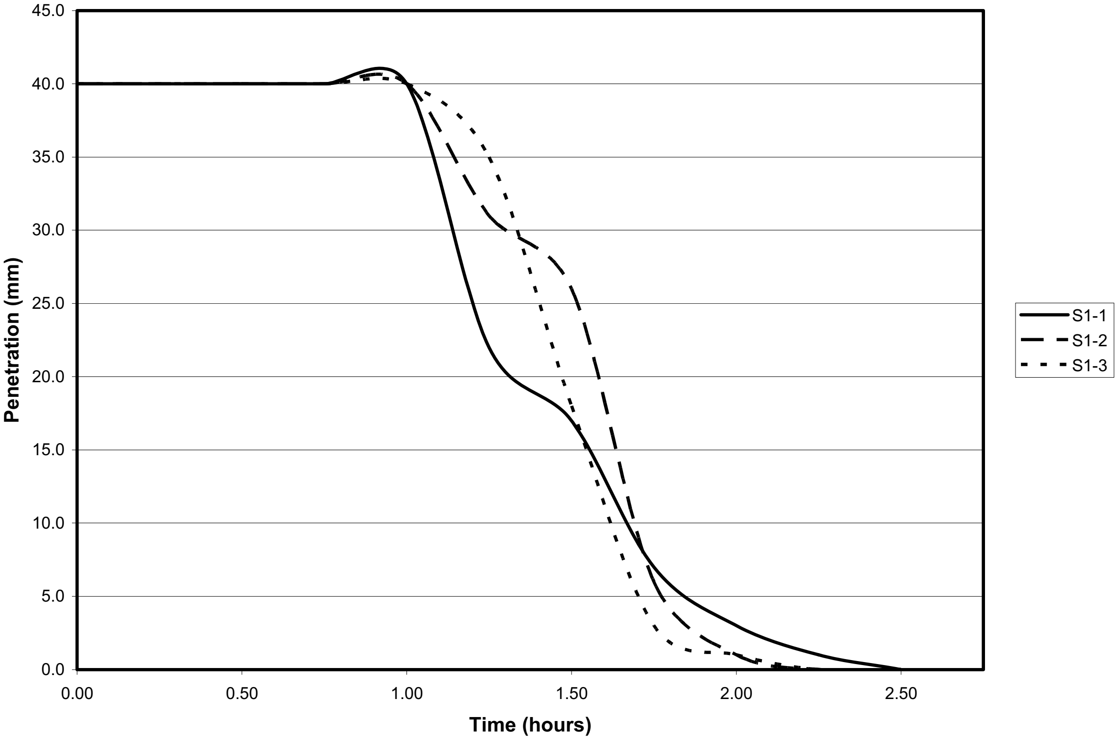
Time Elapsed (hours)	Depth of Penetration (mm)		
	C2-1	C2-2	C2-3
0.00	40	40	39
0.50	33	34	35
0.75	13	14	17
1.00	4	3	8
1.25	1	1	1
1.50	0	0	0



APPENDIX C: TIME OF SETTING – ASTM C191-92

Formulation S1 (3 soil: 1cement)

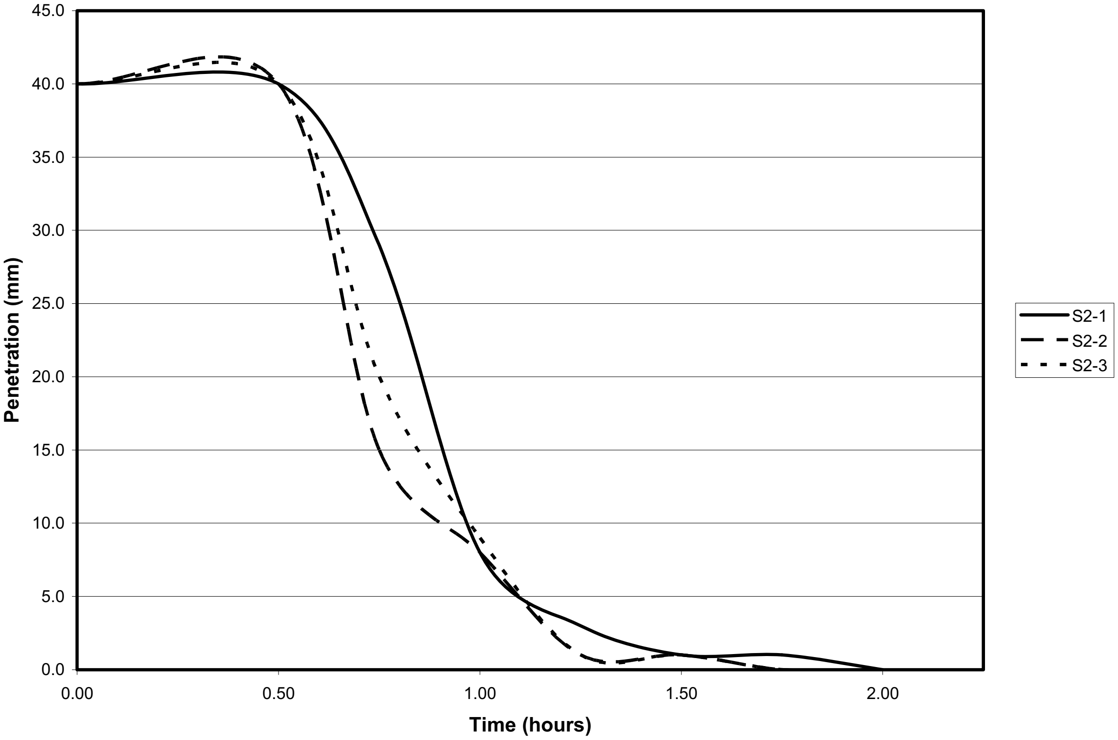
Time Elapsed (hours)	Depth of Penetration (mm)		
	S1-1	S1-2	S1-3
0.00	40	40	40
0.50	40	40	40
0.75	40	40	40
1.00	40	40	40
1.25	22	31	35
1.50	17	26	18
1.75	7	6	3
2.00	3	1	1
2.25	1	0	0
2.50	0	0	0



APPENDIX C: TIME OF SETTING – ASTM C191-92

Formulation S2 (6 soil: 1cement)

Time Elapsed (hours)	Depth of Penetration (mm)		
	S2-1	S2-2	S2-3
0.00	40	40	40
0.50	40	40	40
0.75	29	15	20
1.00	8	8	9
1.25	3	1	1
1.50	1	1	1
1.75	1	0	0
2.00	0	0	0



APPENDIX D: MUNSELL COLOR RATINGS FOR MORTAR SPECIMENS – ASTM D1535

Formulation	Munsell Color Designation (unamended soil)	Munsell Color Designation (mortar)
B1	7.5YR/5/3 Brown	7.5YR/7/2 Pinkish Gray
B2	7.5YR/5/3 Brown	7.5YR/7/2 Pinkish Gray
C1	2.5Y/6/3 Light Yellowish Brown	2.5Y/7/1 Light Gray
C2	2.5Y/6/3 Light Yellowish Brown	2.5Y/6/2 Light Brownish Gray
S1	7.5YR/4/4 Brown	7.5YR/7/2 Pinkish Gray
S2	7.5YR/4/4 Brown	7.5YR/7/2 Pinkish Gray

Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample B1-1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	262.84	0.00	0.00	0.00	0.00	0.00
0.08	267.99	5.15	1.96	5.15	1.96	0.98
0.17	270.56	2.57	0.98	7.72	2.94	2.45
0.25	272.47	1.91	0.73	9.63	3.66	3.30
0.33	274.01	1.54	0.59	11.17	4.25	3.96
0.42	275.29	1.28	0.49	12.45	4.74	4.49
0.50	276.36	1.07	0.41	13.52	5.14	4.94
0.58	277.30	0.94	0.36	14.46	5.50	5.32
0.67	278.14	0.84	0.32	15.30	5.82	5.66
0.75	278.86	0.72	0.27	16.02	6.09	5.96
0.83	279.52	0.66	0.25	16.68	6.35	6.22
0.92	280.09	0.57	0.22	17.25	6.56	6.45
1.00	280.60	0.51	0.19	17.76	6.76	6.66
1.25	281.78	1.18	0.45	18.94	7.21	6.98
1.50	282.68	0.90	0.34	19.84	7.55	7.38
1.75	283.32	0.64	0.24	20.48	7.79	7.67
2.00	283.84	0.52	0.20	21.00	7.99	7.89
2.25	284.29	0.45	0.17	21.45	8.16	8.08
2.50	284.46	0.17	0.06	21.62	8.23	8.19
2.75	284.57	0.11	0.04	21.73	8.27	8.25
3.00	284.73	0.16	0.06	21.89	8.33	8.30
4.00	284.88	0.15	0.06	22.04	8.39	8.36
5.00	284.85	-0.03	0.01	22.01	8.37	8.38
6.00	284.91	0.06	0.02	22.07	8.40	8.39
7.00	284.96	0.05	0.02	22.12	8.42	8.41
8.00	285.03	0.07	0.03	22.19	8.44	8.43
24.0	285.62	0.59	0.22	22.78	8.67	8.55
48.0	285.95	0.33	0.13	23.11	8.79	8.73
72.0	286.19	0.24	0.09	23.35	8.88	8.84
96.0	286.30	0.11	0.04	23.46	8.93	8.90
120.0	286.48	0.18	0.07	23.64	8.99	8.96
144.0	286.59	0.11	0.04	23.75	9.04	9.01
168.0	286.67	0.08	0.03	23.83	9.07	9.05
192.0	286.70	0.03	0.01	23.86	9.08	9.07

Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample B1-2

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	266.38	0.00	0.00	0.00	0.00	0.00
0.08	271.90	5.52	2.07	5.52	2.07	1.04
0.17	274.82	2.92	1.10	8.44	3.17	2.62
0.25	276.91	2.09	0.78	10.53	3.95	3.56
0.33	278.57	1.66	0.62	12.19	4.58	4.26
0.42	279.93	1.36	0.51	13.55	5.09	4.83
0.50	281.10	1.17	0.44	14.72	5.53	5.31
0.58	282.04	0.94	0.35	15.66	5.88	5.70
0.67	282.86	0.82	0.31	16.48	6.19	6.03
0.75	283.58	0.72	0.27	17.20	6.46	6.32
0.83	284.20	0.62	0.23	17.82	6.69	6.57
0.92	284.75	0.55	0.21	18.37	6.90	6.79
1.00	285.22	0.47	0.18	18.84	7.07	6.98
1.25	286.22	1.00	0.38	19.84	7.45	7.26
1.50	286.95	0.73	0.27	20.57	7.72	7.59
1.75	287.49	0.54	0.20	21.11	7.92	7.82
2.00	287.87	0.38	0.14	21.49	8.07	8.00
2.25	287.20	-0.67	0.25	20.82	7.82	7.94
2.50	288.28	1.08	0.41	21.90	8.22	8.02
2.75	288.38	0.10	0.04	22.00	8.26	8.24
3.00	288.48	0.10	0.04	22.10	8.30	8.28
4.00	288.63	0.15	0.06	22.25	8.35	8.32
5.00	288.64	0.01	0.00	22.26	8.36	8.35
6.00	288.72	0.08	0.03	22.34	8.39	8.37
7.00	288.72	0.00	0.00	22.34	8.39	8.39
8.00	288.79	0.07	0.03	22.41	8.41	8.40
24.0	289.40	0.61	0.23	23.02	8.64	8.53
48.0	289.76	0.36	0.14	23.38	8.78	8.71
72.0	290.04	0.28	0.11	23.66	8.88	8.83
96.0	290.16	0.12	0.05	23.78	8.93	8.90
120.0	290.38	0.22	0.08	24.00	9.01	8.97
144.0	290.43	0.05	0.02	24.05	9.03	9.02
168.0	290.53	0.10	0.04	24.15	9.07	9.05
192.0	290.58	0.05	0.02	24.20	9.08	9.08

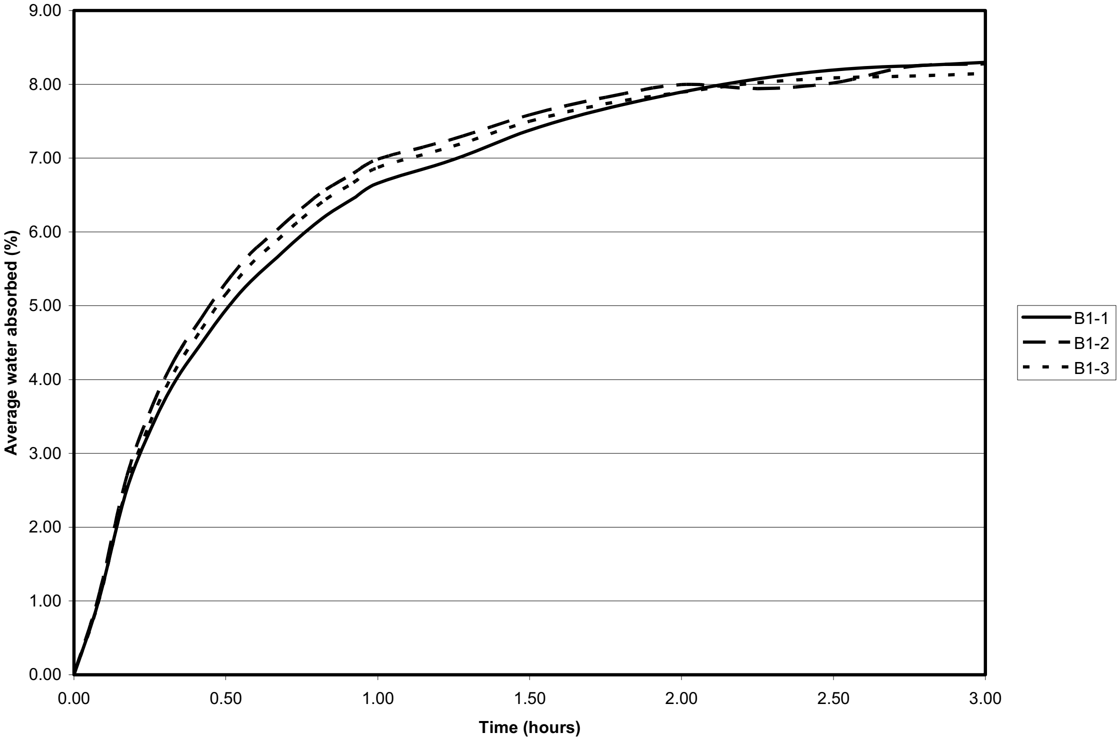
Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample B1-3

Time (hours)	**Weight (g)**	**Difference in successive weighings (g)**	**Difference in successive weighings (%)**	**Change in weight from initial weight (g)**	**Amount of water absorbed (%)**	**Average water absorbed (%)**
0.00	267.51	0.00	0.00	0.00	0.00	0.00
0.08	272.68	5.17	1.93	5.17	1.93	0.97
0.17	275.60	2.92	1.09	8.09	3.02	2.48
0.25	277.65	2.05	0.77	10.14	3.79	3.41
0.33	279.33	1.68	0.63	11.82	4.42	4.10
0.42	280.73	1.40	0.52	13.22	4.94	4.68
0.50	281.88	1.15	0.43	14.37	5.37	5.16
0.58	282.85	0.97	0.36	15.34	5.73	5.55
0.67	283.68	0.83	0.31	16.17	6.04	5.89
0.75	284.42	0.74	0.28	16.91	6.32	6.18
0.83	285.07	0.65	0.24	17.56	6.56	6.44
0.92	285.62	0.55	0.21	18.11	6.77	6.67
1.00	286.16	0.54	0.20	18.65	6.97	6.87
1.25	287.17	1.01	0.38	19.66	7.35	7.16
1.50	287.97	0.80	0.30	20.46	7.65	7.50
1.75	288.44	0.47	0.18	20.93	7.82	7.74
2.00	288.81	0.37	0.14	21.30	7.96	7.89
2.25	289.12	0.31	0.12	21.61	8.08	8.02
2.50	289.17	0.05	0.02	21.66	8.10	8.09
2.75	289.25	0.08	0.03	21.74	8.13	8.11
3.00	289.36	0.11	0.04	21.85	8.17	8.15
4.00	289.44	0.08	0.03	21.93	8.20	8.18
5.00	289.48	0.04	0.01	21.97	8.21	8.21
6.00	289.55	0.07	0.03	22.04	8.24	8.23
7.00	289.57	0.02	0.01	22.06	8.25	8.24
8.00	289.59	0.02	0.01	22.08	8.25	8.25
24.0	290.21	0.62	0.23	22.70	8.49	8.37
48.0	290.59	0.38	0.14	23.08	8.63	8.56
72.0	290.83	0.24	0.09	23.32	8.72	8.67
96.0	290.97	0.14	0.05	23.46	8.77	8.74
120.0	291.10	0.13	0.05	23.59	8.82	8.79
144.0	291.21	0.11	0.04	23.70	8.86	8.84
168.0	291.27	0.06	0.02	23.76	8.88	8.87
192.0	291.32	0.05	0.02	23.81	8.90	8.89

Appendix E: Water Absorption – Normal 7/81

Water absorption curves for samples B1-1,2&3



Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample B2-1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	260.23	0.00	0.00	0.00	0.00	0.00
0.08	270.61	10.38	3.99	10.38	3.99	1.99
0.17	274.44	3.83	1.47	14.21	5.46	4.72
0.25	276.92	2.48	0.95	16.69	6.41	5.94
0.33	278.85	1.93	0.74	18.62	7.16	6.78
0.42	280.54	1.69	0.65	20.31	7.80	7.48
0.50	281.58	1.04	0.40	21.35	8.20	8.00
0.58	282.51	0.93	0.36	22.28	8.56	8.38
0.67	283.32	0.81	0.31	23.09	8.87	8.72
0.75	283.98	0.66	0.25	23.75	9.13	9.00
0.83	284.57	0.59	0.23	24.34	9.35	9.24
0.92	285.00	0.43	0.17	24.77	9.52	9.44
1.00	285.35	0.35	0.13	25.12	9.65	9.59
1.25	285.91	0.56	0.22	25.68	9.87	9.76
1.50	286.07	0.16	0.06	25.84	9.93	9.90
1.75	286.16	0.09	0.03	25.93	9.96	9.95
2.00	286.20	0.04	0.02	25.97	9.98	9.97
2.25	286.23	0.03	0.01	26.00	9.99	9.99
2.50	286.26	0.03	0.01	26.03	10.00	10.00
2.75	286.32	0.06	0.02	26.09	10.03	10.01
3.00	286.31	-0.01	0.00	26.08	10.02	10.02
4.00	286.39	0.08	0.03	26.16	10.05	10.04
5.00	286.46	0.07	0.03	26.23	10.08	10.07
6.00	286.52	0.06	0.02	26.29	10.10	10.09
7.00	286.54	0.02	0.01	26.31	10.11	10.11
8.00	286.60	0.06	0.02	26.37	10.13	10.12
24.0	287.10	0.50	0.19	26.87	10.33	10.23
48.0	287.32	0.22	0.08	27.09	10.41	10.37
72.0	287.46	0.14	0.05	27.23	10.46	10.44
96.0	287.57	0.11	0.04	27.34	10.51	10.48
120.0	287.59	0.02	0.01	27.36	10.51	10.51
144.0	287.62	0.03	0.01	27.39	10.53	10.52

Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample B2-2

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	252.34	0.00	0.00	0.00	0.00	0.00
0.08	262.78	10.44	4.14	10.44	4.14	2.07
0.17	267.01	4.23	1.68	14.67	5.81	4.98
0.25	269.98	2.97	1.18	17.64	6.99	6.40
0.33	272.16	2.18	0.86	19.82	7.85	7.42
0.42	273.96	1.80	0.71	21.62	8.57	8.21
0.50	275.00	1.04	0.41	22.66	8.98	8.77
0.58	275.87	0.87	0.34	23.53	9.32	9.15
0.67	276.51	0.64	0.25	24.17	9.58	9.45
0.75	277.01	0.50	0.20	24.67	9.78	9.68
0.83	277.35	0.34	0.13	25.01	9.91	9.84
0.92	277.52	0.17	0.07	25.18	9.98	9.94
1.00	277.64	0.12	0.05	25.30	10.03	10.00
1.25	277.76	0.12	0.05	25.42	10.07	10.05
1.50	277.76	0.00	0.00	25.42	10.07	10.07
1.75	277.81	0.05	0.02	25.47	10.09	10.08
2.00	277.84	0.03	0.01	25.50	10.11	10.10
2.25	277.88	0.04	0.02	25.54	10.12	10.11
2.50	277.91	0.03	0.01	25.57	10.13	10.13
2.75	277.93	0.02	0.01	25.59	10.14	10.14
3.00	277.94	0.01	0.00	25.60	10.15	10.14
4.00	278.00	0.06	0.02	25.66	10.17	10.16
5.00	278.07	0.07	0.03	25.73	10.20	10.18
6.00	278.20	0.13	0.05	25.86	10.25	10.22
7.00	278.16	-0.04	0.02	25.82	10.23	10.24
8.00	278.23	0.07	0.03	25.89	10.26	10.25
24.0	278.70	0.47	0.19	26.36	10.45	10.35
48.0	278.91	0.21	0.08	26.57	10.53	10.49
72.0	278.96	0.05	0.02	26.62	10.55	10.54
96.0	279.08	0.12	0.05	26.74	10.60	10.57
120.0	279.07	-0.01	0.00	26.73	10.59	10.59
144.0	279.12	0.05	0.02	26.78	10.61	10.60

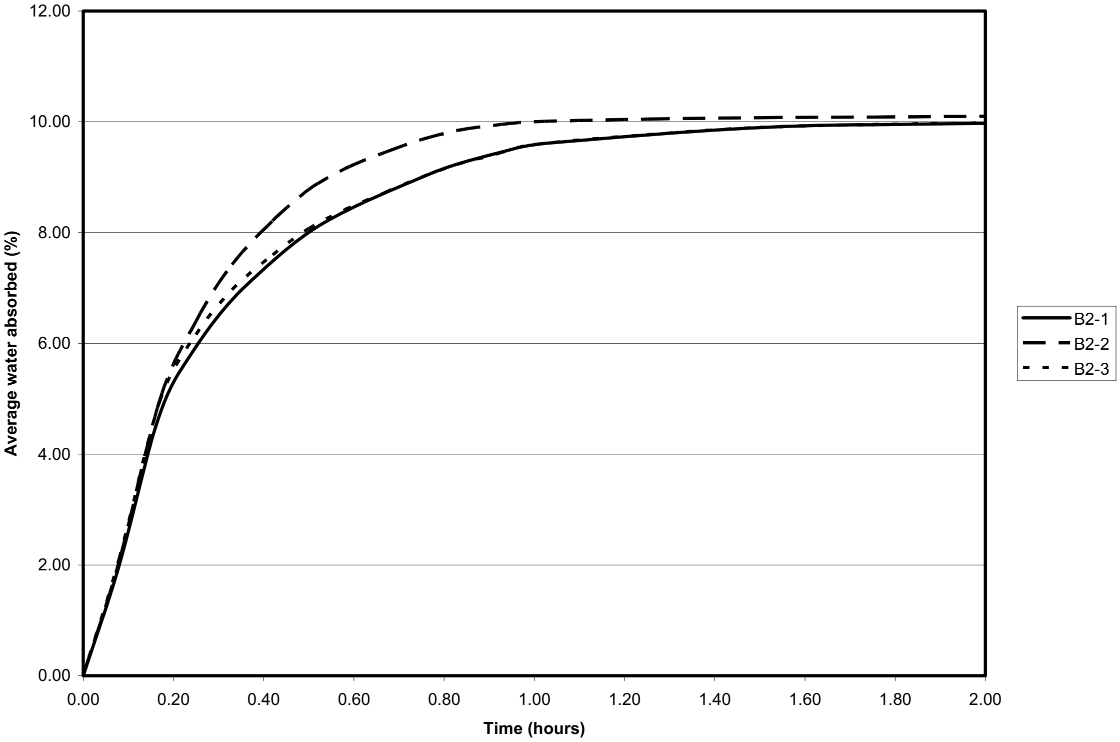
Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample B2-3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	255.81	0.00	0.00	0.00	0.00	0.00
0.08	266.62	10.81	4.23	10.81	4.23	2.11
0.17	270.34	3.72	1.45	14.53	5.68	4.95
0.25	272.78	2.44	0.95	16.97	6.63	6.16
0.33	274.49	1.71	0.67	18.68	7.30	6.97
0.42	276.01	1.52	0.59	20.20	7.90	7.60
0.50	276.90	0.89	0.35	21.09	8.24	8.07
0.58	277.76	0.86	0.34	21.95	8.58	8.41
0.67	278.50	0.74	0.29	22.69	8.87	8.73
0.75	279.16	0.66	0.26	23.35	9.13	9.00
0.83	279.70	0.54	0.21	23.89	9.34	9.23
0.92	280.15	0.45	0.18	24.34	9.51	9.43
1.00	280.53	0.38	0.15	24.72	9.66	9.59
1.25	281.06	0.53	0.21	25.25	9.87	9.77
1.50	281.21	0.15	0.06	25.40	9.93	9.90
1.75	281.31	0.10	0.04	25.50	9.97	9.95
2.00	281.36	0.05	0.02	25.55	9.99	9.98
2.25	281.37	0.01	0.00	25.56	9.99	9.99
2.50	281.40	0.03	0.01	25.59	10.00	10.00
2.75	281.44	0.04	0.02	25.63	10.02	10.01
3.00	281.46	0.02	0.01	25.65	10.03	10.02
4.00	281.50	0.04	0.02	25.69	10.04	10.03
5.00	281.58	0.08	0.03	25.77	10.07	10.06
6.00	281.63	0.05	0.02	25.82	10.09	10.08
7.00	281.67	0.04	0.02	25.86	10.11	10.10
8.00	281.73	0.06	0.02	25.92	10.13	10.12
24.0	282.25	0.52	0.20	26.44	10.34	10.23
48.0	282.53	0.28	0.11	26.72	10.45	10.39
72.0	282.58	0.05	0.02	26.77	10.46	10.46
96.0	282.67	0.09	0.04	26.86	10.50	10.48
120.0	282.76	0.09	0.04	26.95	10.54	10.52
144.0	282.79	0.03	0.01	26.98	10.55	10.54

Appendix E: Water Absorption – Normal 7/81

Water absorption curves for samples B2-1,2&3



Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample C1-1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	244.17	0.00	0.00	0.00	0.00	0.00
0.08	246.36	2.19	0.90	2.19	0.90	0.45
0.17	247.35	0.99	0.41	3.18	1.30	1.10
0.25	248.16	0.81	0.33	3.99	1.63	1.47
0.33	248.88	0.72	0.29	4.71	1.93	1.78
0.42	249.58	0.70	0.29	5.41	2.22	2.07
0.50	250.27	0.69	0.28	6.10	2.50	2.36
0.58	250.94	0.67	0.27	6.77	2.77	2.64
0.67	251.55	0.61	0.25	7.38	3.02	2.90
0.75	252.22	0.67	0.27	8.05	3.30	3.16
0.83	252.84	0.62	0.25	8.67	3.55	3.42
0.92	253.48	0.64	0.26	9.31	3.81	3.68
1.00	254.11	0.63	0.26	9.94	4.07	3.94
1.25	255.63	1.52	0.62	11.46	4.69	4.38
1.50	257.06	1.43	0.59	12.89	5.28	4.99
1.75	258.29	1.23	0.50	14.12	5.78	5.53
2.00	259.40	1.11	0.45	15.23	6.24	6.01
2.25	260.60	1.20	0.49	16.43	6.73	6.48
2.50	261.49	0.89	0.36	17.32	7.09	6.91
2.75	262.45	0.96	0.39	18.28	7.49	7.29
3.00	263.43	0.98	0.40	19.26	7.89	7.69
4.00	266.17	2.74	1.12	22.00	9.01	8.45
5.00	268.49	2.32	0.95	24.32	9.96	9.49
6.00	270.40	1.91	0.78	26.23	10.74	10.35
7.00	271.62	1.22	0.50	27.45	11.24	10.99
8.00	272.58	0.96	0.39	28.41	11.64	11.44
24.0	274.20	1.62	0.66	30.03	12.30	11.97
48.0	274.82	0.62	0.25	30.65	12.55	12.43
72.0	275.09	0.27	0.11	30.92	12.66	12.61
96.0	275.21	0.12	0.05	31.04	12.71	12.69
120.0	275.35	0.14	0.06	31.18	12.77	12.74
144.0	275.38	0.03	0.01	31.21	12.78	12.78
168.0	275.43	0.05	0.02	31.26	12.80	12.79

Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample C1-2

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	236.17	0.00	0.00	0.00	0.00	0.00
0.08	237.90	1.73	0.73	1.73	0.73	0.37
0.17	238.84	0.94	0.40	2.67	1.13	0.93
0.25	239.61	0.77	0.33	3.44	1.46	1.29
0.33	240.31	0.70	0.30	4.14	1.75	1.60
0.42	240.93	0.62	0.26	4.76	2.02	1.88
0.50	241.58	0.65	0.28	5.41	2.29	2.15
0.58	242.23	0.65	0.28	6.06	2.57	2.43
0.67	242.82	0.59	0.25	6.65	2.82	2.69
0.75	243.38	0.56	0.24	7.21	3.05	2.93
0.83	243.96	0.58	0.25	7.79	3.30	3.18
0.92	244.55	0.59	0.25	8.38	3.55	3.42
1.00	245.12	0.57	0.24	8.95	3.79	3.67
1.25	246.45	1.33	0.56	10.28	4.35	4.07
1.50	247.74	1.29	0.55	11.57	4.90	4.63
1.75	248.89	1.15	0.49	12.72	5.39	5.14
2.00	249.98	1.09	0.46	13.81	5.85	5.62
2.25	251.12	1.14	0.48	14.95	6.33	6.09
2.50	252.02	0.90	0.38	15.85	6.71	6.52
2.75	252.95	0.93	0.39	16.78	7.11	6.91
3.00	253.96	1.01	0.43	17.79	7.53	7.32
4.00	256.94	2.98	1.26	20.77	8.79	8.16
5.00	259.45	2.51	1.06	23.28	9.86	9.33
6.00	261.42	1.97	0.83	25.25	10.69	10.27
7.00	262.85	1.43	0.61	26.68	11.30	10.99
8.00	263.95	1.10	0.47	27.78	11.76	11.53
24.0	266.00	2.05	0.87	29.83	12.63	12.20
48.0	266.51	0.51	0.22	30.34	12.85	12.74
72.0	266.78	0.27	0.11	30.61	12.96	12.90
96.0	266.89	0.11	0.05	30.72	13.01	12.98
120.0	267.05	0.16	0.07	30.88	13.08	13.04
144.0	267.05	0.00	0.00	30.88	13.08	13.08
168.0	267.12	0.07	0.03	30.95	13.10	13.09

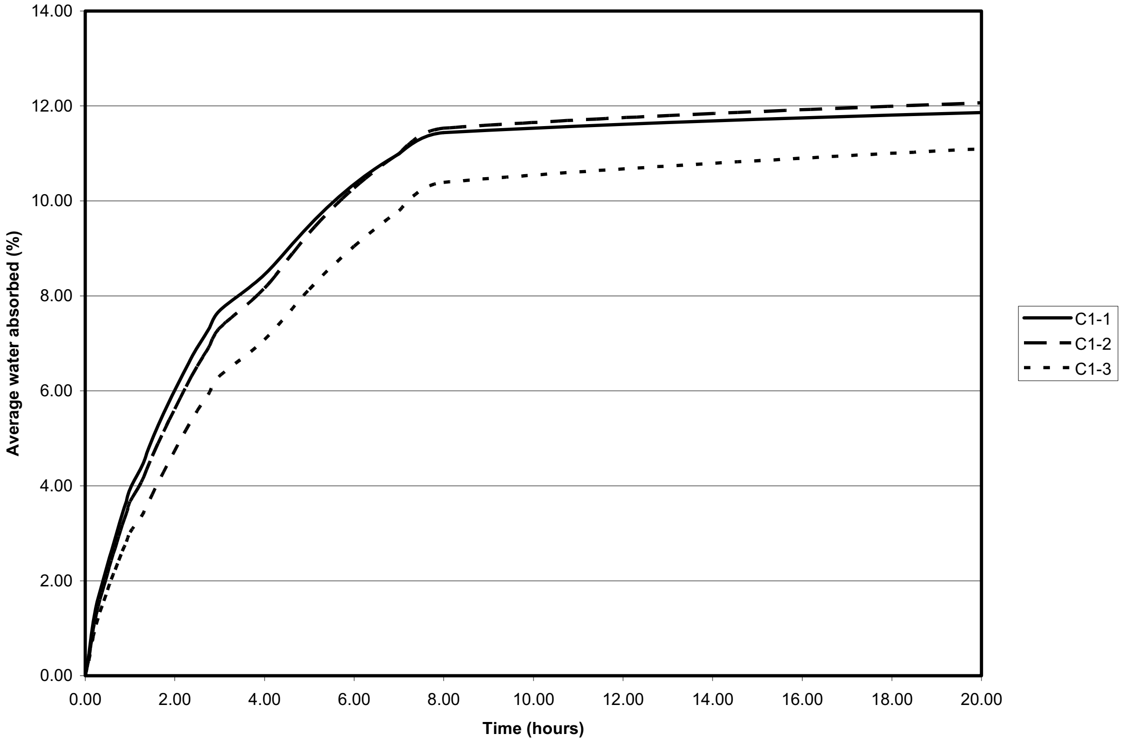
Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample C1-3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	245.16	0.00	0.00	0.00	0.00	0.00
0.08	246.70	1.54	0.63	1.54	0.63	0.31
0.17	247.49	0.79	0.32	2.33	0.95	0.79
0.25	248.14	0.65	0.27	2.98	1.22	1.08
0.33	248.76	0.62	0.25	3.60	1.47	1.34
0.42	249.29	0.53	0.22	4.13	1.68	1.58
0.50	249.87	0.58	0.24	4.71	1.92	1.80
0.58	250.40	0.53	0.22	5.24	2.14	2.03
0.67	250.88	0.48	0.20	5.72	2.33	2.24
0.75	251.36	0.48	0.20	6.20	2.53	2.43
0.83	251.84	0.48	0.20	6.68	2.72	2.63
0.92	252.32	0.48	0.20	7.16	2.92	2.82
1.00	252.81	0.49	0.20	7.65	3.12	3.02
1.25	253.94	1.13	0.46	8.78	3.58	3.35
1.50	255.12	1.18	0.48	9.96	4.06	3.82
1.75	256.25	1.13	0.46	11.09	4.52	4.29
2.00	257.31	1.06	0.43	12.15	4.96	4.74
2.25	258.42	1.11	0.45	13.26	5.41	5.18
2.50	259.26	0.84	0.34	14.10	5.75	5.58
2.75	260.15	0.89	0.36	14.99	6.11	5.93
3.00	261.12	0.97	0.40	15.96	6.51	6.31
4.00	263.90	2.78	1.13	18.74	7.64	7.08
5.00	266.32	2.42	0.99	21.16	8.63	8.14
6.00	268.35	2.03	0.83	23.19	9.46	9.05
7.00	269.98	1.63	0.66	24.82	10.12	9.79
8.00	271.30	1.32	0.54	26.14	10.66	10.39
24.0	274.27	2.97	1.21	29.11	11.87	11.27
48.0	274.75	0.48	0.20	29.59	12.07	11.97
72.0	274.97	0.22	0.09	29.81	12.16	12.11
96.0	275.10	0.13	0.05	29.94	12.21	12.19
120.0	275.27	0.17	0.07	30.11	12.28	12.25
144.0	275.18	-0.09	0.04	30.02	12.25	12.26
168.0	275.28	0.10	0.04	30.12	12.29	12.27

Appendix E: Water Absorption – Normal 7/81

Water absorption curves for samples C1-1,2&3



Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample C2-1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	233.08	0.00	0.00	0.00	0.00	0.00
0.08	240.80	7.72	3.31	7.72	3.31	1.66
0.17	245.08	4.28	1.84	12.00	5.15	4.23
0.25	248.38	3.30	1.42	15.30	6.56	5.86
0.33	251.10	2.72	1.17	18.02	7.73	7.15
0.42	253.43	2.33	1.00	20.35	8.73	8.23
0.50	255.53	2.10	0.90	22.45	9.63	9.18
0.58	257.18	1.65	0.71	24.10	10.34	9.99
0.67	258.65	1.47	0.63	25.57	10.97	10.66
0.75	260.03	1.38	0.59	26.95	11.56	11.27
0.83	261.22	1.19	0.51	28.14	12.07	11.82
0.92	262.27	1.05	0.45	29.19	12.52	12.30
1.00	263.14	0.87	0.37	30.06	12.90	12.71
1.25	265.00	1.86	0.80	31.92	13.69	13.30
1.50	266.24	1.24	0.53	33.16	14.23	13.96
1.75	267.00	0.76	0.33	33.92	14.55	14.39
2.00	267.04	0.04	0.02	33.96	14.57	14.56
2.25	267.10	0.06	0.03	34.02	14.60	14.58
2.50	267.19	0.09	0.04	34.11	14.63	14.62
2.75	267.23	0.04	0.02	34.15	14.65	14.64
3.00	267.26	0.03	0.01	34.18	14.66	14.66
4.00	267.34	0.08	0.03	34.26	14.70	14.68
5.00	267.39	0.05	0.02	34.31	14.72	14.71
6.00	267.45	0.06	0.03	34.37	14.75	14.73
7.00	267.54	0.09	0.04	34.46	14.78	14.77
8.00	267.57	0.03	0.01	34.49	14.80	14.79
24.0	268.06	0.49	0.21	34.98	15.01	14.90
48.0	268.33	0.27	0.12	35.25	15.12	15.07
72.0	268.55	0.22	0.09	35.47	15.22	15.17
96.0	268.68	0.13	0.06	35.60	15.27	15.25
120.0	268.69	0.01	0.00	35.61	15.28	15.28

Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample C2-2

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	231.25	0.00	0.00	0.00	0.00	0.00
0.08	241.58	10.33	4.47	10.33	4.47	2.23
0.17	246.97	5.39	2.33	15.72	6.80	5.63
0.25	250.92	3.95	1.71	19.67	8.51	7.65
0.33	253.94	3.02	1.31	22.69	9.81	9.16
0.42	256.41	2.47	1.07	25.16	10.88	10.35
0.50	258.48	2.07	0.90	27.23	11.78	11.33
0.58	260.03	1.55	0.67	28.78	12.45	12.11
0.67	261.32	1.29	0.56	30.07	13.00	12.72
0.75	262.43	1.11	0.48	31.18	13.48	13.24
0.83	263.30	0.87	0.38	32.05	13.86	13.67
0.92	263.98	0.68	0.29	32.73	14.15	14.01
1.00	264.45	0.47	0.20	33.20	14.36	14.26
1.25	264.85	0.40	0.17	33.60	14.53	14.44
1.50	264.97	0.12	0.05	33.72	14.58	14.56
1.75	265.09	0.12	0.05	33.84	14.63	14.61
2.00	265.02	-0.07	0.03	33.77	14.60	14.62
2.25	265.08	0.06	0.03	33.83	14.63	14.62
2.50	265.16	0.08	0.03	33.91	14.66	14.65
2.75	265.18	0.02	0.01	33.93	14.67	14.67
3.00	265.19	0.01	0.00	33.94	14.68	14.67
4.00	265.24	0.05	0.02	33.99	14.70	14.69
5.00	265.35	0.11	0.05	34.10	14.75	14.72
6.00	265.39	0.04	0.02	34.14	14.76	14.75
7.00	265.48	0.09	0.04	34.23	14.80	14.78
8.00	265.52	0.04	0.02	34.27	14.82	14.81
24.0	266.03	0.51	0.22	34.78	15.04	14.93
48.0	266.26	0.23	0.10	35.01	15.14	15.09
72.0	266.45	0.19	0.08	35.20	15.22	15.18
96.0	266.54	0.09	0.04	35.29	15.26	15.24
120.0	266.57	0.03	0.01	35.32	15.27	15.27

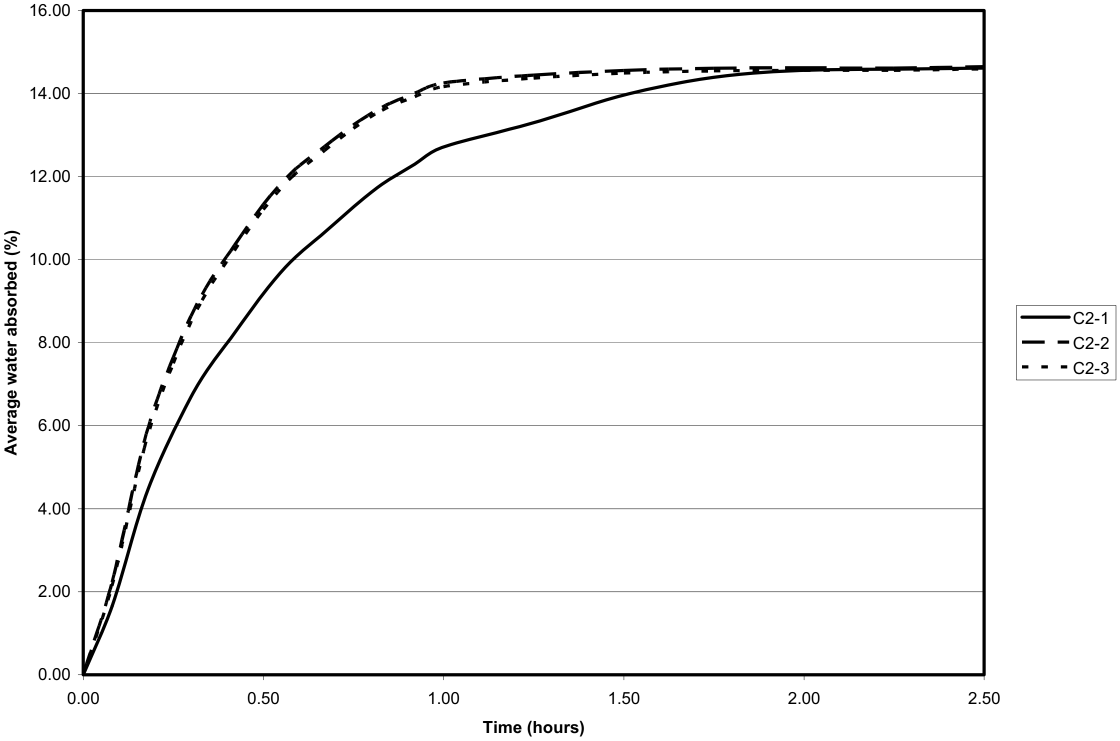
Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample C2-3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	233.09	0.00	0.00	0.00	0.00	0.00
0.08	243.08	9.99	4.29	9.99	4.29	2.14
0.17	248.58	5.50	2.36	15.49	6.65	5.47
0.25	252.58	4.00	1.72	19.49	8.36	7.50
0.33	255.66	3.08	1.32	22.57	9.68	9.02
0.42	258.17	2.51	1.08	25.08	10.76	10.22
0.50	260.25	2.08	0.89	27.16	11.65	11.21
0.58	261.85	1.60	0.69	28.76	12.34	12.00
0.67	263.20	1.35	0.58	30.11	12.92	12.63
0.75	264.34	1.14	0.49	31.25	13.41	13.16
0.83	265.22	0.88	0.38	32.13	13.78	13.60
0.92	265.87	0.65	0.28	32.78	14.06	13.92
1.00	266.35	0.48	0.21	33.26	14.27	14.17
1.25	266.82	0.47	0.20	33.73	14.47	14.37
1.50	266.93	0.11	0.05	33.84	14.52	14.49
1.75	267.06	0.13	0.06	33.97	14.57	14.55
2.00	267.00	-0.06	0.03	33.91	14.55	14.56
2.25	267.06	0.06	0.03	33.97	14.57	14.56
2.50	267.15	0.09	0.04	34.06	14.61	14.59
2.75	267.13	-0.02	0.01	34.04	14.60	14.61
3.00	267.18	0.05	0.02	34.09	14.63	14.61
4.00	267.24	0.06	0.03	34.15	14.65	14.64
5.00	267.36	0.12	0.05	34.27	14.70	14.68
6.00	267.37	0.01	0.00	34.28	14.71	14.70
7.00	267.49	0.12	0.05	34.40	14.76	14.73
8.00	267.52	0.03	0.01	34.43	14.77	14.76
24.0	267.98	0.46	0.20	34.89	14.97	14.87
48.0	268.23	0.25	0.11	35.14	15.08	15.02
72.0	268.43	0.20	0.09	35.34	15.16	15.12
96.0	268.53	0.10	0.04	35.44	15.20	15.18
120.0	268.55	0.02	0.01	35.46	15.21	15.21

Appendix E: Water Absorption – Normal 7/81

Water absorption curves for samples C2-1,2&3



Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample S1-1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	216.99	0.00	0.00	0.00	0.00	0.00
0.08	225.41	8.42	3.88	8.42	3.88	1.94
0.17	228.66	3.25	1.50	11.67	5.38	4.63
0.25	230.88	2.22	1.02	13.89	6.40	5.89
0.33	232.86	1.98	0.91	15.87	7.31	6.86
0.42	234.59	1.73	0.80	17.60	8.11	7.71
0.50	236.10	1.51	0.70	19.11	8.81	8.46
0.58	237.48	1.38	0.64	20.49	9.44	9.12
0.67	238.51	1.03	0.47	21.52	9.92	9.68
0.75	239.52	1.01	0.47	22.53	10.38	10.15
0.83	240.45	0.93	0.43	23.46	10.81	10.60
0.92	241.26	0.81	0.37	24.27	11.18	11.00
1.00	241.92	0.66	0.30	24.93	11.49	11.34
1.25	243.39	1.47	0.68	26.40	12.17	11.83
1.50	244.57	1.18	0.54	27.58	12.71	12.44
1.75	245.48	0.91	0.42	28.49	13.13	12.92
2.00	246.23	0.75	0.35	29.24	13.48	13.30
2.25	246.81	0.58	0.27	29.82	13.74	13.61
2.50	247.33	0.52	0.24	30.34	13.98	13.86
2.75	248.02	0.69	0.32	31.03	14.30	14.14
3.00	248.10	0.08	0.04	31.11	14.34	14.32
4.00	249.14	1.04	0.48	32.15	14.82	14.58
5.00	249.56	0.42	0.19	32.57	15.01	14.91
6.00	249.77	0.21	0.10	32.78	15.11	15.06
7.00	249.86	0.09	0.04	32.87	15.15	15.13
8.00	249.90	0.04	0.02	32.91	15.17	15.16
24.0	250.64	0.74	0.34	33.65	15.51	15.34
48.0	251.02	0.38	0.18	34.03	15.68	15.60
72.0	251.20	0.18	0.08	34.21	15.77	15.72
96.0	251.34	0.14	0.06	34.35	15.83	15.80
120.0	251.37	0.03	0.01	34.38	15.84	15.84

Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample S1-2

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	217.27	0.00	0.00	0.00	0.00	0.00
0.08	226.06	8.79	4.05	8.79	4.05	2.02
0.17	229.60	3.54	1.63	12.33	5.67	4.86
0.25	231.95	2.35	1.08	14.68	6.76	6.22
0.33	233.94	1.99	0.92	16.67	7.67	7.21
0.42	235.62	1.68	0.77	18.35	8.45	8.06
0.50	237.02	1.40	0.64	19.75	9.09	8.77
0.58	238.29	1.27	0.58	21.02	9.67	9.38
0.67	239.32	1.03	0.47	22.05	10.15	9.91
0.75	240.28	0.96	0.44	23.01	10.59	10.37
0.83	241.16	0.88	0.41	23.89	11.00	10.79
0.92	241.97	0.81	0.37	24.70	11.37	11.18
1.00	242.63	0.66	0.30	25.36	11.67	11.52
1.25	244.17	1.54	0.71	26.90	12.38	12.03
1.50	245.41	1.24	0.57	28.14	12.95	12.67
1.75	246.44	1.03	0.47	29.17	13.43	13.19
2.00	247.28	0.84	0.39	30.01	13.81	13.62
2.25	247.91	0.63	0.29	30.64	14.10	13.96
2.50	248.46	0.55	0.25	31.19	14.36	14.23
2.75	249.06	0.60	0.28	31.79	14.63	14.49
3.00	249.30	0.24	0.11	32.03	14.74	14.69
4.00	250.17	0.87	0.40	32.90	15.14	14.94
5.00	250.41	0.24	0.11	33.14	15.25	15.20
6.00	250.58	0.17	0.08	33.31	15.33	15.29
7.00	250.65	0.07	0.03	33.38	15.36	15.35
8.00	250.70	0.05	0.02	33.43	15.39	15.37
24.0	251.47	0.77	0.35	34.20	15.74	15.56
48.0	251.80	0.33	0.15	34.53	15.89	15.82
72.0	252.04	0.24	0.11	34.77	16.00	15.95
96.0	252.20	0.16	0.07	34.93	16.08	16.04
120.0	252.23	0.03	0.01	34.96	16.09	16.08

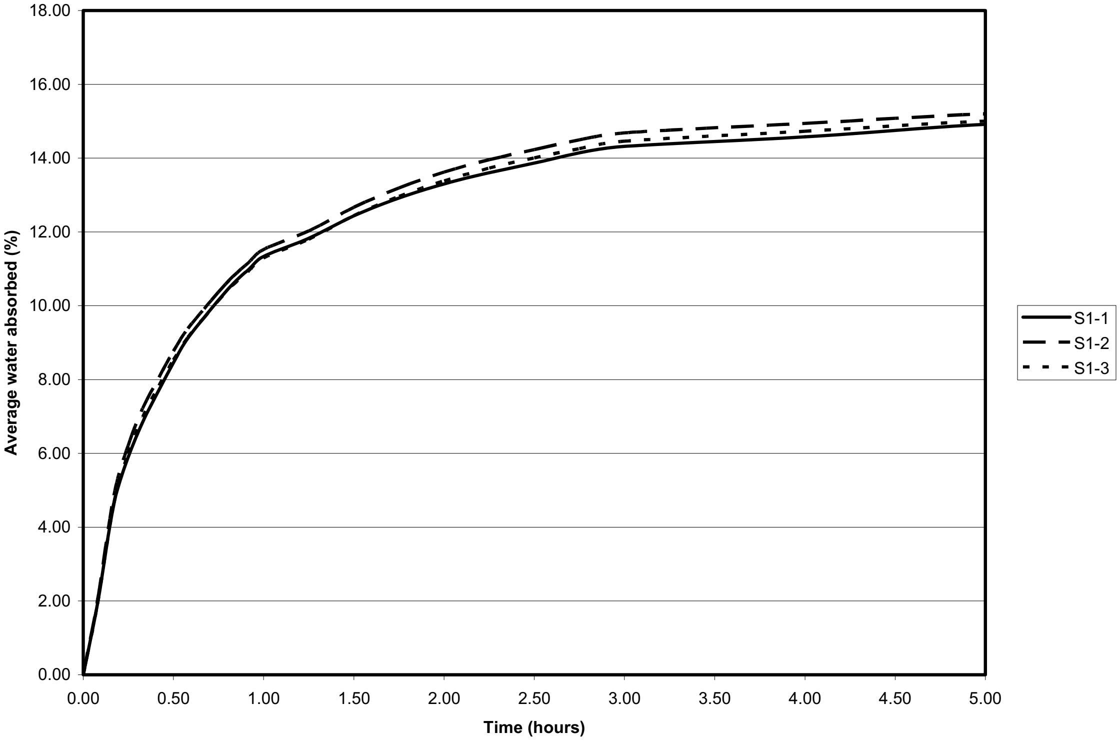
Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample S1-3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	218.84	0.00	0.00	0.00	0.00	0.00
0.08	227.32	8.48	3.87	8.48	3.87	1.94
0.17	230.76	3.44	1.57	11.92	5.45	4.66
0.25	233.11	2.35	1.07	14.27	6.52	5.98
0.33	235.14	2.03	0.93	16.30	7.45	6.98
0.42	236.82	1.68	0.77	17.98	8.22	7.83
0.50	238.20	1.38	0.63	19.36	8.85	8.53
0.58	239.49	1.29	0.59	20.65	9.44	9.14
0.67	240.53	1.04	0.48	21.69	9.91	9.67
0.75	241.51	0.98	0.45	22.67	10.36	10.14
0.83	242.42	0.91	0.42	23.58	10.77	10.57
0.92	243.21	0.79	0.36	24.37	11.14	10.96
1.00	243.89	0.68	0.31	25.05	11.45	11.29
1.25	245.45	1.56	0.71	26.61	12.16	11.80
1.50	246.69	1.24	0.57	27.85	12.73	12.44
1.75	247.72	1.03	0.47	28.88	13.20	12.96
2.00	248.54	0.82	0.37	29.70	13.57	13.38
2.25	249.22	0.68	0.31	30.38	13.88	13.73
2.50	249.75	0.53	0.24	30.91	14.12	14.00
2.75	250.34	0.59	0.27	31.50	14.39	14.26
3.00	250.62	0.28	0.13	31.78	14.52	14.46
4.00	251.53	0.91	0.42	32.69	14.94	14.73
5.00	251.81	0.28	0.13	32.97	15.07	15.00
6.00	251.99	0.18	0.08	33.15	15.15	15.11
7.00	252.05	0.06	0.03	33.21	15.18	15.16
8.00	252.11	0.06	0.03	33.27	15.20	15.19
24.0	252.83	0.72	0.33	33.99	15.53	15.37
48.0	253.22	0.39	0.18	34.38	15.71	15.62
72.0	253.42	0.20	0.09	34.58	15.80	15.76
96.0	253.50	0.08	0.04	34.66	15.84	15.82
120.0	253.56	0.06	0.03	34.72	15.87	15.85

Appendix E: Water Absorption – Normal 7/81

Water absorption curves for samples S1-1,2&3



Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample S2-1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	219.37	0.00	0.00	0.00	0.00	0.00
0.08	232.13	12.76	5.82	12.76	5.82	2.91
0.17	235.50	3.37	1.54	16.13	7.35	6.58
0.25	238.13	2.63	1.20	18.76	8.55	7.95
0.33	240.25	2.12	0.97	20.88	9.52	9.03
0.42	242.36	2.11	0.96	22.99	10.48	10.00
0.50	243.32	0.96	0.44	23.95	10.92	10.70
0.58	244.44	1.12	0.51	25.07	11.43	11.17
0.67	245.45	1.01	0.46	26.08	11.89	11.66
0.75	246.43	0.98	0.45	27.06	12.34	12.11
0.83	247.19	0.76	0.35	27.82	12.68	12.51
0.92	247.91	0.72	0.33	28.54	13.01	12.85
1.00	248.59	0.68	0.31	29.22	13.32	13.16
1.25	249.99	1.40	0.64	30.62	13.96	13.64
1.50	250.96	0.97	0.44	31.59	14.40	14.18
1.75	251.72	0.76	0.35	32.35	14.75	14.57
2.00	252.19	0.47	0.21	32.82	14.96	14.85
2.25	252.69	0.50	0.23	33.32	15.19	15.07
2.50	252.99	0.30	0.14	33.62	15.33	15.26
2.75	253.13	0.14	0.06	33.76	15.39	15.36
3.00	253.31	0.18	0.08	33.94	15.47	15.43
4.00	253.49	0.18	0.08	34.12	15.55	15.51
5.00	253.58	0.09	0.04	34.21	15.59	15.57
6.00	253.64	0.06	0.03	34.27	15.62	15.61
7.00	253.72	0.08	0.04	34.35	15.66	15.64
8.00	253.78	0.06	0.03	34.41	15.69	15.67
24.0	254.36	0.58	0.26	34.99	15.95	15.82
48.0	254.81	0.45	0.21	35.44	16.16	16.05
72.0	255.13	0.32	0.15	35.76	16.30	16.23
96.0	255.28	0.15	0.07	35.91	16.37	16.34
120.0	255.45	0.17	0.08	36.08	16.45	16.41
144.0	255.70	0.25	0.11	36.33	16.56	16.50
168.0	256.12	0.42	0.19	36.75	16.75	16.66
192.0	256.03	-0.09	0.04	36.66	16.71	16.73
216.0	256.15	0.12	0.05	36.78	16.77	16.74

Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample S2-2

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	216.15	0.00	0.00	0.00	0.00	0.00
0.08	227.87	11.72	5.42	11.72	5.42	2.71
0.17	230.54	2.67	1.24	14.39	6.66	6.04
0.25	233.15	2.61	1.21	17.00	7.86	7.26
0.33	235.06	1.91	0.88	18.91	8.75	8.31
0.42	237.02	1.96	0.91	20.87	9.66	9.20
0.50	237.99	0.97	0.45	21.84	10.10	9.88
0.58	239.08	1.09	0.50	22.93	10.61	10.36
0.67	240.13	1.05	0.49	23.98	11.09	10.85
0.75	241.15	1.02	0.47	25.00	11.57	11.33
0.83	241.96	0.81	0.37	25.81	11.94	11.75
0.92	242.70	0.74	0.34	26.55	12.28	12.11
1.00	243.38	0.68	0.31	27.23	12.60	12.44
1.25	244.96	1.58	0.73	28.81	13.33	12.96
1.50	247.07	2.11	0.98	30.92	14.30	13.82
1.75	246.92	-0.15	0.07	30.77	14.24	14.27
2.00	247.51	0.59	0.27	31.36	14.51	14.37
2.25	248.06	0.55	0.25	31.91	14.76	14.64
2.50	248.49	0.43	0.20	32.34	14.96	14.86
2.75	248.81	0.32	0.15	32.66	15.11	15.04
3.00	249.04	0.23	0.11	32.89	15.22	15.16
4.00	249.42	0.38	0.18	33.27	15.39	15.30
5.00	249.59	0.17	0.08	33.44	15.47	15.43
6.00	249.66	0.07	0.03	33.51	15.50	15.49
7.00	249.74	0.08	0.04	33.59	15.54	15.52
8.00	249.76	0.02	0.01	33.61	15.55	15.54
24.0	250.37	0.61	0.28	34.22	15.83	15.69
48.0	250.84	0.47	0.22	34.69	16.05	15.94
72.0	251.10	0.26	0.12	34.95	16.17	16.11
96.0	251.35	0.25	0.12	35.20	16.28	16.23
120.0	251.49	0.14	0.06	35.34	16.35	16.32
144.0	251.72	0.23	0.11	35.57	16.46	16.40
168.0	251.88	0.16	0.07	35.73	16.53	16.49
192.0	252.00	0.12	0.06	35.85	16.59	16.56
216.0	252.15	0.15	0.07	36.00	16.66	16.62

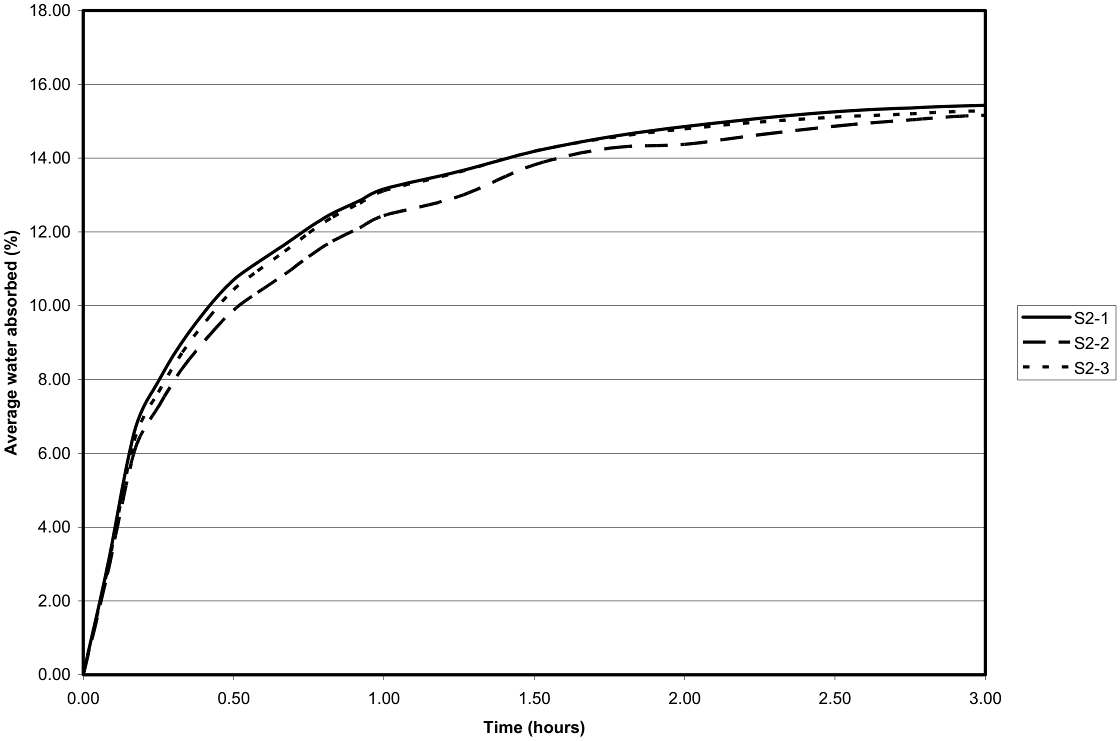
Appendix E: Water Absorption – Normal 7/81

Water absorption measurements for sample S2-3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Difference in successive weighings (%)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	219.26	0.00	0.00	0.00	0.00	0.00
0.08	231.64	12.38	5.65	12.38	5.65	2.82
0.17	234.70	3.06	1.40	15.44	7.04	6.34
0.25	237.38	2.68	1.22	18.12	8.26	7.65
0.33	239.46	2.08	0.95	20.20	9.21	8.74
0.42	241.62	2.16	0.99	22.36	10.20	9.71
0.50	242.65	1.03	0.47	23.39	10.67	10.43
0.58	243.85	1.20	0.55	24.59	11.21	10.94
0.67	244.98	1.13	0.52	25.72	11.73	11.47
0.75	246.04	1.06	0.48	26.78	12.21	11.97
0.83	246.88	0.84	0.38	27.62	12.60	12.41
0.92	247.66	0.78	0.36	28.40	12.95	12.77
1.00	248.36	0.70	0.32	29.10	13.27	13.11
1.25	249.88	1.52	0.69	30.62	13.97	13.62
1.50	250.86	0.98	0.45	31.60	14.41	14.19
1.75	251.47	0.61	0.28	32.21	14.69	14.55
2.00	251.92	0.45	0.21	32.66	14.90	14.79
2.25	252.30	0.38	0.17	33.04	15.07	14.98
2.50	252.49	0.19	0.09	33.23	15.16	15.11
2.75	252.68	0.19	0.09	33.42	15.24	15.20
3.00	252.87	0.19	0.09	33.61	15.33	15.29
4.00	253.15	0.28	0.13	33.89	15.46	15.39
5.00	253.31	0.16	0.07	34.05	15.53	15.49
6.00	253.37	0.06	0.03	34.11	15.56	15.54
7.00	253.48	0.11	0.05	34.22	15.61	15.58
8.00	253.51	0.03	0.01	34.25	15.62	15.61
24.0	254.10	0.59	0.27	34.84	15.89	15.76
48.0	254.51	0.41	0.19	35.25	16.08	15.98
72.0	254.73	0.22	0.10	35.47	16.18	16.13
96.0	255.04	0.31	0.14	35.78	16.32	16.25
120.0	255.14	0.10	0.05	35.88	16.36	16.34
144.0	255.33	0.19	0.09	36.07	16.45	16.41
168.0	255.93	0.60	0.27	36.67	16.72	16.59
192.0	255.64	-0.29	0.13	36.38	16.59	16.66
216.0	255.75	0.11	0.05	36.49	16.64	16.62

Appendix E: Water Absorption – Normal 7/81

Water absorption curves for samples S2-1,2&3



APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B1-1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	286.88	259.44	10.58	27.44	27.44	1.00	100.00	0.00	0.000	0.5322
0.08	0.08	286.72	259.44	10.51	27.44	27.28	0.99	99.42	0.58	7.289	0.5291
0.17	0.09	286.66	259.44	10.49	27.44	27.22	0.99	99.20	0.22	2.430	0.5279
0.25	0.08	286.60	259.44	10.47	27.44	27.16	0.99	98.98	0.22	2.733	0.5268
0.33	0.08	286.54	259.44	10.45	27.44	27.10	0.99	98.76	0.22	2.733	0.5256
0.42	0.09	286.49	259.44	10.43	27.44	27.05	0.99	98.58	0.18	2.025	0.5246
0.50	0.08	286.44	259.44	10.41	27.44	27.00	0.98	98.40	0.18	2.278	0.5237
0.58	0.08	286.37	259.44	10.38	27.44	26.93	0.98	98.14	0.26	3.189	0.5223
0.67	0.09	286.33	259.44	10.36	27.44	26.89	0.98	98.00	0.15	1.620	0.5215
0.75	0.08	286.29	259.44	10.35	27.44	26.85	0.98	97.85	0.15	1.822	0.5208
0.83	0.08	286.25	259.44	10.33	27.44	26.81	0.98	97.70	0.15	1.822	0.5200
0.92	0.09	286.21	259.44	10.32	27.44	26.77	0.98	97.56	0.15	1.620	0.5192
1.00	0.08	286.17	259.44	10.30	27.44	26.73	0.97	97.41	0.15	1.822	0.5184
1.25	0.25	286.08	259.44	10.27	27.44	26.64	0.97	97.08	0.33	1.312	0.5167
1.50	0.25	286.00	259.44	10.24	27.44	26.56	0.97	96.79	0.29	1.166	0.5151
1.75	0.25	285.95	259.44	10.22	27.44	26.51	0.97	96.61	0.18	0.729	0.5142
2.00	0.25	285.87	259.44	10.19	27.44	26.43	0.96	96.32	0.29	1.166	0.5126
2.25	0.25	285.78	259.44	10.15	27.44	26.34	0.96	95.99	0.33	1.312	0.5109

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B1-1 (cont.)

Time (hours)	**Time difference, Δt (hours)**	**Weight, W_t (g)**	**Dry weight**	**Residual water content, Q_i (g)**	**Initial water content, U_0 (g)**	**Water content, U_t (g)**	**Relative moisture content, Y**	**Relative moisture content, Y (%)**	**Difference in relative moisture content, ΔY**	**Relative moisture content lost/unit time, $\Delta Y/\Delta t$**	**Moisture content, Ψ (g/cm^3)**
2.50	0.25	285.70	259.44	10.12	27.44	26.26	0.96	95.70	0.29	1.166	0.5093
2.75	0.25	285.65	259.44	10.10	27.44	26.21	0.96	95.52	0.18	0.729	0.5083
3.00	0.25	285.56	259.44	10.07	27.44	26.12	0.95	95.19	0.33	1.312	0.5066
24.0	21.00	283.74	259.44	9.37	27.44	24.30	0.89	88.56	6.63	0.316	0.4713
48.0	24.00	282.18	259.44	8.77	27.44	22.74	0.83	82.87	5.69	0.237	0.4410
72.0	24.00	281.30	259.44	8.43	27.44	21.86	0.80	79.66	3.21	0.134	0.4240
96.0	24.00	280.30	259.44	8.04	27.44	20.86	0.76	76.02	3.64	0.152	0.4046
120.0	24.00	279.37	259.44	7.68	27.44	19.93	0.73	72.63	3.39	0.141	0.3865
144.0	24.00	278.39	259.44	7.30	27.44	18.95	0.69	69.06	3.57	0.149	0.3675
168.0	24.00	277.51	259.44	6.97	27.44	18.07	0.66	65.85	3.21	0.134	0.3505
192.0	24.00	276.89	259.44	6.73	27.44	17.45	0.64	63.59	2.26	0.094	0.3384
216.0	24.00	276.34	259.44	6.51	27.44	16.90	0.62	61.59	2.00	0.084	0.3278
240.0	24.00	275.70	259.44	6.27	27.44	16.26	0.59	59.26	2.33	0.097	0.3154
264.0	24.00	275.28	259.44	6.11	27.44	15.84	0.58	57.73	1.53	0.064	0.3072
288.0	24.00	274.84	259.44	5.94	27.44	15.40	0.56	56.12	1.60	0.067	0.2987
312.0	24.00	274.46	259.44	5.79	27.44	15.02	0.55	54.74	1.38	0.058	0.2913
336.0	24.00	274.12	259.44	5.66	27.44	14.68	0.53	53.50	1.24	0.052	0.2847

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B1-2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	290.66	263.03	10.50	27.63	27.63	1.00	100.00	0.00	0.000	0.5359
0.08	0.08	290.53	263.03	10.46	27.63	27.50	1.00	99.53	0.47	5.881	0.5334
0.17	0.09	290.48	263.03	10.44	27.63	27.45	0.99	99.35	0.18	2.011	0.5324
0.25	0.08	290.44	263.03	10.42	27.63	27.41	0.99	99.20	0.14	1.810	0.5316
0.33	0.08	290.38	263.03	10.40	27.63	27.35	0.99	98.99	0.22	2.714	0.5304
0.42	0.09	290.33	263.03	10.38	27.63	27.30	0.99	98.81	0.18	2.011	0.5295
0.50	0.08	290.29	263.03	10.36	27.63	27.26	0.99	98.66	0.14	1.810	0.5287
0.58	0.08	290.22	263.03	10.34	27.63	27.19	0.98	98.41	0.25	3.167	0.5273
0.67	0.09	290.18	263.03	10.32	27.63	27.15	0.98	98.26	0.14	1.609	0.5266
0.75	0.08	290.13	263.03	10.30	27.63	27.10	0.98	98.08	0.18	2.262	0.5256
0.83	0.08	290.09	263.03	10.29	27.63	27.06	0.98	97.94	0.14	1.810	0.5248
0.92	0.09	290.05	263.03	10.27	27.63	27.02	0.98	97.79	0.14	1.609	0.5240
1.00	0.08	290.01	263.03	10.26	27.63	26.98	0.98	97.65	0.14	1.810	0.5233
1.25	0.25	289.91	263.03	10.22	27.63	26.88	0.97	97.29	0.36	1.448	0.5213
1.50	0.25	289.83	263.03	10.19	27.63	26.80	0.97	97.00	0.29	1.158	0.5198
1.75	0.25	289.77	263.03	10.17	27.63	26.74	0.97	96.78	0.22	0.869	0.5186
2.00	0.25	289.71	263.03	10.14	27.63	26.68	0.97	96.56	0.22	0.869	0.5175
2.25	0.25	289.62	263.03	10.11	27.63	26.59	0.96	96.24	0.33	1.303	0.5157

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B1-2 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.50	0.25	289.56	263.03	10.09	27.63	26.53	0.96	96.02	0.22	0.869	0.5145
2.75	0.25	289.50	263.03	10.06	27.63	26.47	0.96	95.80	0.22	0.869	0.5134
3.00	0.25	289.44	263.03	10.04	27.63	26.41	0.96	95.58	0.22	0.869	0.5122
24.0	21.00	287.58	263.03	9.33	27.63	24.55	0.89	88.85	6.73	0.321	0.4761
48.0	24.00	286.03	263.03	8.74	27.63	23.00	0.83	83.24	5.61	0.234	0.4461
72.0	24.00	285.19	263.03	8.42	27.63	22.16	0.80	80.20	3.04	0.127	0.4298
96.0	24.00	284.19	263.03	8.04	27.63	21.16	0.77	76.58	3.62	0.151	0.4104
120.0	24.00	283.27	263.03	7.69	27.63	20.24	0.73	73.25	3.33	0.139	0.3926
144.0	24.00	282.31	263.03	7.33	27.63	19.28	0.70	69.78	3.47	0.145	0.3739
168.0	24.00	281.46	263.03	7.01	27.63	18.43	0.67	66.70	3.08	0.128	0.3574
192.0	24.00	280.80	263.03	6.76	27.63	17.77	0.64	64.31	2.39	0.100	0.3446
216.0	24.00	280.24	263.03	6.54	27.63	17.21	0.62	62.29	2.03	0.084	0.3338
240.0	24.00	279.60	263.03	6.30	27.63	16.57	0.60	59.97	2.32	0.097	0.3214
264.0	24.00	279.16	263.03	6.13	27.63	16.13	0.58	58.38	1.59	0.066	0.3128
288.0	24.00	278.69	263.03	5.95	27.63	15.66	0.57	56.68	1.70	0.071	0.3037
312.0	24.00	278.31	263.03	5.81	27.63	15.28	0.55	55.30	1.38	0.057	0.2964
336.0	24.00	277.95	263.03	5.67	27.63	14.92	0.54	54.00	1.30	0.054	0.2894

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B1-3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry Weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	291.39	264.07	10.35	27.32	27.32	1.00	100.00	0.00	0.000	0.5299
0.08	0.08	291.25	264.07	10.29	27.32	27.18	0.99	99.49	0.51	6.406	0.5272
0.17	0.09	291.19	264.07	10.27	27.32	27.12	0.99	99.27	0.22	2.440	0.5260
0.25	0.08	291.11	264.07	10.24	27.32	27.04	0.99	98.98	0.29	3.660	0.5244
0.33	0.08	291.06	264.07	10.22	27.32	26.99	0.99	98.79	0.18	2.288	0.5235
0.42	0.09	291.01	264.07	10.20	27.32	26.94	0.99	98.61	0.18	2.034	0.5225
0.50	0.08	290.95	264.07	10.18	27.32	26.88	0.98	98.39	0.22	2.745	0.5213
0.58	0.08	290.89	264.07	10.16	27.32	26.82	0.98	98.17	0.22	2.745	0.5202
0.67	0.09	290.82	264.07	10.13	27.32	26.75	0.98	97.91	0.26	2.847	0.5188
0.75	0.08	290.77	264.07	10.11	27.32	26.70	0.98	97.73	0.18	2.288	0.5178
0.83	0.08	290.72	264.07	10.09	27.32	26.65	0.98	97.55	0.18	2.288	0.5169
0.92	0.09	290.67	264.07	10.07	27.32	26.60	0.97	97.36	0.18	2.034	0.5159
1.00	0.08	290.63	264.07	10.06	27.32	26.56	0.97	97.22	0.15	1.830	0.5151
1.25	0.25	290.52	264.07	10.02	27.32	26.45	0.97	96.82	0.40	1.611	0.5130
1.50	0.25	290.41	264.07	9.97	27.32	26.34	0.96	96.41	0.40	1.611	0.5109
1.75	0.25	290.35	264.07	9.95	27.32	26.28	0.96	96.19	0.22	0.878	0.5097
2.00	0.25	290.28	264.07	9.93	27.32	26.21	0.96	95.94	0.26	1.025	0.5083
2.25	0.25	290.25	264.07	9.91	27.32	26.18	0.96	95.83	0.11	0.439	0.5078

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B1-3 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry Weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.50	0.25	290.16	264.07	9.88	27.32	26.09	0.95	95.50	0.33	1.318	0.5060
2.75	0.25	290.11	264.07	9.86	27.32	26.04	0.95	95.31	0.18	0.732	0.5050
3.00	0.25	290.05	264.07	9.84	27.32	25.98	0.95	95.10	0.22	0.878	0.5039
24.0	21.00	288.27	264.07	9.16	27.32	24.20	0.89	88.58	6.52	0.310	0.4694
48.0	24.00	286.61	264.07	8.54	27.32	22.54	0.83	82.50	6.08	0.253	0.4372
72.0	24.00	285.62	264.07	8.16	27.32	21.55	0.79	78.88	3.62	0.151	0.4180
96.0	24.00	284.55	264.07	7.76	27.32	20.48	0.75	74.96	3.92	0.163	0.3972
120.0	24.00	283.66	264.07	7.42	27.32	19.59	0.72	71.71	3.26	0.136	0.3799
144.0	24.00	282.76	264.07	7.08	27.32	18.69	0.68	68.41	3.29	0.137	0.3625
168.0	24.00	282.00	264.07	6.79	27.32	17.93	0.66	65.63	2.78	0.116	0.3478
192.0	24.00	281.44	264.07	6.58	27.32	17.37	0.64	63.58	2.05	0.085	0.3369
216.0	24.00	280.93	264.07	6.38	27.32	16.86	0.62	61.71	1.87	0.078	0.3270
240.0	24.00	280.34	264.07	6.16	27.32	16.27	0.60	59.55	2.16	0.090	0.3156
264.0	24.00	279.93	264.07	6.01	27.32	15.86	0.58	58.05	1.50	0.063	0.3076
288.0	24.00	279.49	264.07	5.84	27.32	15.42	0.56	56.44	1.61	0.067	0.2991
312.0	24.00	279.12	264.07	5.70	27.32	15.05	0.55	55.09	1.35	0.056	0.2919
336.0	24.00	278.81	264.07	5.58	27.32	14.74	0.54	53.95	1.13	0.047	0.2859

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B2-1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	287.78	260.95	10.28	26.83	26.83	1.00	100.00	0.00	0.000	0.5204
0.08	0.08	287.63	260.95	10.22	26.83	26.68	0.99	99.44	0.56	6.988	0.5175
0.17	0.09	287.56	260.95	10.20	26.83	26.61	0.99	99.18	0.26	2.899	0.5161
0.25	0.08	287.49	260.95	10.17	26.83	26.54	0.99	98.92	0.26	3.261	0.5147
0.33	0.08	287.41	260.95	10.14	26.83	26.46	0.99	98.62	0.30	3.727	0.5132
0.42	0.09	287.34	260.95	10.11	26.83	26.39	0.98	98.36	0.26	2.899	0.5118
0.50	0.08	287.27	260.95	10.09	26.83	26.32	0.98	98.10	0.26	3.261	0.5105
0.58	0.08	287.20	260.95	10.06	26.83	26.25	0.98	97.84	0.26	3.261	0.5091
0.67	0.09	287.13	260.95	10.03	26.83	26.18	0.98	97.58	0.26	2.899	0.5078
0.75	0.08	287.06	260.95	10.01	26.83	26.11	0.97	97.32	0.26	3.261	0.5064
0.83	0.08	286.99	260.95	9.98	26.83	26.04	0.97	97.06	0.26	3.261	0.5050
0.92	0.09	286.91	260.95	9.95	26.83	25.96	0.97	96.76	0.30	3.313	0.5035
1.00	0.08	286.85	260.95	9.93	26.83	25.90	0.97	96.53	0.22	2.795	0.5023
1.25	0.25	286.71	260.95	9.87	26.83	25.76	0.96	96.01	0.52	2.087	0.4996
1.50	0.25	286.57	260.95	9.82	26.83	25.62	0.95	95.49	0.52	2.087	0.4969

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B2-1 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
1.75	0.25	286.44	260.95	9.77	26.83	25.49	0.95	95.01	0.48	1.938	0.4944
2.00	0.25	286.34	260.95	9.73	26.83	25.39	0.95	94.63	0.37	1.491	0.4924
2.25	0.25	286.22	260.95	9.68	26.83	25.27	0.94	94.19	0.45	1.789	0.4901
2.50	0.25	286.07	260.95	9.63	26.83	25.12	0.94	93.63	0.56	2.236	0.4872
2.75	0.25	286.00	260.95	9.60	26.83	25.05	0.93	93.37	0.26	1.044	0.4858
3.00	0.25	285.89	260.95	9.56	26.83	24.94	0.93	92.96	0.41	1.640	0.4837
24.0	21.00	283.81	260.95	8.76	26.83	22.86	0.85	85.20	7.75	0.369	0.4434
48.0	24.00	279.27	260.95	7.02	26.83	18.32	0.68	68.28	16.92	0.705	0.3553
72.0	24.00	276.60	260.95	6.00	26.83	15.65	0.58	58.33	9.95	0.415	0.3035
96.0	24.00	275.15	260.95	5.44	26.83	14.20	0.53	52.93	5.40	0.225	0.2754
120.0	24.00	273.75	260.95	4.91	26.83	12.80	0.48	47.71	5.22	0.217	0.2483
144.0	24.00	272.33	260.95	4.36	26.83	11.38	0.42	42.42	5.29	0.221	0.2207
168.0	24.00	271.17	260.95	3.92	26.83	10.22	0.38	38.09	4.32	0.180	0.1982
192.0	24.00	270.15	260.95	3.53	26.83	9.20	0.34	34.29	3.80	0.158	0.1784
216.0	24.00	269.45	260.95	3.26	26.83	8.50	0.32	31.68	2.61	0.109	0.1649
240.0	24.00	269.08	260.95	3.12	26.83	8.13	0.30	30.30	1.38	0.057	0.1577

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B2-2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	279.20	253.05	10.33	26.15	26.15	1.00	100.00	0.00	0.000	0.5072
0.08	0.08	279.09	253.05	10.29	26.15	26.04	1.00	99.58	0.42	5.258	0.5050
0.17	0.09	279.02	253.05	10.26	26.15	25.97	0.99	99.31	0.27	2.974	0.5037
0.25	0.08	278.96	253.05	10.24	26.15	25.91	0.99	99.08	0.23	2.868	0.5025
0.33	0.08	278.91	253.05	10.22	26.15	25.86	0.99	98.89	0.19	2.390	0.5016
0.42	0.09	278.82	253.05	10.18	26.15	25.77	0.99	98.55	0.34	3.824	0.4998
0.50	0.08	278.76	253.05	10.16	26.15	25.71	0.98	98.32	0.23	2.868	0.4986
0.58	0.08	278.69	253.05	10.13	26.15	25.64	0.98	98.05	0.27	3.346	0.4973
0.67	0.09	278.63	253.05	10.11	26.15	25.58	0.98	97.82	0.23	2.549	0.4961
0.75	0.08	278.56	253.05	10.08	26.15	25.51	0.98	97.55	0.27	3.346	0.4948
0.83	0.08	278.50	253.05	10.06	26.15	25.45	0.97	97.32	0.23	2.868	0.4936
0.92	0.09	278.41	253.05	10.02	26.15	25.36	0.97	96.98	0.34	3.824	0.4919
1.00	0.08	278.36	253.05	10.00	26.15	25.31	0.97	96.79	0.19	2.390	0.4909
1.25	0.25	278.23	253.05	9.95	26.15	25.18	0.96	96.29	0.50	1.989	0.4884
1.50	0.25	278.12	253.05	9.91	26.15	25.07	0.96	95.87	0.42	1.683	0.4862

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B2-2 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
1.75	0.25	278.03	253.05	9.87	26.15	24.98	0.96	95.53	0.34	1.377	0.4845
2.00	0.25	277.92	253.05	9.83	26.15	24.87	0.95	95.11	0.42	1.683	0.4824
2.25	0.25	277.79	253.05	9.78	26.15	24.74	0.95	94.61	0.50	1.989	0.4798
2.50	0.25	277.65	253.05	9.72	26.15	24.60	0.94	94.07	0.54	2.141	0.4771
2.75	0.25	277.56	253.05	9.69	26.15	24.51	0.94	93.73	0.34	1.377	0.4754
3.00	0.25	277.47	253.05	9.65	26.15	24.42	0.93	93.38	0.34	1.377	0.4736
24.0	21.00	275.74	253.05	8.97	26.15	22.69	0.87	86.77	6.62	0.315	0.4401
48.0	24.00	271.31	253.05	7.22	26.15	18.26	0.70	69.83	16.94	0.706	0.3542
72.0	24.00	268.42	253.05	6.07	26.15	15.37	0.59	58.78	11.05	0.460	0.2981
96.0	24.00	266.85	253.05	5.45	26.15	13.80	0.53	52.77	6.00	0.250	0.2676
120.0	24.00	265.48	253.05	4.91	26.15	12.43	0.48	47.53	5.24	0.218	0.2411
144.0	24.00	264.06	253.05	4.35	26.15	11.01	0.42	42.10	5.43	0.226	0.2135
168.0	24.00	262.93	253.05	3.90	26.15	9.88	0.38	37.78	4.32	0.180	0.1916
192.0	24.00	261.96	253.05	3.52	26.15	8.91	0.34	34.07	3.71	0.155	0.1728
216.0	24.00	261.29	253.05	3.26	26.15	8.24	0.32	31.51	2.56	0.107	0.1598
240.0	24.00	260.93	253.05	3.11	26.15	7.88	0.30	30.13	1.38	0.057	0.1528

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B2-3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	282.82	256.70	10.18	26.12	26.12	1.00	100.00	0.00	0.000	0.5066
0.08	0.08	282.70	256.70	10.13	26.12	26.00	1.00	99.54	0.46	5.743	0.5043
0.17	0.09	282.62	256.70	10.10	26.12	25.92	0.99	99.23	0.31	3.403	0.5027
0.25	0.08	282.54	256.70	10.07	26.12	25.84	0.99	98.93	0.31	3.828	0.5012
0.33	0.08	282.47	256.70	10.04	26.12	25.77	0.99	98.66	0.27	3.350	0.4998
0.42	0.09	282.37	256.70	10.00	26.12	25.67	0.98	98.28	0.38	4.254	0.4979
0.50	0.08	282.30	256.70	9.97	26.12	25.60	0.98	98.01	0.27	3.350	0.4965
0.58	0.08	282.22	256.70	9.94	26.12	25.52	0.98	97.70	0.31	3.828	0.4950
0.67	0.09	282.15	256.70	9.91	26.12	25.45	0.97	97.43	0.27	2.978	0.4936
0.75	0.08	282.07	256.70	9.88	26.12	25.37	0.97	97.13	0.31	3.828	0.4920
0.83	0.08	282.00	256.70	9.86	26.12	25.30	0.97	96.86	0.27	3.350	0.4907
0.92	0.09	281.92	256.70	9.82	26.12	25.22	0.97	96.55	0.31	3.403	0.4891
1.00	0.08	281.86	256.70	9.80	26.12	25.16	0.96	96.32	0.23	2.871	0.4880
1.25	0.25	281.74	256.70	9.75	26.12	25.04	0.96	95.87	0.46	1.838	0.4856
1.50	0.25	281.60	256.70	9.70	26.12	24.90	0.95	95.33	0.54	2.144	0.4829

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample B2-3 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
1.75	0.25	281.47	256.70	9.65	26.12	24.77	0.95	94.83	0.50	1.991	0.4804
2.00	0.25	281.33	256.70	9.59	26.12	24.63	0.94	94.30	0.54	2.144	0.4777
2.25	0.25	281.19	256.70	9.54	26.12	24.49	0.94	93.76	0.54	2.144	0.4750
2.50	0.25	281.03	256.70	9.48	26.12	24.33	0.93	93.15	0.61	2.450	0.4719
2.75	0.25	280.93	256.70	9.44	26.12	24.23	0.93	92.76	0.38	1.531	0.4699
3.00	0.25	280.82	256.70	9.40	26.12	24.12	0.92	92.34	0.42	1.685	0.4678
24.0	21.00	278.67	256.70	8.56	26.12	21.97	0.84	84.11	8.23	0.392	0.4261
48.0	24.00	273.41	256.70	6.51	26.12	16.71	0.64	63.97	20.14	0.839	0.3241
72.0	24.00	270.98	256.70	5.56	26.12	14.28	0.55	54.67	9.30	0.388	0.2770
96.0	24.00	269.55	256.70	5.01	26.12	12.85	0.49	49.20	5.47	0.228	0.2492
120.0	24.00	268.28	256.70	4.51	26.12	11.58	0.44	44.33	4.86	0.203	0.2246
144.0	24.00	267.00	256.70	4.01	26.12	10.30	0.39	39.43	4.90	0.204	0.1998
168.0	24.00	265.96	256.70	3.61	26.12	9.26	0.35	35.45	3.98	0.166	0.1796
192.0	24.00	265.06	256.70	3.26	26.12	8.36	0.32	32.01	3.45	0.144	0.1621
216.0	24.00	264.46	256.70	3.02	26.12	7.76	0.30	29.71	2.30	0.096	0.1505
240.0	24.00	264.16	256.70	2.91	26.12	7.46	0.29	28.56	1.15	0.048	0.1447

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C1-1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	275.50	236.79	16.35	38.71	38.71	1.00	100.00	0.00	0.000	0.7508
0.08	0.08	275.36	236.79	16.29	38.71	38.57	1.00	99.64	0.36	4.521	0.7481
0.17	0.09	275.30	236.79	16.26	38.71	38.51	0.99	99.48	0.15	1.722	0.7469
0.25	0.08	275.25	236.79	16.24	38.71	38.46	0.99	99.35	0.13	1.615	0.7459
0.33	0.08	275.19	236.79	16.22	38.71	38.40	0.99	99.20	0.15	1.937	0.7448
0.42	0.09	275.14	236.79	16.20	38.71	38.35	0.99	99.07	0.13	1.435	0.7438
0.50	0.08	275.10	236.79	16.18	38.71	38.31	0.99	98.97	0.10	1.292	0.7430
0.58	0.08	275.04	236.79	16.15	38.71	38.25	0.99	98.81	0.15	1.937	0.7419
0.67	0.09	275.01	236.79	16.14	38.71	38.22	0.99	98.73	0.08	0.861	0.7413
0.75	0.08	274.97	236.79	16.12	38.71	38.18	0.99	98.63	0.10	1.292	0.7405
0.83	0.08	274.92	236.79	16.10	38.71	38.13	0.99	98.50	0.13	1.615	0.7395
0.92	0.09	274.88	236.79	16.09	38.71	38.09	0.98	98.40	0.10	1.148	0.7388
1.00	0.08	274.85	236.79	16.07	38.71	38.06	0.98	98.32	0.08	0.969	0.7382
1.25	0.25	274.78	236.79	16.04	38.71	37.99	0.98	98.14	0.18	0.723	0.7368
1.50	0.25	274.70	236.79	16.01	38.71	37.91	0.98	97.93	0.21	0.827	0.7353
1.75	0.25	274.60	236.79	15.97	38.71	37.81	0.98	97.68	0.26	1.033	0.7333
2.00	0.25	274.53	236.79	15.94	38.71	37.74	0.97	97.49	0.18	0.723	0.7320
2.25	0.25	274.46	236.79	15.91	38.71	37.67	0.97	97.31	0.18	0.723	0.7306

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C1-1 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.50	0.25	274.38	236.79	15.87	38.71	37.59	0.97	97.11	0.21	0.827	0.7291
2.75	0.25	274.31	236.79	15.85	38.71	37.52	0.97	96.93	0.18	0.723	0.7277
3.00	0.25	274.26	236.79	15.82	38.71	37.47	0.97	96.80	0.13	0.517	0.7267
24.0	21.00	269.90	236.79	13.98	38.71	33.11	0.86	85.53	11.26	0.536	0.6422
48.0	24.00	267.92	236.79	13.15	38.71	31.13	0.80	80.42	5.11	0.213	0.6038
72.0	24.00	266.35	236.79	12.48	38.71	29.56	0.76	76.36	4.06	0.169	0.5733
96.0	24.00	264.97	236.79	11.90	38.71	28.18	0.73	72.80	3.56	0.149	0.5465
120.0	24.00	263.51	236.79	11.28	38.71	26.72	0.69	69.03	3.77	0.157	0.5182
144.0	24.00	262.22	236.79	10.74	38.71	25.43	0.66	65.69	3.33	0.139	0.4932
168.0	24.00	261.02	236.79	10.23	38.71	24.23	0.63	62.59	3.10	0.129	0.4699
192.0	24.00	259.93	236.79	9.77	38.71	23.14	0.60	59.78	2.82	0.117	0.4488
216.0	24.00	259.29	236.79	9.50	38.71	22.50	0.58	58.12	1.65	0.069	0.4364
240.0	24.00	258.59	236.79	9.21	38.71	21.80	0.56	56.32	1.81	0.075	0.4228
264.0	24.00	257.72	236.79	8.84	38.71	20.93	0.54	54.07	2.25	0.094	0.4059
288.0	24.00	257.16	236.79	8.60	38.71	20.37	0.53	52.62	1.45	0.060	0.3951
312.0	24.00	256.54	236.79	8.34	38.71	19.75	0.51	51.02	1.60	0.067	0.3830
336.0	24.00	255.97	236.79	8.10	38.71	19.18	0.50	49.55	1.47	0.061	0.3720
360.0	24.00	255.57	236.79	7.93	38.71	18.78	0.49	48.51	1.03	0.043	0.3642

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C1-2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	267.10	229.82	16.22	37.28	37.28	1.00	100.00	0.00	0.000	0.7230
0.08	0.08	266.99	229.82	16.17	37.28	37.17	1.00	99.70	0.30	3.688	0.7209
0.17	0.09	266.93	229.82	16.15	37.28	37.11	1.00	99.54	0.16	1.788	0.7197
0.25	0.08	266.88	229.82	16.13	37.28	37.06	0.99	99.41	0.13	1.677	0.7188
0.33	0.08	266.83	229.82	16.10	37.28	37.01	0.99	99.28	0.13	1.677	0.7178
0.42	0.09	266.78	229.82	16.08	37.28	36.96	0.99	99.14	0.13	1.490	0.7168
0.50	0.08	266.74	229.82	16.06	37.28	36.92	0.99	99.03	0.11	1.341	0.7161
0.58	0.08	266.70	229.82	16.05	37.28	36.88	0.99	98.93	0.11	1.341	0.7153
0.67	0.09	266.65	229.82	16.03	37.28	36.83	0.99	98.79	0.13	1.490	0.7143
0.75	0.08	266.62	229.82	16.01	37.28	36.80	0.99	98.71	0.08	1.006	0.7137
0.83	0.08	266.58	229.82	16.00	37.28	36.76	0.99	98.61	0.11	1.341	0.7130
0.92	0.09	266.54	229.82	15.98	37.28	36.72	0.98	98.50	0.11	1.192	0.7122
1.00	0.08	266.50	229.82	15.96	37.28	36.68	0.98	98.39	0.11	1.341	0.7114
1.25	0.25	266.44	229.82	15.93	37.28	36.62	0.98	98.23	0.16	0.644	0.7102
1.50	0.25	266.36	229.82	15.90	37.28	36.54	0.98	98.02	0.21	0.858	0.7087
1.75	0.25	266.27	229.82	15.86	37.28	36.45	0.98	97.77	0.24	0.966	0.7069
2.00	0.25	266.19	229.82	15.83	37.28	36.37	0.98	97.56	0.21	0.858	0.7054
2.25	0.25	266.13	229.82	15.80	37.28	36.31	0.97	97.40	0.16	0.644	0.7042

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C1-2 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.50	0.25	266.04	229.82	15.76	37.28	36.22	0.97	97.16	0.24	0.966	0.7025
2.75	0.25	265.99	229.82	15.74	37.28	36.17	0.97	97.02	0.13	0.536	0.7015
3.00	0.25	265.90	229.82	15.70	37.28	36.08	0.97	96.78	0.24	0.966	0.6998
24.0	21.00	261.68	229.82	13.86	37.28	31.86	0.85	85.46	11.32	0.539	0.6179
48.0	24.00	259.83	229.82	13.06	37.28	30.01	0.80	80.50	4.96	0.207	0.5820
72.0	24.00	258.29	229.82	12.39	37.28	28.47	0.76	76.37	4.13	0.172	0.5522
96.0	24.00	256.92	229.82	11.79	37.28	27.10	0.73	72.69	3.67	0.153	0.5256
120.0	24.00	255.52	229.82	11.18	37.28	25.70	0.69	68.94	3.76	0.156	0.4984
144.0	24.00	254.27	229.82	10.64	37.28	24.45	0.66	65.58	3.35	0.140	0.4742
168.0	24.00	253.08	229.82	10.12	37.28	23.26	0.62	62.39	3.19	0.133	0.4511
192.0	24.00	252.07	229.82	9.68	37.28	22.25	0.60	59.68	2.71	0.113	0.4315
216.0	24.00	251.45	229.82	9.41	37.28	21.63	0.58	58.02	1.66	0.069	0.4195
240.0	24.00	250.75	229.82	9.11	37.28	20.93	0.56	56.14	1.88	0.078	0.4059
264.0	24.00	249.93	229.82	8.75	37.28	20.11	0.54	53.94	2.20	0.092	0.3900
288.0	24.00	249.38	229.82	8.51	37.28	19.56	0.52	52.47	1.48	0.061	0.3794
312.0	24.00	248.76	229.82	8.24	37.28	18.94	0.51	50.80	1.66	0.069	0.3673
336.0	24.00	248.19	229.82	7.99	37.28	18.37	0.49	49.28	1.53	0.064	0.3563
360.0	24.00	247.78	229.82	7.81	37.28	17.96	0.48	48.18	1.10	0.046	0.3483

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C1-3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	275.29	237.45	15.94	37.84	37.84	1.00	100.00	0.00	0.000	0.7339
0.08	0.08	275.14	237.45	15.87	37.84	37.69	1.00	99.60	0.40	4.955	0.7310
0.17	0.09	275.06	237.45	15.84	37.84	37.61	0.99	99.39	0.21	2.349	0.7294
0.25	0.08	274.99	237.45	15.81	37.84	37.54	0.99	99.21	0.18	2.312	0.7281
0.33	0.08	274.92	237.45	15.78	37.84	37.47	0.99	99.02	0.18	2.312	0.7267
0.42	0.09	274.86	237.45	15.75	37.84	37.41	0.99	98.86	0.16	1.762	0.7256
0.50	0.08	274.79	237.45	15.73	37.84	37.34	0.99	98.68	0.18	2.312	0.7242
0.58	0.08	274.74	237.45	15.70	37.84	37.29	0.99	98.55	0.13	1.652	0.7232
0.67	0.09	274.68	237.45	15.68	37.84	37.23	0.98	98.39	0.16	1.762	0.7221
0.75	0.08	274.62	237.45	15.65	37.84	37.17	0.98	98.23	0.16	1.982	0.7209
0.83	0.08	274.57	237.45	15.63	37.84	37.12	0.98	98.10	0.13	1.652	0.7199
0.92	0.09	274.51	237.45	15.61	37.84	37.06	0.98	97.94	0.16	1.762	0.7188
1.00	0.08	274.47	237.45	15.59	37.84	37.02	0.98	97.83	0.11	1.321	0.7180
1.25	0.25	274.35	237.45	15.54	37.84	36.90	0.98	97.52	0.32	1.268	0.7157
1.50	0.25	274.24	237.45	15.49	37.84	36.79	0.97	97.23	0.29	1.163	0.7135
1.75	0.25	274.09	237.45	15.43	37.84	36.64	0.97	96.83	0.40	1.586	0.7106
2.00	0.25	273.97	237.45	15.38	37.84	36.52	0.97	96.51	0.32	1.268	0.7083
2.25	0.25	273.88	237.45	15.34	37.84	36.43	0.96	96.27	0.24	0.951	0.7066

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C1-3 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.50	0.25	273.76	237.45	15.29	37.84	36.31	0.96	95.96	0.32	1.268	0.7042
2.75	0.25	273.68	237.45	15.26	37.84	36.23	0.96	95.75	0.21	0.846	0.7027
3.00	0.25	273.54	237.45	15.20	37.84	36.09	0.95	95.38	0.37	1.480	0.7000
24.0	21.00	268.53	237.45	13.09	37.84	31.08	0.82	82.14	13.24	0.630	0.6028
48.0	24.00	266.58	237.45	12.27	37.84	29.13	0.77	76.98	5.15	0.215	0.5650
72.0	24.00	265.02	237.45	11.61	37.84	27.57	0.73	72.86	4.12	0.172	0.5347
96.0	24.00	263.60	237.45	11.01	37.84	26.15	0.69	69.11	3.75	0.156	0.5072
120.0	24.00	262.22	237.45	10.43	37.84	24.77	0.65	65.46	3.65	0.152	0.4804
144.0	24.00	260.97	237.45	9.91	37.84	23.52	0.62	62.16	3.30	0.138	0.4562
168.0	24.00	259.82	237.45	9.42	37.84	22.37	0.59	59.12	3.04	0.127	0.4339
192.0	24.00	258.91	237.45	9.04	37.84	21.46	0.57	56.71	2.40	0.100	0.4162
216.0	24.00	258.33	237.45	8.79	37.84	20.88	0.55	55.18	1.53	0.064	0.4050
240.0	24.00	257.70	237.45	8.53	37.84	20.25	0.54	53.51	1.66	0.069	0.3927
264.0	24.00	256.95	237.45	8.21	37.84	19.50	0.52	51.53	1.98	0.083	0.3782
288.0	24.00	256.43	237.45	7.99	37.84	18.98	0.50	50.16	1.37	0.057	0.3681
312.0	24.00	255.86	237.45	7.75	37.84	18.41	0.49	48.65	1.51	0.063	0.3571
336.0	24.00	255.33	237.45	7.53	37.84	17.88	0.47	47.25	1.40	0.058	0.3468
360.0	24.00	254.96	237.45	7.37	37.84	17.51	0.46	46.27	0.98	0.041	0.3396

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C2-1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	268.73	233.62	15.03	35.11	35.11	1.00	100.00	0.00	0.000	0.6810
0.08	0.08	268.62	233.62	14.98	35.11	35.00	1.00	99.69	0.31	3.916	0.6788
0.17	0.09	268.53	233.62	14.94	35.11	34.91	0.99	99.43	0.26	2.848	0.6771
0.25	0.08	268.48	233.62	14.92	35.11	34.86	0.99	99.29	0.14	1.780	0.6761
0.33	0.08	268.41	233.62	14.89	35.11	34.79	0.99	99.09	0.20	2.492	0.6747
0.42	0.09	268.33	233.62	14.86	35.11	34.71	0.99	98.86	0.23	2.532	0.6732
0.50	0.08	268.27	233.62	14.83	35.11	34.65	0.99	98.69	0.17	2.136	0.6720
0.58	0.08	268.22	233.62	14.81	35.11	34.60	0.99	98.55	0.14	1.780	0.6711
0.67	0.09	268.13	233.62	14.77	35.11	34.51	0.98	98.29	0.26	2.848	0.6693
0.75	0.08	268.05	233.62	14.74	35.11	34.43	0.98	98.06	0.23	2.848	0.6678
0.83	0.08	267.99	233.62	14.71	35.11	34.37	0.98	97.89	0.17	2.136	0.6666
0.92	0.09	267.93	233.62	14.69	35.11	34.31	0.98	97.72	0.17	1.899	0.6654
1.00	0.08	267.87	233.62	14.66	35.11	34.25	0.98	97.55	0.17	2.136	0.6643
1.25	0.25	267.79	233.62	14.63	35.11	34.17	0.97	97.32	0.23	0.911	0.6627
1.50	0.25	267.69	233.62	14.58	35.11	34.07	0.97	97.04	0.28	1.139	0.6608

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C2-1 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
1.75	0.25	267.61	233.62	14.55	35.11	33.99	0.97	96.81	0.23	0.911	0.6592
2.00	0.25	267.54	233.62	14.52	35.11	33.92	0.97	96.61	0.20	0.797	0.6579
2.25	0.25	267.45	233.62	14.48	35.11	33.83	0.96	96.35	0.26	1.025	0.6561
2.50	0.25	267.36	233.62	14.44	35.11	33.74	0.96	96.10	0.26	1.025	0.6544
2.75	0.25	267.22	233.62	14.38	35.11	33.60	0.96	95.70	0.40	1.595	0.6517
3.00	0.25	267.10	233.62	14.33	35.11	33.48	0.95	95.36	0.34	1.367	0.6493
24.0	21.00	264.69	233.62	13.30	35.11	31.07	0.88	88.49	6.86	0.327	0.6026
48.0	24.00	259.15	233.62	10.93	35.11	25.53	0.73	72.71	15.78	0.657	0.4952
72.0	24.00	256.10	233.62	9.62	35.11	22.48	0.64	64.03	8.69	0.362	0.4360
96.0	24.00	254.10	233.62	8.77	35.11	20.48	0.58	58.33	5.70	0.237	0.3972
120.0	24.00	252.12	233.62	7.92	35.11	18.50	0.53	52.69	5.64	0.235	0.3588
144.0	24.00	250.13	233.62	7.07	35.11	16.51	0.47	47.02	5.67	0.236	0.3202
168.0	24.00	248.49	233.62	6.37	35.11	14.87	0.42	42.35	4.67	0.195	0.2884
192.0	24.00	246.99	233.62	5.72	35.11	13.37	0.38	38.08	4.27	0.178	0.2593
216.0	24.00	245.84	233.62	5.23	35.11	12.22	0.35	34.80	3.28	0.136	0.2370
240.0	24.00	245.32	233.62	5.01	35.11	11.70	0.33	33.32	1.48	0.062	0.2269

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C2-2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	266.62	231.97	14.94	34.65	34.65	1.00	100.00	0.00	0.000	0.6720
0.08	0.08	266.52	231.97	14.89	34.65	34.55	1.00	99.71	0.29	3.608	0.6701
0.17	0.09	266.43	231.97	14.86	34.65	34.46	0.99	99.45	0.26	2.886	0.6683
0.25	0.08	266.38	231.97	14.83	34.65	34.41	0.99	99.31	0.14	1.804	0.6674
0.33	0.08	266.31	231.97	14.80	34.65	34.34	0.99	99.11	0.20	2.525	0.6660
0.42	0.09	266.24	231.97	14.77	34.65	34.27	0.99	98.90	0.20	2.245	0.6647
0.50	0.08	266.18	231.97	14.75	34.65	34.21	0.99	98.73	0.17	2.165	0.6635
0.58	0.08	266.12	231.97	14.72	34.65	34.15	0.99	98.56	0.17	2.165	0.6623
0.67	0.09	266.02	231.97	14.68	34.65	34.05	0.98	98.27	0.29	3.207	0.6604
0.75	0.08	265.96	231.97	14.65	34.65	33.99	0.98	98.10	0.17	2.165	0.6592
0.83	0.08	265.90	231.97	14.63	34.65	33.93	0.98	97.92	0.17	2.165	0.6581
0.92	0.09	265.83	231.97	14.60	34.65	33.86	0.98	97.72	0.20	2.245	0.6567
1.00	0.08	265.78	231.97	14.58	34.65	33.81	0.98	97.58	0.14	1.804	0.6557
1.25	0.25	265.67	231.97	14.53	34.65	33.70	0.97	97.26	0.32	1.270	0.6536
1.50	0.25	265.59	231.97	14.49	34.65	33.62	0.97	97.03	0.23	0.924	0.6521

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C2-2 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
1.75	0.25	265.50	231.97	14.45	34.65	33.53	0.97	96.77	0.26	1.039	0.6503
2.00	0.25	265.42	231.97	14.42	34.65	33.45	0.97	96.54	0.23	0.924	0.6488
2.25	0.25	265.35	231.97	14.39	34.65	33.38	0.96	96.33	0.20	0.808	0.6474
2.50	0.25	265.24	231.97	14.34	34.65	33.27	0.96	96.02	0.32	1.270	0.6453
2.75	0.25	265.08	231.97	14.27	34.65	33.11	0.96	95.56	0.46	1.847	0.6422
3.00	0.25	264.96	231.97	14.22	34.65	32.99	0.95	95.21	0.35	1.385	0.6398
24.0	21.00	262.49	231.97	13.16	34.65	30.52	0.88	88.08	7.13	0.339	0.5919
48.0	24.00	256.18	231.97	10.44	34.65	24.21	0.70	69.87	18.21	0.759	0.4696
72.0	24.00	253.00	231.97	9.07	34.65	21.03	0.61	60.69	9.18	0.382	0.4079
96.0	24.00	251.06	231.97	8.23	34.65	19.09	0.55	55.09	5.60	0.233	0.3702
120.0	24.00	249.17	231.97	7.41	34.65	17.20	0.50	49.64	5.45	0.227	0.3336
144.0	24.00	247.26	231.97	6.59	34.65	15.29	0.44	44.13	5.51	0.230	0.2965
168.0	24.00	245.69	231.97	5.91	34.65	13.72	0.40	39.60	4.53	0.189	0.2661
192.0	24.00	244.31	231.97	5.32	34.65	12.34	0.36	35.61	3.98	0.166	0.2393
216.0	24.00	243.26	231.97	4.87	34.65	11.29	0.33	32.58	3.03	0.126	0.2190
240.0	24.00	242.80	231.97	4.67	34.65	10.83	0.31	31.26	1.33	0.055	0.2100

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C2-3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	268.6	234.09	14.74	34.51	34.51	1.00	100.00	0.00	0.000	0.6693
0.08	0.08	268.48	234.09	14.69	34.51	34.39	1.00	99.65	0.35	4.347	0.6670
0.17	0.09	268.39	234.09	14.65	34.51	34.30	0.99	99.39	0.26	2.898	0.6652
0.25	0.08	268.32	234.09	14.62	34.51	34.23	0.99	99.19	0.20	2.535	0.6639
0.33	0.08	268.26	234.09	14.60	34.51	34.17	0.99	99.01	0.17	2.173	0.6627
0.42	0.09	268.27	234.09	14.60	34.51	34.18	0.99	99.04	0.03	0.322	0.6629
0.50	0.08	268.11	234.09	14.53	34.51	34.02	0.99	98.58	0.46	5.795	0.6598
0.58	0.08	268.05	234.09	14.51	34.51	33.96	0.98	98.41	0.17	2.173	0.6587
0.67	0.09	267.95	234.09	14.46	34.51	33.86	0.98	98.12	0.29	3.220	0.6567
0.75	0.08	267.88	234.09	14.43	34.51	33.79	0.98	97.91	0.20	2.535	0.6554
0.83	0.08	267.83	234.09	14.41	34.51	33.74	0.98	97.77	0.14	1.811	0.6544
0.92	0.09	267.75	234.09	14.38	34.51	33.66	0.98	97.54	0.23	2.576	0.6528
1.00	0.08	267.70	234.09	14.36	34.51	33.61	0.97	97.39	0.14	1.811	0.6519
1.25	0.25	267.58	234.09	14.31	34.51	33.49	0.97	97.04	0.35	1.391	0.6495
1.50	0.25	267.50	234.09	14.27	34.51	33.41	0.97	96.81	0.23	0.927	0.6480

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample C2-3 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
1.75	0.25	267.41	234.09	14.23	34.51	33.32	0.97	96.55	0.26	1.043	0.6462
2.00	0.25	267.33	234.09	14.20	34.51	33.24	0.96	96.32	0.23	0.927	0.6447
2.25	0.25	267.25	234.09	14.17	34.51	33.16	0.96	96.09	0.23	0.927	0.6431
2.50	0.25	267.11	234.09	14.11	34.51	33.02	0.96	95.68	0.41	1.623	0.6404
2.75	0.25	266.94	234.09	14.03	34.51	32.85	0.95	95.19	0.49	1.970	0.6371
3.00	0.25	266.81	234.09	13.98	34.51	32.72	0.95	94.81	0.38	1.507	0.6346
24.0	21.00	263.86	234.09	12.72	34.51	29.77	0.86	86.26	8.55	0.407	0.5774
48.0	24.00	256.88	234.09	9.74	34.51	22.79	0.66	66.04	20.23	0.843	0.4420
72.0	24.00	253.84	234.09	8.44	34.51	19.75	0.57	57.23	8.81	0.367	0.3830
96.0	24.00	251.99	234.09	7.65	34.51	17.90	0.52	51.87	5.36	0.223	0.3472
120.0	24.00	250.19	234.09	6.88	34.51	16.10	0.47	46.65	5.22	0.217	0.3123
144.0	24.00	248.39	234.09	6.11	34.51	14.30	0.41	41.44	5.22	0.217	0.2773
168.0	24.00	246.90	234.09	5.47	34.51	12.81	0.37	37.12	4.32	0.180	0.2484
192.0	24.00	245.68	234.09	4.95	34.51	11.59	0.34	33.58	3.54	0.147	0.2248
216.0	24.00	244.81	234.09	4.58	34.51	10.72	0.31	31.06	2.52	0.105	0.2079
240.0	24.00	244.38	234.09	4.40	34.51	10.29	0.30	29.82	1.25	0.052	0.1996

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S1-1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	251.44	211.30	19.00	40.14	40.14	1.00	100.00	0.00	0.000	0.7785
0.08	0.08	251.32	211.30	18.94	40.14	40.02	1.00	99.70	0.30	3.737	0.7762
0.17	0.09	251.25	211.30	18.91	40.14	39.95	1.00	99.53	0.17	1.938	0.7748
0.25	0.08	251.18	211.30	18.87	40.14	39.88	0.99	99.35	0.17	2.180	0.7735
0.33	0.08	251.12	211.30	18.85	40.14	39.82	0.99	99.20	0.15	1.868	0.7723
0.42	0.09	251.04	211.30	18.81	40.14	39.74	0.99	99.00	0.20	2.214	0.7708
0.50	0.08	250.93	211.30	18.76	40.14	39.63	0.99	98.73	0.27	3.426	0.7686
0.58	0.08	250.85	211.30	18.72	40.14	39.55	0.99	98.53	0.20	2.491	0.7671
0.67	0.09	250.77	211.30	18.68	40.14	39.47	0.98	98.33	0.20	2.214	0.7655
0.75	0.08	250.68	211.30	18.64	40.14	39.38	0.98	98.11	0.22	2.803	0.7638
0.83	0.08	250.61	211.30	18.60	40.14	39.31	0.98	97.93	0.17	2.180	0.7624
0.92	0.09	250.54	211.30	18.57	40.14	39.24	0.98	97.76	0.17	1.938	0.7611
1.00	0.08	250.48	211.30	18.54	40.14	39.18	0.98	97.61	0.15	1.868	0.7599
1.25	0.25	250.38	211.30	18.50	40.14	39.08	0.97	97.36	0.25	0.997	0.7580
1.50	0.25	250.28	211.30	18.45	40.14	38.98	0.97	97.11	0.25	0.997	0.7560
1.75	0.25	250.15	211.30	18.39	40.14	38.85	0.97	96.79	0.32	1.295	0.7535

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S1-1 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.00	0.25	250.04	211.30	18.33	40.14	38.74	0.97	96.51	0.27	1.096	0.7514
2.25	0.25	249.92	211.30	18.28	40.14	38.62	0.96	96.21	0.30	1.196	0.7490
2.50	0.25	249.78	211.30	18.21	40.14	38.48	0.96	95.86	0.35	1.395	0.7463
2.75	0.25	249.67	211.30	18.16	40.14	38.37	0.96	95.59	0.27	1.096	0.7442
3.00	0.25	249.57	211.30	18.11	40.14	38.27	0.95	95.34	0.25	0.997	0.7422
24.0	21.00	247.01	211.30	16.90	40.14	35.71	0.89	88.96	6.38	0.304	0.6926
48.0	24.00	241.10	211.30	14.10	40.14	29.80	0.74	74.24	14.72	0.613	0.5780
72.0	24.00	238.90	211.30	13.06	40.14	27.60	0.69	68.76	5.48	0.228	0.5353
96.0	24.00	237.18	211.30	12.25	40.14	25.88	0.64	64.47	4.29	0.179	0.5019
120.0	24.00	236.02	211.30	11.70	40.14	24.72	0.62	61.58	2.89	0.120	0.4794
144.0	24.00	234.64	211.30	11.05	40.14	23.34	0.58	58.15	3.44	0.143	0.4527
168.0	24.00	233.38	211.30	10.45	40.14	22.08	0.55	55.01	3.14	0.131	0.4282
192.0	24.00	232.24	211.30	9.91	40.14	20.94	0.52	52.17	2.84	0.118	0.4061
216.0	24.00	231.22	211.30	9.43	40.14	19.92	0.50	49.63	2.54	0.106	0.3863
240.0	24.00	230.81	211.30	9.23	40.14	19.51	0.49	48.60	1.02	0.043	0.3784

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S1-2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	252.24	211.59	19.21	40.65	40.65	1.00	100.00	0.00	0.000	0.7884
0.08	0.08	252.13	211.59	19.16	40.65	40.54	1.00	99.73	0.27	3.383	0.7863
0.17	0.09	252.07	211.59	19.13	40.65	40.48	1.00	99.58	0.15	1.640	0.7851
0.25	0.08	252.00	211.59	19.10	40.65	40.41	0.99	99.41	0.17	2.153	0.7837
0.33	0.08	251.93	211.59	19.07	40.65	40.34	0.99	99.24	0.17	2.153	0.7824
0.42	0.09	251.86	211.59	19.03	40.65	40.27	0.99	99.07	0.17	1.913	0.7810
0.50	0.08	251.76	211.59	18.98	40.65	40.17	0.99	98.82	0.25	3.075	0.7791
0.58	0.08	251.69	211.59	18.95	40.65	40.10	0.99	98.65	0.17	2.153	0.7777
0.67	0.09	251.63	211.59	18.92	40.65	40.04	0.98	98.50	0.15	1.640	0.7766
0.75	0.08	251.54	211.59	18.88	40.65	39.95	0.98	98.28	0.22	2.768	0.7748
0.83	0.08	251.48	211.59	18.85	40.65	39.89	0.98	98.13	0.15	1.845	0.7737
0.92	0.09	251.42	211.59	18.82	40.65	39.83	0.98	97.98	0.15	1.640	0.7725
1.00	0.08	251.36	211.59	18.80	40.65	39.77	0.98	97.84	0.15	1.845	0.7713
1.25	0.25	251.28	211.59	18.76	40.65	39.69	0.98	97.64	0.20	0.787	0.7698
1.50	0.25	251.18	211.59	18.71	40.65	39.59	0.97	97.39	0.25	0.984	0.7678
1.75	0.25	251.07	211.59	18.66	40.65	39.48	0.97	97.12	0.27	1.082	0.7657

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S1-2 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.00	0.25	250.98	211.59	18.62	40.65	39.39	0.97	96.90	0.22	0.886	0.7640
2.25	0.25	250.83	211.59	18.55	40.65	39.24	0.97	96.53	0.37	1.476	0.7611
2.50	0.25	250.72	211.59	18.49	40.65	39.13	0.96	96.26	0.27	1.082	0.7589
2.75	0.25	250.63	211.59	18.45	40.65	39.04	0.96	96.04	0.22	0.886	0.7572
3.00	0.25	250.53	211.59	18.40	40.65	38.94	0.96	95.79	0.25	0.984	0.7552
24.0	21.00	248.08	211.59	17.25	40.65	36.49	0.90	89.77	6.03	0.287	0.7077
48.0	24.00	241.97	211.59	14.36	40.65	30.38	0.75	74.74	15.03	0.626	0.5892
72.0	24.00	239.67	211.59	13.27	40.65	28.08	0.69	69.08	5.66	0.236	0.5446
96.0	24.00	237.78	211.59	12.38	40.65	26.19	0.64	64.43	4.65	0.194	0.5080
120.0	24.00	236.48	211.59	11.76	40.65	24.89	0.61	61.23	3.20	0.133	0.4827
144.0	24.00	235.11	211.59	11.12	40.65	23.52	0.58	57.86	3.37	0.140	0.4562
168.0	24.00	233.86	211.59	10.53	40.65	22.27	0.55	54.78	3.08	0.128	0.4319
192.0	24.00	232.73	211.59	9.99	40.65	21.14	0.52	52.00	2.78	0.116	0.4100
216.0	24.00	231.78	211.59	9.54	40.65	20.19	0.50	49.67	2.34	0.097	0.3916
240.0	24.00	231.33	211.59	9.33	40.65	19.74	0.49	48.56	1.11	0.046	0.3829

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S1-3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	253.57	213.33	18.86	40.24	40.24	1.00	100.00	0.00	0.000	0.7804
0.08	0.08	253.46	213.33	18.81	40.24	40.13	1.00	99.73	0.27	3.417	0.7783
0.17	0.09	253.39	213.33	18.78	40.24	40.06	1.00	99.55	0.17	1.933	0.7770
0.25	0.08	253.31	213.33	18.74	40.24	39.98	0.99	99.35	0.20	2.485	0.7754
0.33	0.08	253.22	213.33	18.70	40.24	39.89	0.99	99.13	0.22	2.796	0.7737
0.42	0.09	253.14	213.33	18.66	40.24	39.81	0.99	98.93	0.20	2.209	0.7721
0.50	0.08	253.02	213.33	18.60	40.24	39.69	0.99	98.63	0.30	3.728	0.7698
0.58	0.08	252.96	213.33	18.58	40.24	39.63	0.98	98.48	0.15	1.864	0.7686
0.67	0.09	252.89	213.33	18.54	40.24	39.56	0.98	98.31	0.17	1.933	0.7673
0.75	0.08	252.80	213.33	18.50	40.24	39.47	0.98	98.09	0.22	2.796	0.7655
0.83	0.08	252.75	213.33	18.48	40.24	39.42	0.98	97.96	0.12	1.553	0.7645
0.92	0.09	252.69	213.33	18.45	40.24	39.36	0.98	97.81	0.15	1.657	0.7634
1.00	0.08	252.63	213.33	18.42	40.24	39.30	0.98	97.66	0.15	1.864	0.7622
1.25	0.25	252.54	213.33	18.38	40.24	39.21	0.97	97.44	0.22	0.895	0.7605
1.50	0.25	252.43	213.33	18.33	40.24	39.10	0.97	97.17	0.27	1.093	0.7583
1.75	0.25	252.33	213.33	18.28	40.24	39.00	0.97	96.92	0.25	0.994	0.7564

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S1-3 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.00	0.25	252.24	213.33	18.24	40.24	38.91	0.97	96.69	0.22	0.895	0.7547
2.25	0.25	252.05	213.33	18.15	40.24	38.72	0.96	96.22	0.47	1.889	0.7510
2.50	0.25	251.94	213.33	18.10	40.24	38.61	0.96	95.95	0.27	1.093	0.7488
2.75	0.25	251.85	213.33	18.06	40.24	38.52	0.96	95.73	0.22	0.895	0.7471
3.00	0.25	251.78	213.33	18.02	40.24	38.45	0.96	95.55	0.17	0.696	0.7457
24.0	21.00	248.70	213.33	16.58	40.24	35.37	0.88	87.90	7.65	0.364	0.6860
48.0	24.00	242.81	213.33	13.82	40.24	29.48	0.73	73.26	14.64	0.610	0.5718
72.0	24.00	240.58	213.33	12.77	40.24	27.25	0.68	67.72	5.54	0.231	0.5285
96.0	24.00	238.77	213.33	11.93	40.24	25.44	0.63	63.22	4.50	0.187	0.4934
120.0	24.00	237.42	213.33	11.29	40.24	24.09	0.60	59.87	3.35	0.140	0.4672
144.0	24.00	236.13	213.33	10.69	40.24	22.80	0.57	56.66	3.21	0.134	0.4422
168.0	24.00	234.89	213.33	10.11	40.24	21.56	0.54	53.58	3.08	0.128	0.4182
192.0	24.00	233.80	213.33	9.60	40.24	20.47	0.51	50.87	2.71	0.113	0.3970
216.0	24.00	232.98	213.33	9.21	40.24	19.65	0.49	48.83	2.04	0.085	0.3811
240.0	24.00	232.57	213.33	9.02	40.24	19.24	0.48	47.81	1.02	0.042	0.3732

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S2-1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	256.16	214.43	19.46	41.73	41.73	1.00	100.00	0.00	0.000	0.8093
0.08	0.08	256.07	214.43	19.42	41.73	41.64	1.00	99.78	0.22	2.696	0.8076
0.17	0.09	256.01	214.43	19.39	41.73	41.58	1.00	99.64	0.14	1.598	0.8064
0.25	0.08	255.95	214.43	19.36	41.73	41.52	0.99	99.50	0.14	1.797	0.8053
0.33	0.08	255.91	214.43	19.34	41.73	41.48	0.99	99.40	0.10	1.198	0.8045
0.42	0.09	255.86	214.43	19.32	41.73	41.43	0.99	99.28	0.12	1.331	0.8035
0.50	0.08	255.82	214.43	19.30	41.73	41.39	0.99	99.19	0.10	1.198	0.8028
0.58	0.08	255.78	214.43	19.28	41.73	41.35	0.99	99.09	0.10	1.198	0.8020
0.67	0.09	255.73	214.43	19.26	41.73	41.30	0.99	98.97	0.12	1.331	0.8010
0.75	0.08	255.69	214.43	19.24	41.73	41.26	0.99	98.87	0.10	1.198	0.8002
0.83	0.08	255.64	214.43	19.22	41.73	41.21	0.99	98.75	0.12	1.498	0.7993
0.92	0.09	255.60	214.43	19.20	41.73	41.17	0.99	98.66	0.10	1.065	0.7985
1.00	0.08	255.55	214.43	19.18	41.73	41.12	0.99	98.54	0.12	1.498	0.7975
1.25	0.25	255.45	214.43	19.13	41.73	41.02	0.98	98.30	0.24	0.959	0.7956
1.50	0.25	255.37	214.43	19.09	41.73	40.94	0.98	98.11	0.19	0.767	0.7940
1.75	0.25	255.28	214.43	19.05	41.73	40.85	0.98	97.89	0.22	0.863	0.7923
2.00	0.25	255.19	214.43	19.01	41.73	40.76	0.98	97.68	0.22	0.863	0.7905

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S2-1 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	255.12	214.43	18.98	41.73	40.69	0.98	97.51	0.17	0.671	0.7892
2.50	0.25	255.04	214.43	18.94	41.73	40.61	0.97	97.32	0.19	0.767	0.7876
2.75	0.25	254.95	214.43	18.90	41.73	40.52	0.97	97.10	0.22	0.863	0.7859
3.00	0.25	254.87	214.43	18.86	41.73	40.44	0.97	96.91	0.19	0.767	0.7843
24.0	21.00	251.16	214.43	17.13	41.73	36.73	0.88	88.02	8.89	0.423	0.7124
48.0	24.00	246.07	214.43	14.76	41.73	31.64	0.76	75.82	12.20	0.508	0.6137
72.0	24.00	240.94	214.43	12.36	41.73	26.51	0.64	63.53	12.29	0.512	0.5142
96.0	24.00	237.05	214.43	10.55	41.73	22.62	0.54	54.21	9.32	0.388	0.4387
120.0	24.00	234.19	214.43	9.22	41.73	19.76	0.47	47.35	6.85	0.286	0.3832
144.0	24.00	232.90	214.43	8.61	41.73	18.47	0.44	44.26	3.09	0.129	0.3582
168.0	24.00	230.65	214.43	7.56	41.73	16.22	0.39	38.87	5.39	0.225	0.3146
192.0	24.00	229.14	214.43	6.86	41.73	14.71	0.35	35.25	3.62	0.151	0.2853
216.0	24.00	228.05	214.43	6.35	41.73	13.62	0.33	32.64	2.61	0.109	0.2642
240.0	24.00	226.96	214.43	5.84	41.73	12.53	0.30	30.03	2.61	0.109	0.2430
264.0	24.00	226.32	214.43	5.54	41.73	11.89	0.28	28.49	1.53	0.064	0.2306
288.0	24.00	225.73	214.43	5.27	41.73	11.30	0.27	27.08	1.41	0.059	0.2192

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S2-2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	252.1	211.18	19.38	40.92	40.92	1.00	100.00	0.00	0.000	0.7936
0.08	0.08	252.01	211.18	19.33	40.92	40.83	1.00	99.78	0.22	2.749	0.7919
0.17	0.09	251.95	211.18	19.31	40.92	40.77	1.00	99.63	0.15	1.629	0.7907
0.25	0.08	251.90	211.18	19.28	40.92	40.72	1.00	99.51	0.12	1.527	0.7898
0.33	0.08	251.85	211.18	19.26	40.92	40.67	0.99	99.39	0.12	1.527	0.7888
0.42	0.09	251.79	211.18	19.23	40.92	40.61	0.99	99.24	0.15	1.629	0.7876
0.50	0.08	251.75	211.18	19.21	40.92	40.57	0.99	99.14	0.10	1.222	0.7869
0.58	0.08	251.71	211.18	19.19	40.92	40.53	0.99	99.05	0.10	1.222	0.7861
0.67	0.09	251.66	211.18	19.17	40.92	40.48	0.99	98.92	0.12	1.358	0.7851
0.75	0.08	251.61	211.18	19.14	40.92	40.43	0.99	98.80	0.12	1.527	0.7841
0.83	0.08	251.56	211.18	19.12	40.92	40.38	0.99	98.68	0.12	1.527	0.7832
0.92	0.09	251.53	211.18	19.11	40.92	40.35	0.99	98.61	0.07	0.815	0.7826
1.00	0.08	251.48	211.18	19.08	40.92	40.30	0.98	98.48	0.12	1.527	0.7816
1.25	0.25	251.36	211.18	19.03	40.92	40.18	0.98	98.19	0.29	1.173	0.7793
1.50	0.25	251.26	211.18	18.98	40.92	40.08	0.98	97.95	0.24	0.978	0.7773
1.75	0.25	251.15	211.18	18.93	40.92	39.97	0.98	97.68	0.27	1.075	0.7752
2.00	0.25	251.05	211.18	18.88	40.92	39.87	0.97	97.43	0.24	0.978	0.7733

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S2-2 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	250.97	211.18	18.84	40.92	39.79	0.97	97.24	0.20	0.782	0.7717
2.50	0.25	250.88	211.18	18.80	40.92	39.70	0.97	97.02	0.22	0.880	0.7700
2.75	0.25	250.79	211.18	18.76	40.92	39.61	0.97	96.80	0.22	0.880	0.7682
3.00	0.25	250.70	211.18	18.71	40.92	39.52	0.97	96.58	0.22	0.880	0.7665
24.0	21.00	247.43	211.18	17.17	40.92	36.25	0.89	88.59	7.99	0.381	0.7031
48.0	24.00	242.65	211.18	14.90	40.92	31.47	0.77	76.91	11.68	0.487	0.6104
72.0	24.00	237.90	211.18	12.65	40.92	26.72	0.65	65.30	11.61	0.484	0.5182
96.0	24.00	234.12	211.18	10.86	40.92	22.94	0.56	56.06	9.24	0.385	0.4449
120.0	24.00	231.31	211.18	9.53	40.92	20.13	0.49	49.19	6.87	0.286	0.3904
144.0	24.00	229.96	211.18	8.89	40.92	18.78	0.46	45.89	3.30	0.137	0.3642
168.0	24.00	227.68	211.18	7.81	40.92	16.50	0.40	40.32	5.57	0.232	0.3200
192.0	24.00	226.10	211.18	7.07	40.92	14.92	0.36	36.46	3.86	0.161	0.2894
216.0	24.00	224.92	211.18	6.51	40.92	13.74	0.34	33.58	2.88	0.120	0.2665
240.0	24.00	223.78	211.18	5.97	40.92	12.60	0.31	30.79	2.79	0.116	0.2444
264.0	24.00	223.10	211.18	5.64	40.92	11.92	0.29	29.13	1.66	0.069	0.2312
288.0	24.00	222.50	211.18	5.36	40.92	11.32	0.28	27.66	1.47	0.061	0.2196

APPENDIX F: DRYING RATE – NORMAL 29/88

Drying measurements for sample S2-3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	255.74	214.63	19.15	41.11	41.11	1.00	100.00	0.00	0.000	0.7973
0.08	0.08	255.63	214.63	19.10	41.11	41.00	1.00	99.73	0.27	0.000	0.7952
0.17	0.09	255.56	214.63	19.07	41.11	40.93	1.00	99.56	0.17	0.000	0.7938
0.25	0.08	255.49	214.63	19.04	41.11	40.86	0.99	99.39	0.17	2.128	0.7925
0.33	0.08	255.41	214.63	19.00	41.11	40.78	0.99	99.20	0.19	2.432	0.7909
0.42	0.09	255.35	214.63	18.97	41.11	40.72	0.99	99.05	0.15	1.622	0.7898
0.50	0.08	255.28	214.63	18.94	41.11	40.65	0.99	98.88	0.17	2.128	0.7884
0.58	0.08	255.22	214.63	18.91	41.11	40.59	0.99	98.74	0.15	1.824	0.7872
0.67	0.09	255.16	214.63	18.88	41.11	40.53	0.99	98.59	0.15	1.622	0.7861
0.75	0.08	255.09	214.63	18.85	41.11	40.46	0.98	98.42	0.17	2.128	0.7847
0.83	0.08	255.02	214.63	18.82	41.11	40.39	0.98	98.25	0.17	2.128	0.7834
0.92	0.09	254.96	214.63	18.79	41.11	40.33	0.98	98.10	0.15	1.622	0.7822
1.00	0.08	254.89	214.63	18.76	41.11	40.26	0.98	97.93	0.17	2.128	0.7808
1.25	0.25	254.74	214.63	18.69	41.11	40.11	0.98	97.57	0.36	1.459	0.7779
1.50	0.25	254.57	214.63	18.61	41.11	39.94	0.97	97.15	0.41	1.654	0.7746
1.75	0.25	254.41	214.63	18.53	41.11	39.78	0.97	96.76	0.39	1.557	0.7715
2.00	0.25	254.26	214.63	18.46	41.11	39.63	0.96	96.40	0.36	1.459	0.7686

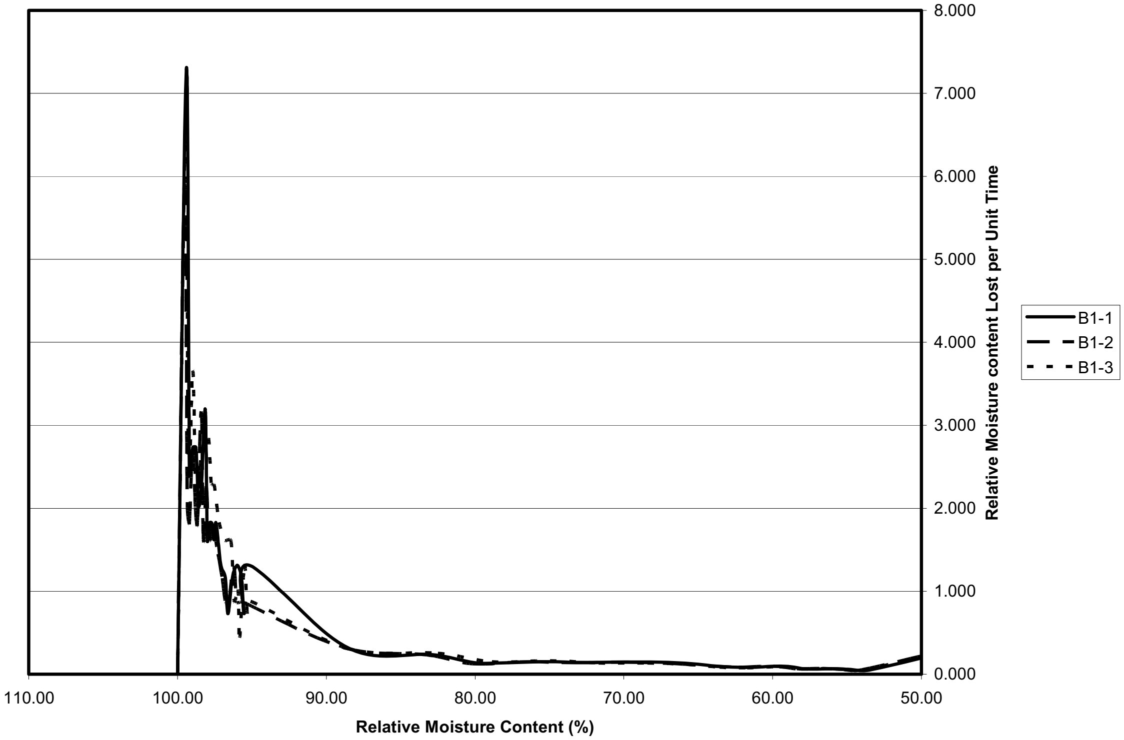
APPENDIX F: DRYING RATE – NORMAL 29/88

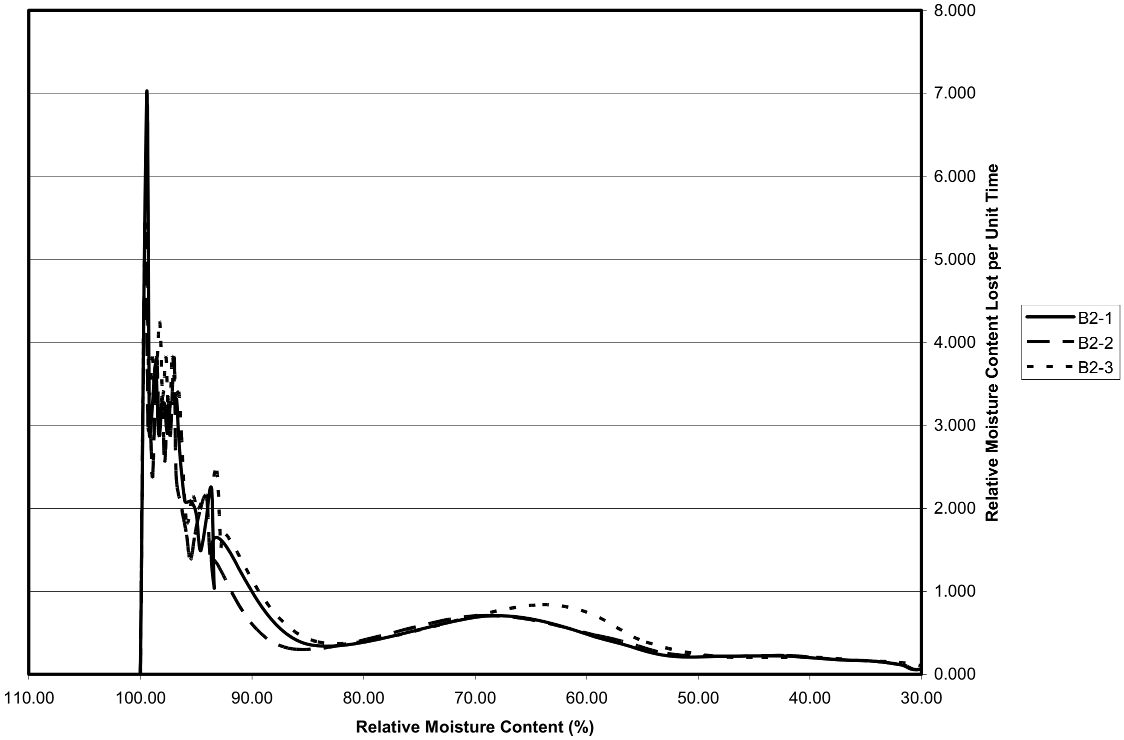
Drying measurements for sample S2-3 (cont.)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight (g)	Residual water content, Q_i (g)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y	Relative moisture content, Y (%)	Difference in relative moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	254.11	214.63	18.39	41.11	39.48	0.96	96.04	0.36	1.459	0.7657
2.50	0.25	253.97	214.63	18.33	41.11	39.34	0.96	95.69	0.34	1.362	0.7630
2.75	0.25	253.82	214.63	18.26	41.11	39.19	0.95	95.33	0.36	1.459	0.7601
3.00	0.25	253.67	214.63	18.19	41.11	39.04	0.95	94.96	0.36	1.459	0.7572
24.0	21.00	248.60	214.63	15.83	41.11	33.97	0.83	82.63	12.33	0.587	0.6588
48.0	24.00	242.71	214.63	13.08	41.11	28.08	0.68	68.30	14.33	0.597	0.5446
72.0	24.00	238.54	214.63	11.14	41.11	23.91	0.58	58.16	10.14	0.423	0.4637
96.0	24.00	235.51	214.63	9.73	41.11	20.88	0.51	50.79	7.37	0.307	0.4050
120.0	24.00	233.26	214.63	8.68	41.11	18.63	0.45	45.32	5.47	0.228	0.3613
144.0	24.00	232.11	214.63	8.14	41.11	17.48	0.43	42.52	2.80	0.117	0.3390
168.0	24.00	230.09	214.63	7.20	41.11	15.46	0.38	37.61	4.91	0.205	0.2998
192.0	24.00	228.67	214.63	6.54	41.11	14.04	0.34	34.15	3.45	0.144	0.2723
216.0	24.00	227.57	214.63	6.03	41.11	12.94	0.31	31.48	2.68	0.111	0.2510
240.0	24.00	226.52	214.63	5.54	41.11	11.89	0.29	28.92	2.55	0.106	0.2306
264.0	24.00	225.89	214.63	5.25	41.11	11.26	0.27	27.39	1.53	0.064	0.2184
288.0	24.00	225.36	214.63	5.00	41.11	10.73	0.26	26.10	1.29	0.054	0.2081

APPENDIX F: DRYING RATE – NORMAL 29/88

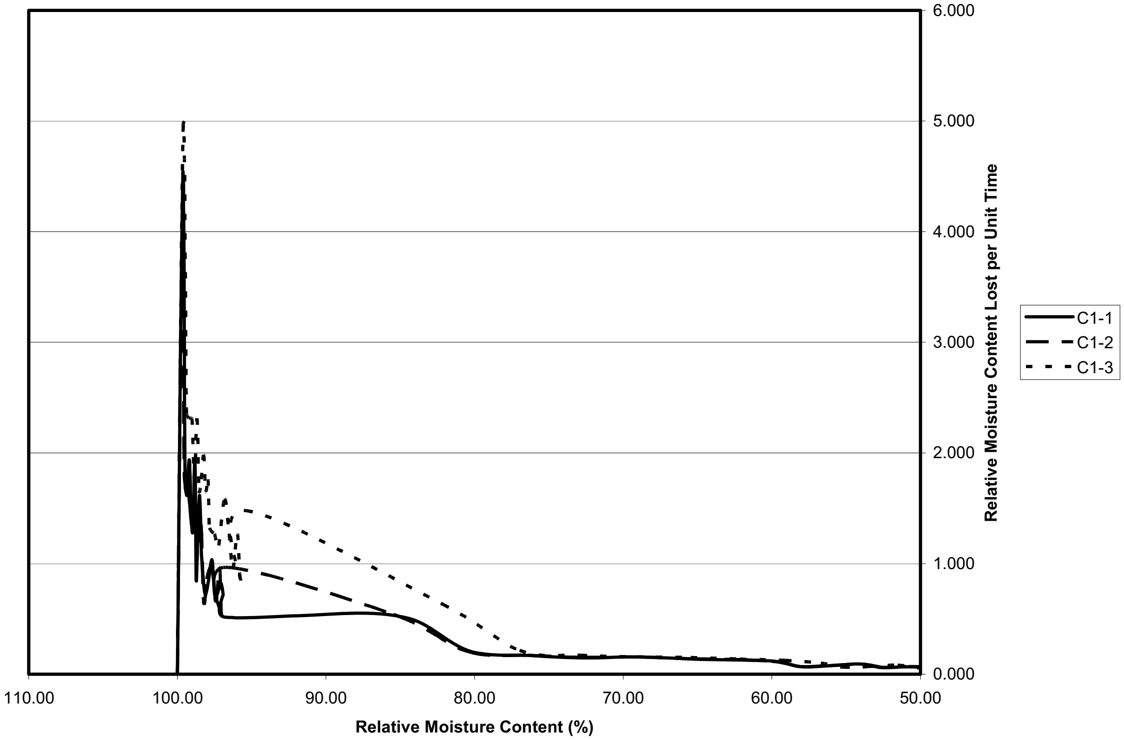
Formulations B1 and B2

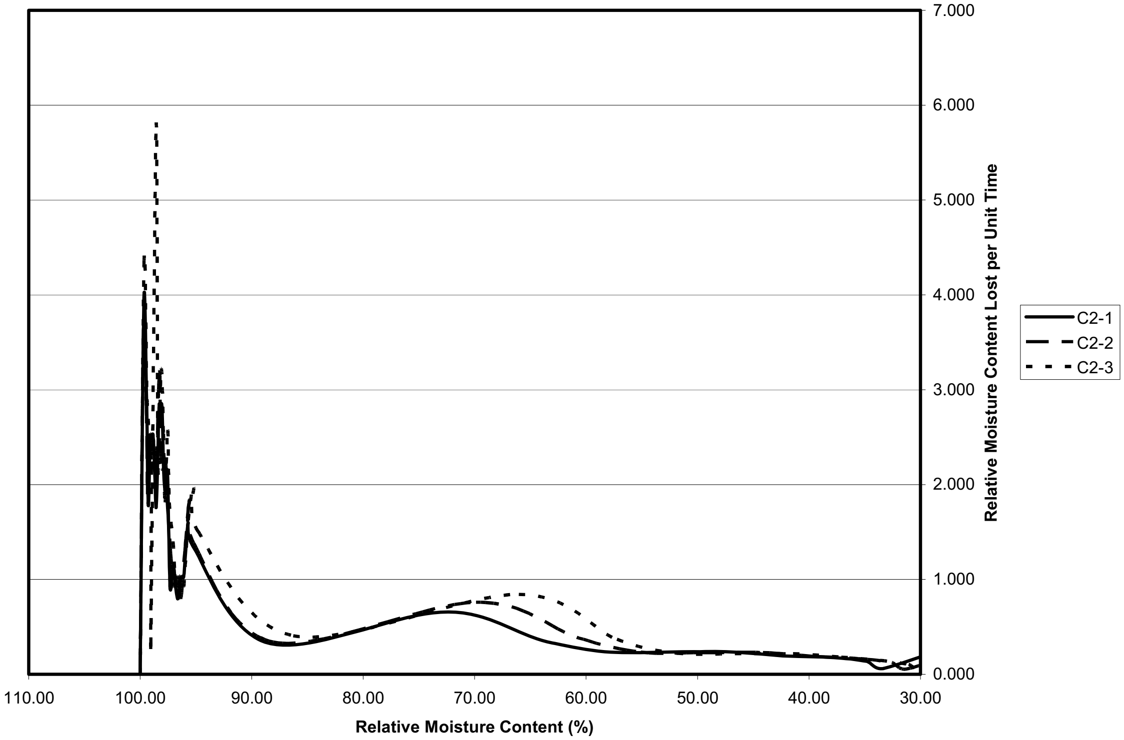




APPENDIX F: DRYING RATE – NORMAL 29/88

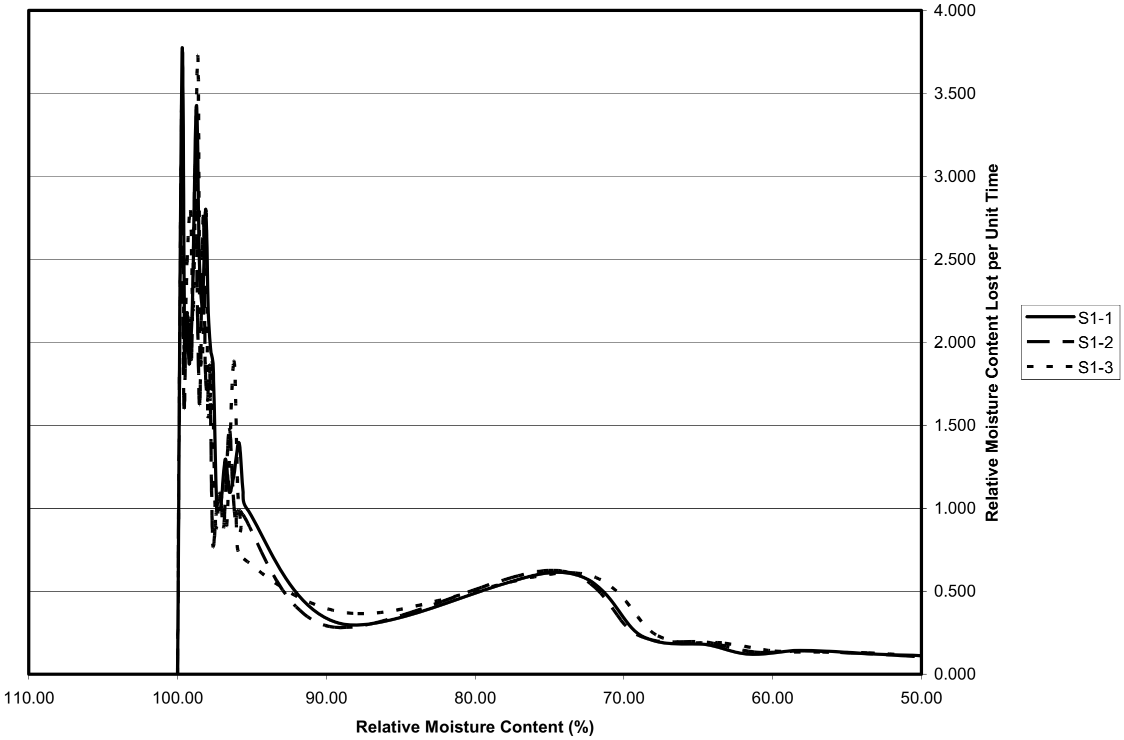
Formulations C1 and C2

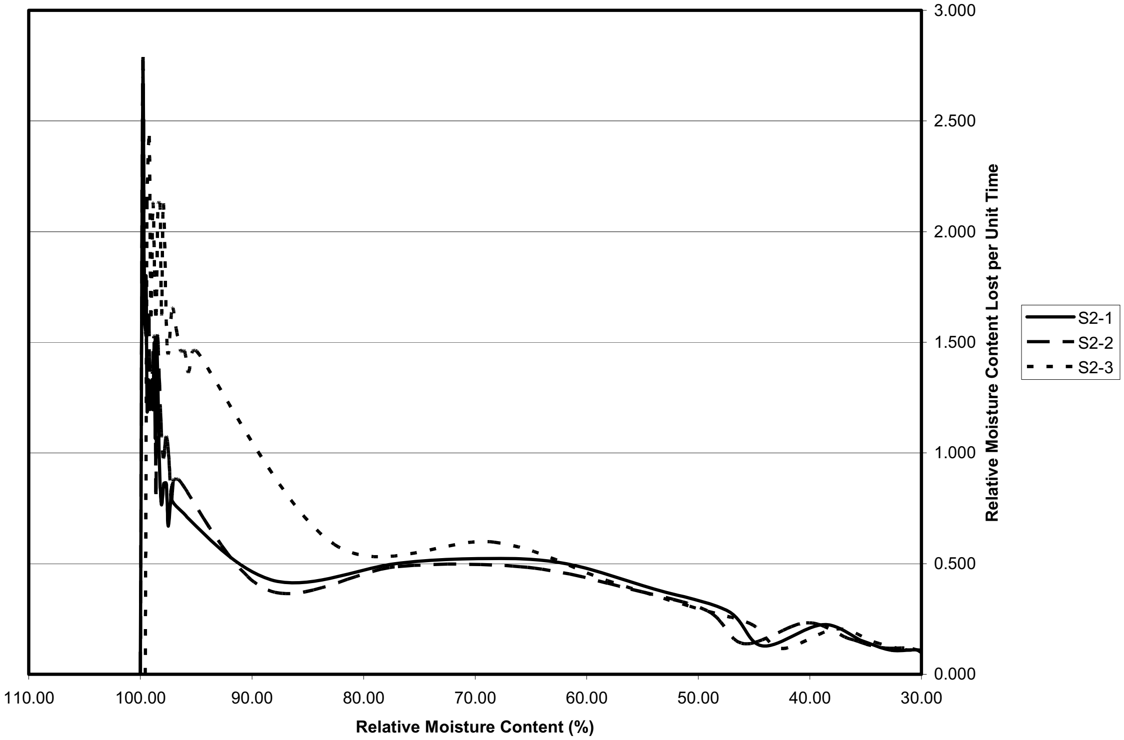




APPENDIX F: DRYING RATE – NORMAL 29/88

Formulations S1 and S2





APPENDIX G: WATER VAPOR TRANSMISSION – ASTM E96-95

Experiment Conditions
Average Temperature: 31°C
Average Relative Humidity: 49% in chamber, 100% in dish
Water Vapor Partial Pressure: 33.72mm Hg

Samples
Area: 0.013 m^2
Height: 1.3 cm
3 samples per set

DAILY WEIGHT MEASUREMENTS (g)

Sample	Days										
	0	1	2	3	4	5	6	7	8	9	10
B1-1	78.66	78.69	78.65	78.56	78.51	78.44	78.36	78.26	78.19	78.12	78.06
B1-2	73.97	73.98	73.92	73.85	73.78	73.69	73.61	73.52	73.43	73.36	73.28
B1-3	79.45	79.48	79.43	79.36	79.28	79.20	79.12	79.04	78.95	78.87	78.81
B2-1	75.60	75.53	75.35	75.18	74.99	74.82	74.63	74.44	74.28	74.12	74.01
B2-2	76.16	76.09	75.90	75.73	75.55	75.37	75.20	75.00	74.84	74.68	74.54
B2-3	76.81	76.75	76.57	76.39	76.22	76.05	75.88	75.68	75.51	75.37	74.24
C1-1	73.87	73.92	73.86	73.79	73.69	73.59	73.49	73.34	73.26	73.16	73.08
C1-2	76.34	76.38	76.32	76.24	76.15	76.04	75.92	75.80	75.68	75.58	75.48
C1-3	74.75	74.80	74.76	74.69	74.60	74.50	74.41	74.28	74.18	74.08	74.00
C2-1	73.40	73.35	73.17	72.97	72.78	72.58	72.39	72.16	71.99	71.82	71.68
C2-2	73.61	73.56	73.36	73.15	72.94	72.73	72.51	72.28	72.08	71.90	71.76
C2-3	72.75	72.71	72.52	72.33	72.13	71.94	71.74	71.51	71.32	71.13	70.99
S1-1	71.01	71.03	70.94	70.82	70.70	70.57	70.43	70.27	70.13	70.01	69.90
S1-2	71.97	72.00	71.92	71.81	71.69	71.57	71.44	71.29	71.16	71.05	70.96
S1-3	70.49	70.54	70.46	70.37	70.25	70.13	70.01	69.87	69.74	69.62	69.53
S2-1	72.57	72.55	72.37	72.19	72.01	71.82	71.62	71.42	71.21	71.04	70.90
S2-2	70.50	70.48	70.33	70.16	70.00	69.82	69.64	69.45	69.27	69.13	69.00
S2-3	71.54	71.52	71.36	71.19	71.03	70.84	70.66	70.45	70.28	70.13	69.99

APPENDIX G: WATER VAPOR TRANSMISSION – ASTM E96-95

WATER VAPOR TRANSMISSION CALCULATIONS

Sample	% weight loss	Average weight loss	Weight change (g)	WVT (g/h·m^2)	Average WVT
B1-1	0.76	0.83	0.60	0.19	0.21
B1-2	0.93		0.69	0.22	
B1-3	0.81		0.64	0.21	
B2-1	2.10	2.53	1.59	0.51	0.62
B2-2	2.13		1.62	0.52	
B2-3	3.35		2.57	0.82	
C1-1	1.07	1.07	0.79	0.25	0.26
C1-2	1.13		0.86	0.28	
C1-3	1.00		0.75	0.24	
C2-1	2.34	2.43	1.72	0.55	0.57
C2-2	2.51		1.85	0.59	
C2-3	2.42		1.76	0.56	
S1-1	1.56	1.44	1.11	0.36	0.33
S1-2	1.40		1.01	0.32	
S1-3	1.36		0.96	0.31	
S2-1	2.30	1.90	1.67	0.54	0.50
S2-2	1.22		0.86	0.46	
S2-3	2.17		1.55	0.50	

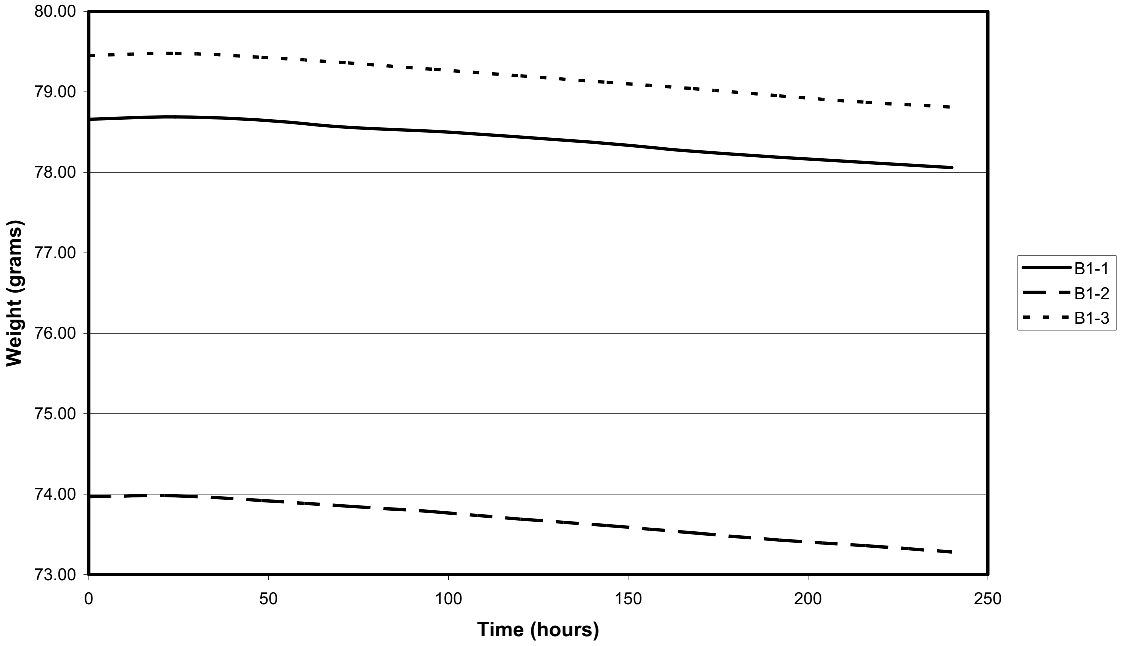
APPENDIX G: WATER VAPOR TRANSMISSION – ASTM E96-95

PERMEANCE AND PERMEABILITY CALCULATIONS

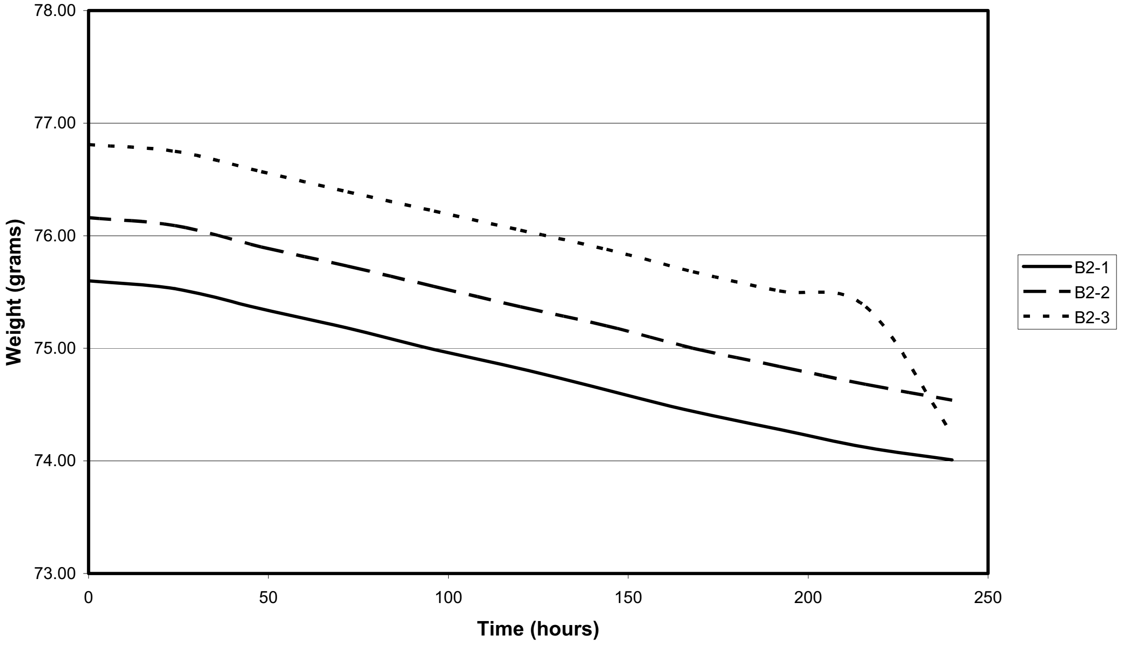
Sample	Time (hours)	S (Pa)	$S(R_1-R_2)$	Permeance ($g/Pa\cdot s\cdot m^2$)	Average Permeance	Permeability (perm·cm)	Average Permeability
B1-1	240	4.50E+03	2.25E+03	2.38E-08	2.55E-08	3.09E-08	3.31E-08
B1-2	240	4.50E+03	2.25E+03	2.73E-08		3.55E-08	
B1-3	240	4.50E+03	2.25E+03	2.54E-08		3.30E-08	
B2-1	240	4.50E+03	2.25E+03	6.30E-08	7.63E-08	8.19E-08	9.92E-08
B2-2	240	4.50E+03	2.25E+03	6.42E-08		8.34E-08	
B2-3	240	4.50E+03	2.25E+03	1.02E-07		1.32E-07	
C1-1	240	4.50E+03	2.25E+03	3.13E-08	3.17E-08	4.07E-08	4.12E-08
C1-2	240	4.50E+03	2.25E+03	3.41E-08		4.43E-08	
C1-3	240	4.50E+03	2.25E+03	2.97E-08		3.86E-08	
C2-1	240	4.50E+03	2.25E+03	6.81E-08	7.04E-08	8.86E-08	9.15E-08
C2-2	240	4.50E+03	2.25E+03	7.33E-08		9.53E-08	
C2-3	240	4.50E+03	2.25E+03	6.97E-08		9.06E-08	
S1-1	240	4.50E+03	2.25E+03	4.40E-08	4.07E-08	5.72E-08	5.29E-08
S1-2	240	4.50E+03	2.25E+03	4.00E-08		5.20E-08	
S1-3	240	4.50E+03	2.25E+03	3.80E-08		4.94E-08	
S2-1	240	4.50E+03	2.25E+03	6.62E-08	6.14E-08	8.60E-08	7.99E-08
S2-2	240	4.50E+03	2.25E+03	5.68E-08		7.38E-08	
S2-3	240	4.50E+03	2.25E+03	6.14E-08		7.98E-08	

APPENDIX G: WATER VAPOR TRANSMISSION – ASTM E96-95

WATER VAPOR TRANSMISSION GRAPHS



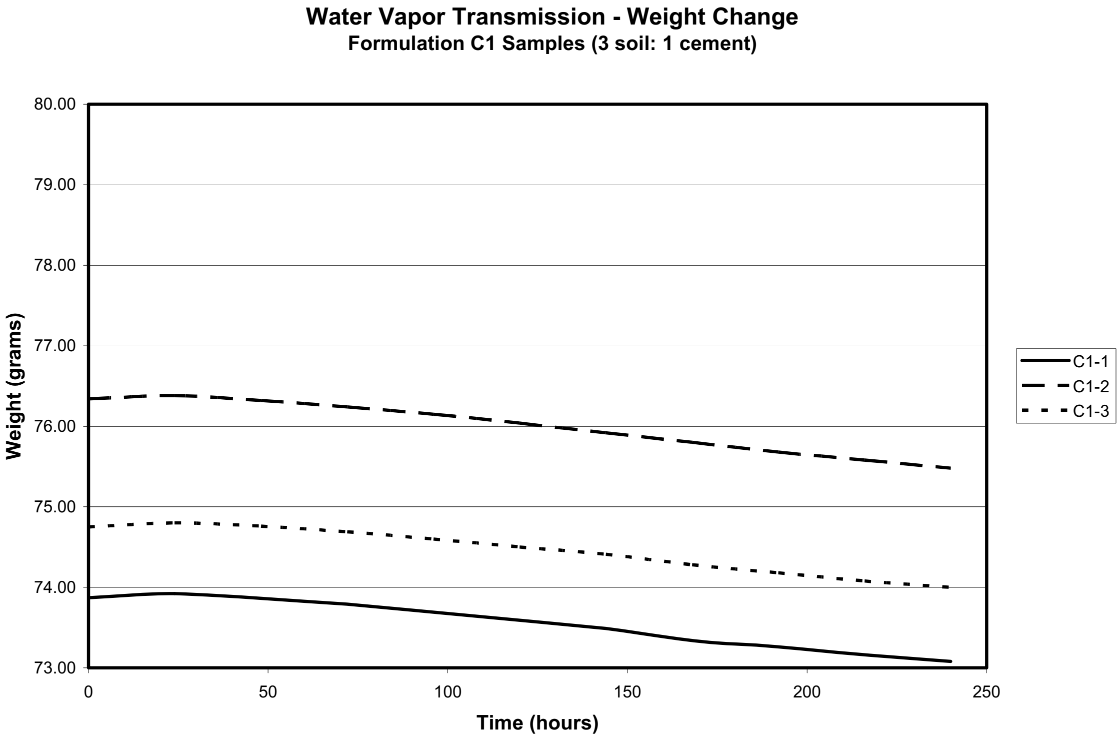
Water Vapor Transmission - Weight Change
Formulation B1 Samples (3 soil: 1 cement)

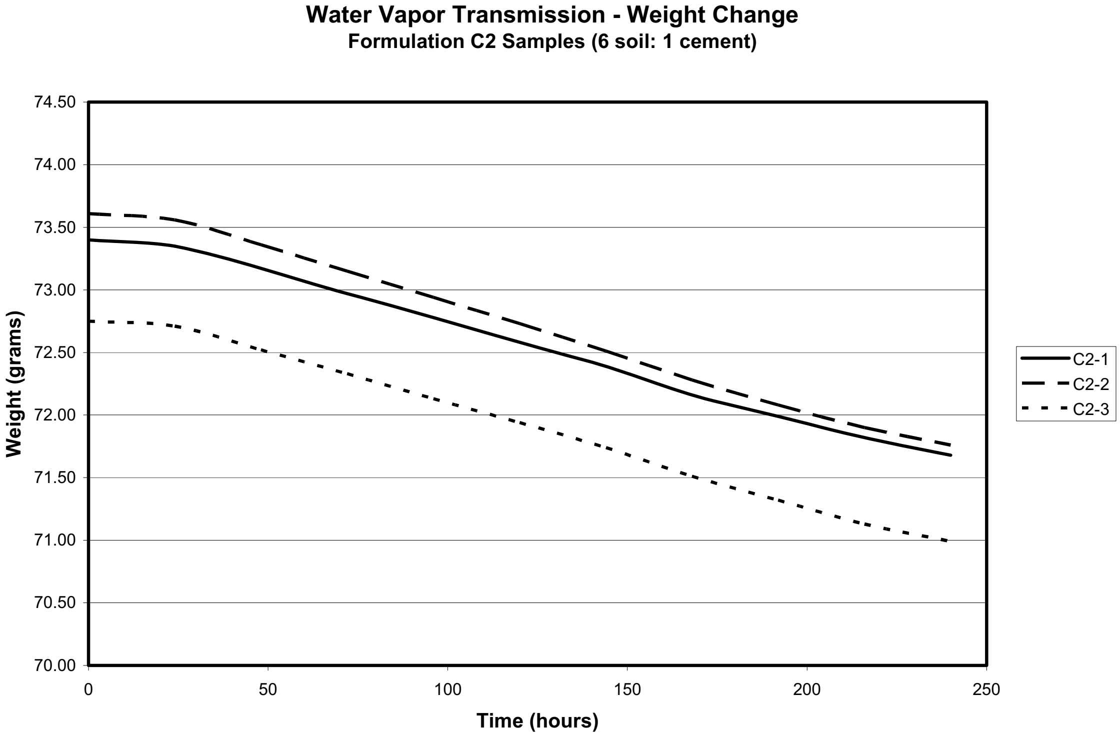


Water Vapor Transmission - Weight Change
Formulation B2 Samples (3 soil: 1 cement)

APPENDIX G: WATER VAPOR TRANSMISSION – ASTM E96-95

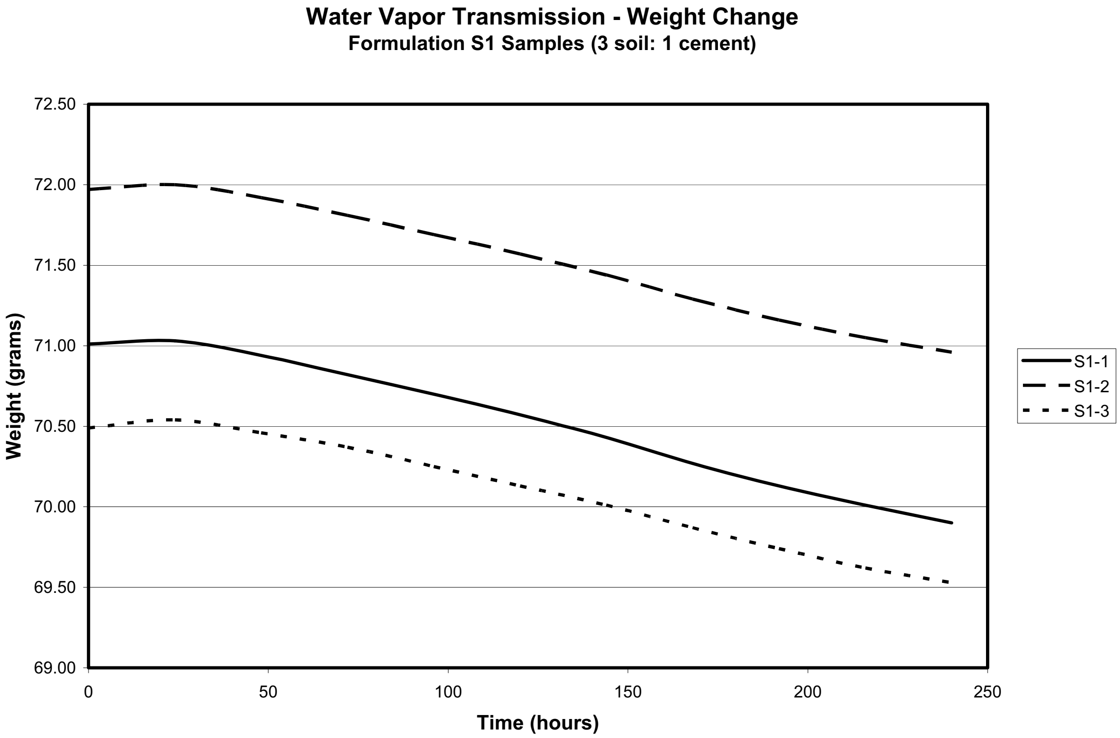
WATER VAPOR TRANSMISSION GRAPHS

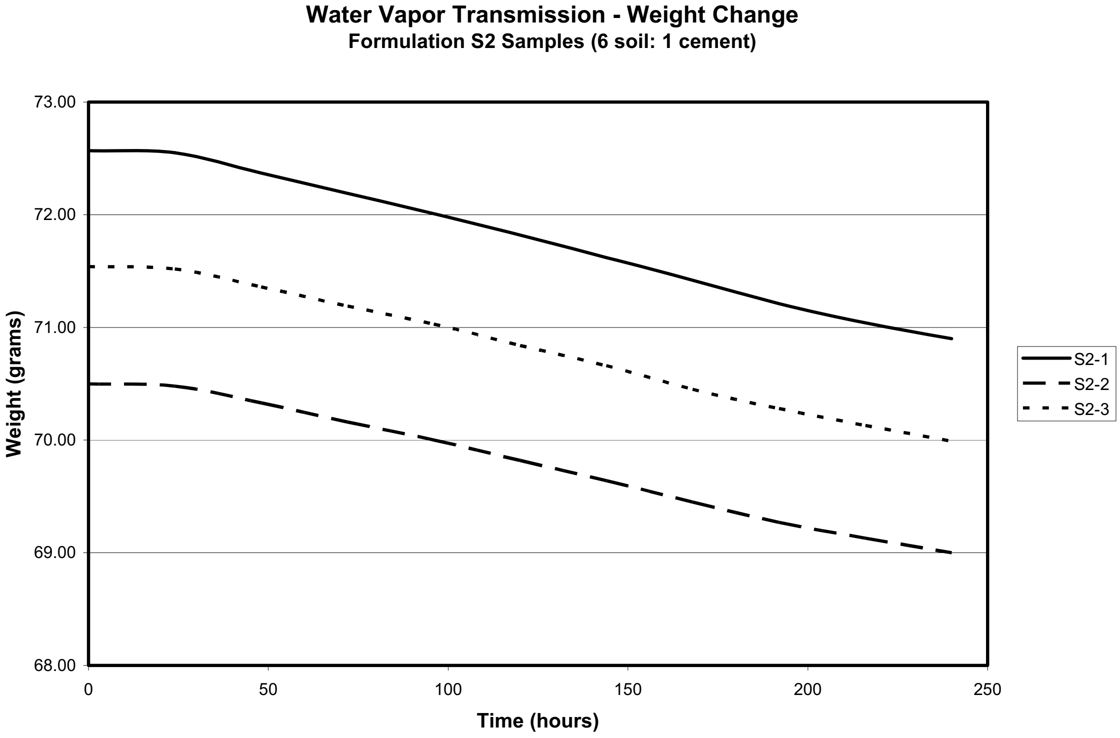




APPENDIX G: WATER VAPOR TRANSMISSION – ASTM E96-95

WATER VAPOR TRANSMISSION GRAPHS





APPENDIX H: FROST RESISTANCE – RILEM V.3

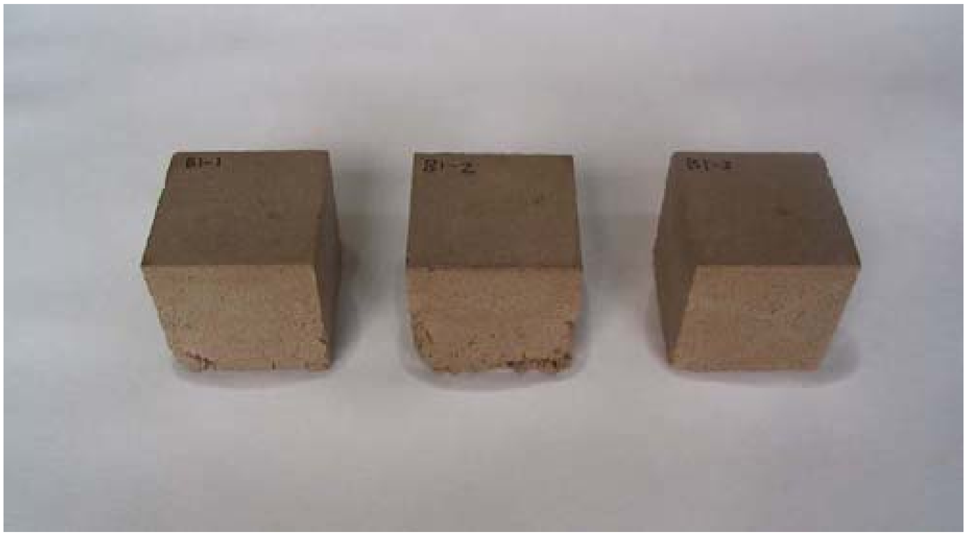


Figure I1. Formulation B1 samples photographed during fist freeze/thaw cycle.

Figure I2. Formulation B1 samples photographed after fifteenth freeze/thaw cycle showing no visible deterioration.

APPENDIX H: FROST RESISTANCE – RILEM V.3

Figure I3. Formulation B2 samples photographed during fist freeze/thaw cycle.

Figure I4. Formulation B2 samples photographed after fifteenth freeze/thaw cycle showing no visible deterioration.

APPENDIX H: FROST RESISTANCE – RILEM V.3

Figure I5. Formulation C1 samples photographed during fist freeze/thaw cycle.

Figure I6. Formulation C1 samples photographed after fifteenth freeze/thaw cycle showing no visible deterioration.

APPENDIX H: FROST RESISTANCE – RILEM V.3

Figure I7. Formulation C2 samples photographed during fist freeze/thaw cycle.

Figure I8. Formulation C2 samples photographed after fifteenth freeze/thaw cycle showing no visible deterioration.

APPENDIX H: FROST RESISTANCE – RILEM V.3

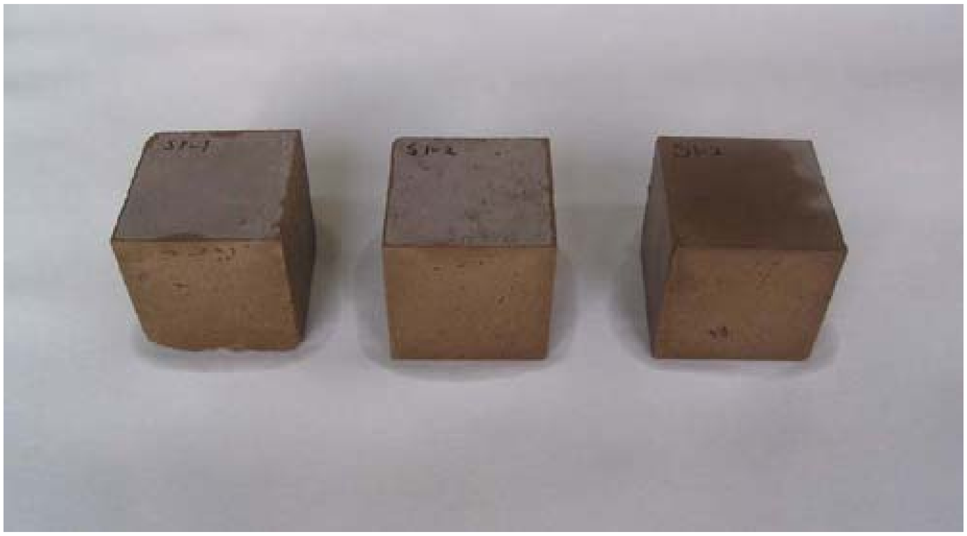


Figure I9. Formulation S1 samples photographed during fist freeze/thaw cycle.

Figure I10. Formulation S1 samples photographed after fifteenth freeze/thaw cycle showing no visible deterioration.

APPENDIX H: FROST RESISTANCE – RILEM V.3

Figure I11. Formulation S2 samples photographed during fist freeze/thaw cycle.

Figure I12. Formulation S2 samples photographed after fifteenth freeze/thaw cycle showing visible surface delamination and some dimensional loss on corners.

APPENDIX I: WATER DROP EROSION TEST – CRATerre

Sample	Depth of Penetration (mm)	Average Depth of Penetration (mm)
B1-1	0.00	0.00
B1-2	0.00	
B1-3	0.00	
B2-1	0.00	0.00
B2-2	0.00	
B2-3	0.00	
BU-1	22.73	20.61
BU-2	20.42	
BU-3	18.69	
C1-1	0.00	0.00
C1-2	0.00	
C1-3	0.00	
C2-1	0.00	0.00
C2-2	0.00	
C2-3	0.00	
CU-1	14.08	15.04
CU-2	13.42	
CU-3	17.62	
S1-1	0.00	0.00
S1-2	0.00	
S1-3	0.00	
S2-1	0.00	0.00
S2-2	0.00	
S2-3	0.00	
SU-1	7.68	8.75
SU-2	10.11	
SU-3	8.47	

APPENDIX I: WATER DROP EROSION TEST – CRATerre

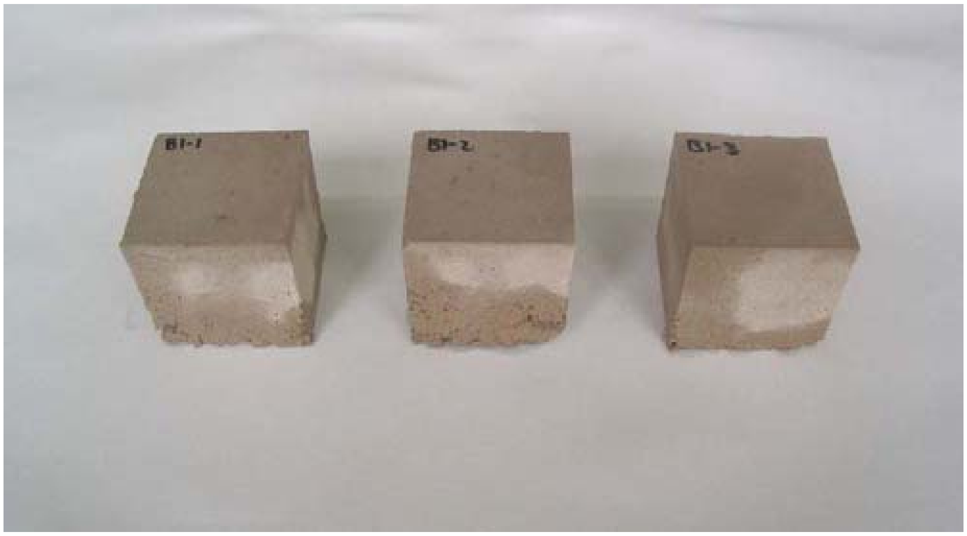


Figure I1. Formulation B1 samples following 1 hour of exposure to falling water droplets displayed no evidence of penetration on exposed surfaces.

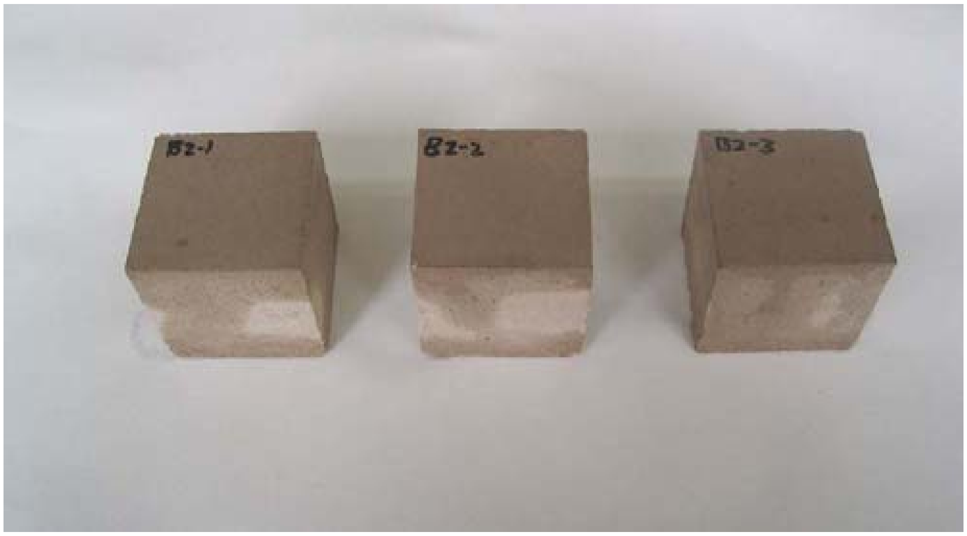


Figure I2. Formulation B2 samples following 1 hour of exposure to falling water droplets displayed no evidence of penetration on exposed surfaces.

APPENDIX I: WATER DROP EROSION TEST – CRATerre

Figure I3. Unamended samples of Bandelier soil (Garcia Landscape Materials blend) displayed an average penetration depth of 20.61 mm following 1 hour of exposure to falling water droplets.

Figure I4. Formulation C1 samples following 1 hour of exposure to falling water droplets displayed no evidence of penetration on exposed surfaces.

APPENDIX I: WATER DROP EROSION TEST – CRATerre

Figure I5. Formulation C2 samples following 1 hour of exposure to falling water droplets displayed no evidence of penetration on exposed surfaces.

Figure I6. Unamended samples of Chaco soil (BLM quarry) displayed an average penetration depth of 15.04 mm following 1 hour of exposure to falling water droplets.

APPENDIX I: WATER DROP EROSION TEST – CRATerre

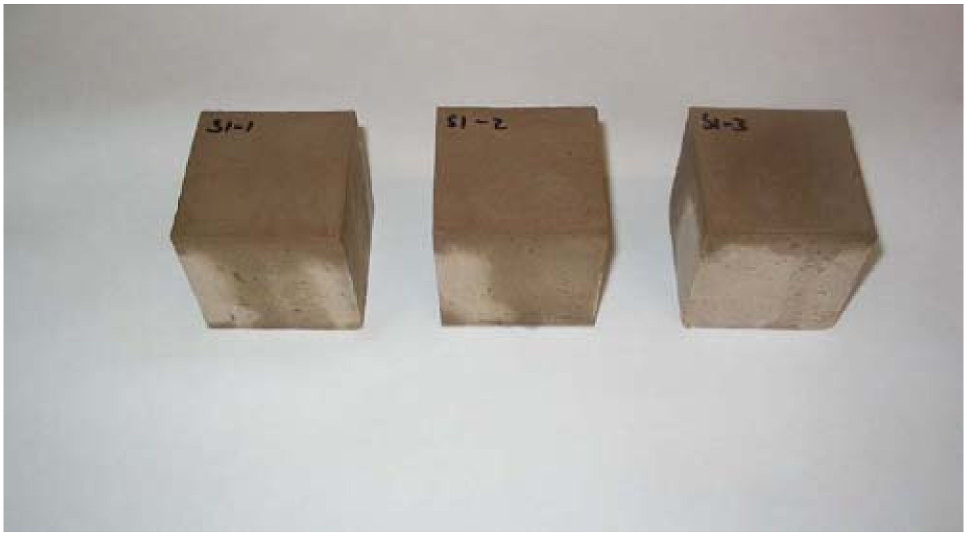


Figure I7. Formulation S1 samples following 1 hour of exposure to falling water droplets displayed no evidence of penetration on exposed surfaces.

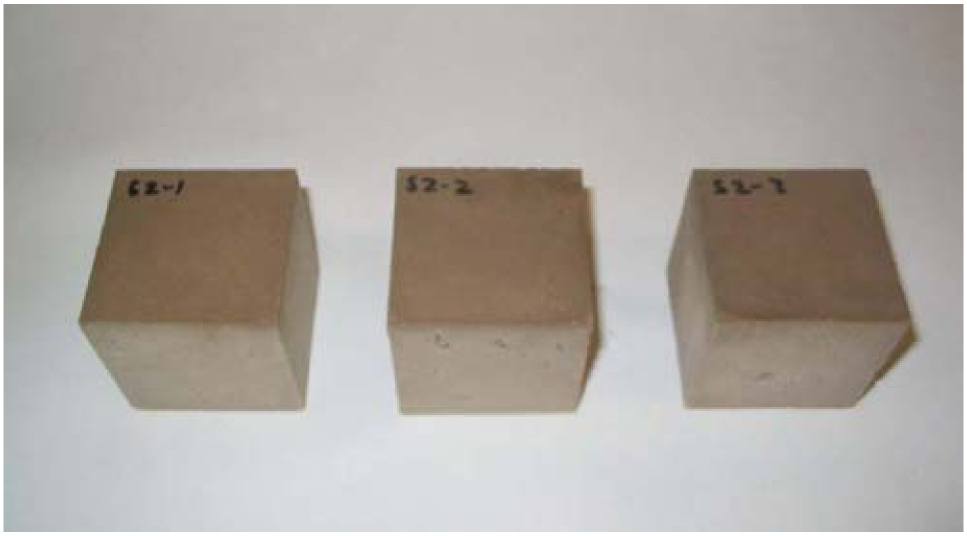


Figure I8. Formulation S1 samples following 1 hour of exposure to falling water droplets displayed no evidence of penetration on exposed surfaces.

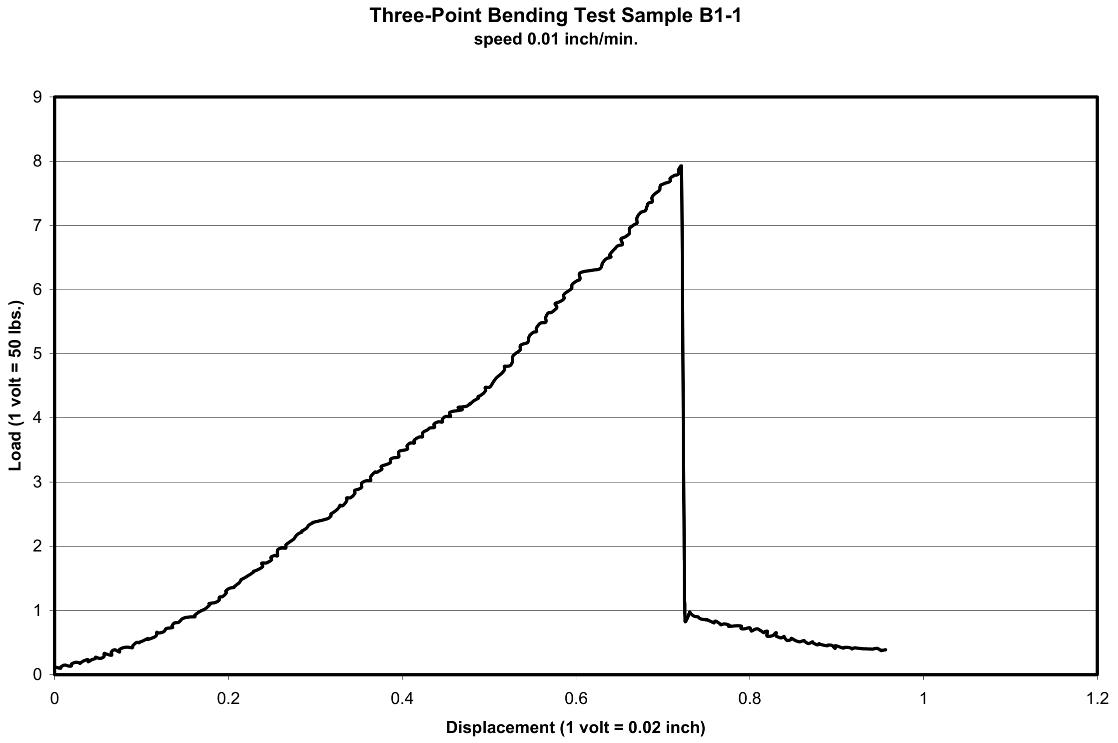
APPENDIX I: WATER DROP EROSION TEST – CRATerre

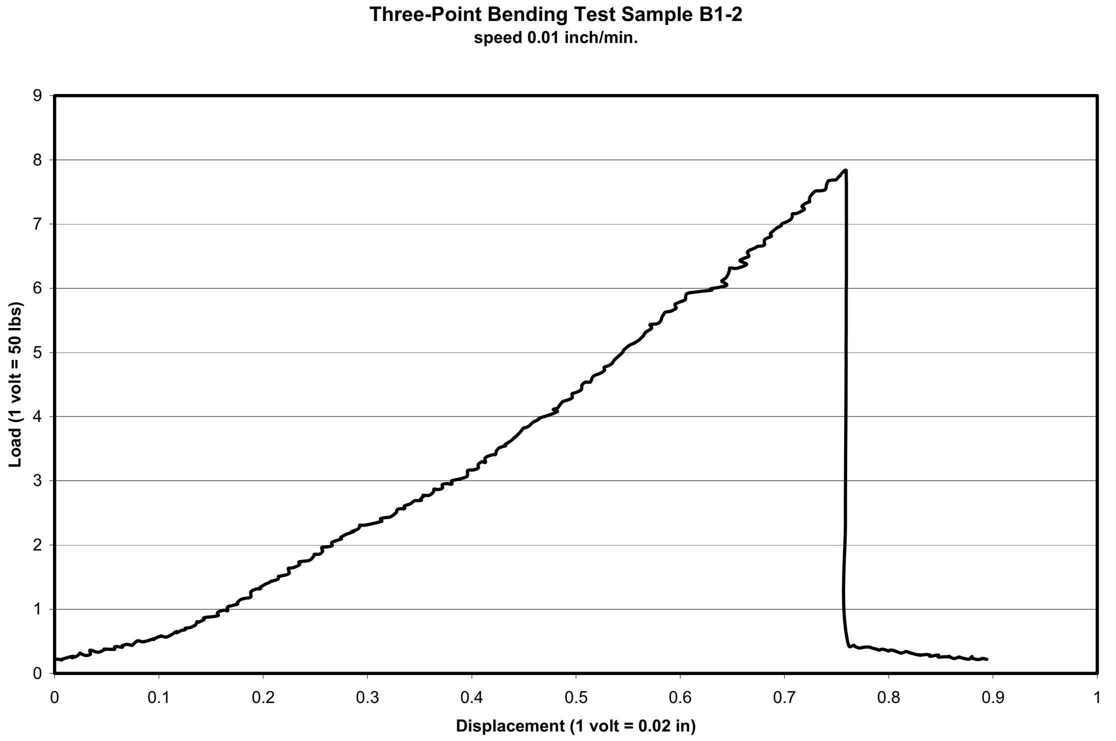
Figure I9. Unamended samples of Salinas soil (local quarry) displayed an average penetration depth of 8.75 mm following 1 hour of exposure to falling water droplets.

APPENDIX J: MODULUS OF RUPTURE – ASTM D1635

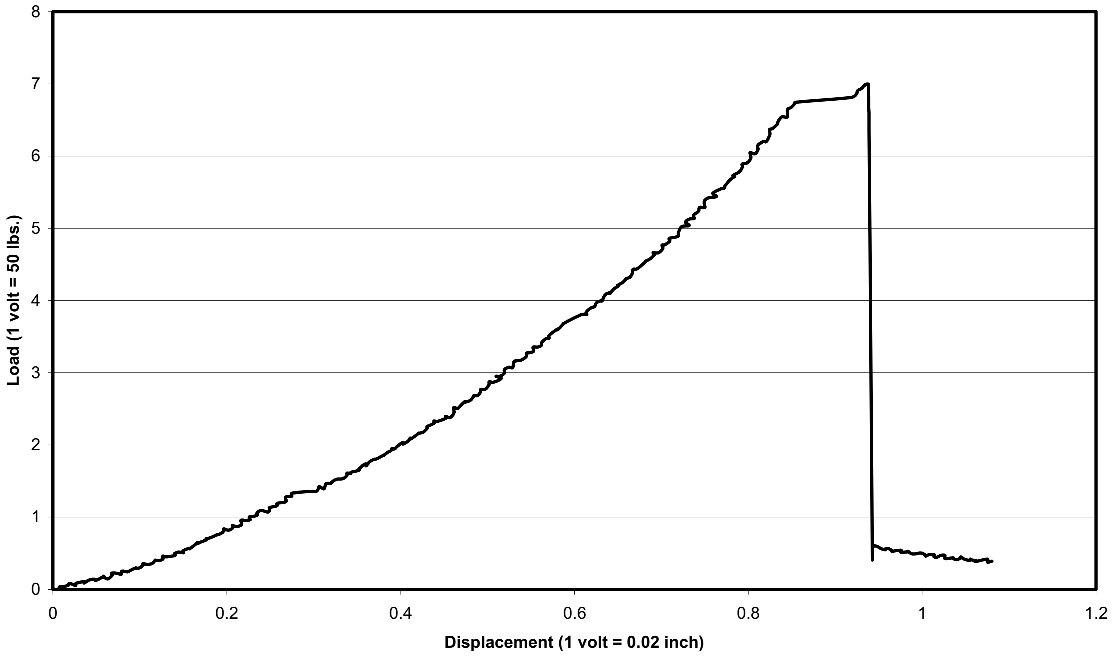
Sample	Maximum Applied Load, P (lb)	Span Length, L (in)	Specimen Width, *b* (in)	Specimen Depth, *d* (in)	Modulus of Rupture, R (psi)	Average Modulus of Rupture (psi)
B1-1	396	3.0	1.008	0.978	1222.41	1130.11
B1-2	391	3.0	1.032	0.985	1135.18	
B1-3	349	3.0	1.015	0.992	1032.74	
B2-1	81	3.0	1.038	0.989	230.58	309.88
B2-2	66	3.0	1.026	0.985	193.86	
B2-3	170	3.0	1.019	0.986	505.21	
C1-1	293	3.0	1.013	0.979	893.73	838.72
C1-2	244	3.0	1.024	0.976	732.84	
C1-3	307	3.0	1.033	0.985	889.58	
C2-1	120	3.0	1.014	0.970	372.12	394.17
C2-2	142	3.0	1.009	0.963	451.21	
C2-3	118	3.0	1.012	0.981	359.17	
S1-1	161	3.0	1.030	0.986	468.29	637.52
S1-2	210	3.0	1.022	0.995	609.25	
S1-3	269	3.0	0.991	0.992	835.03	
S2-1	161	3.0	1.001	0.984	497.84	485.48
S2-2		3.0	1.019	0.975		
S2-3	145	3.0	1.003	0.956	473.12	

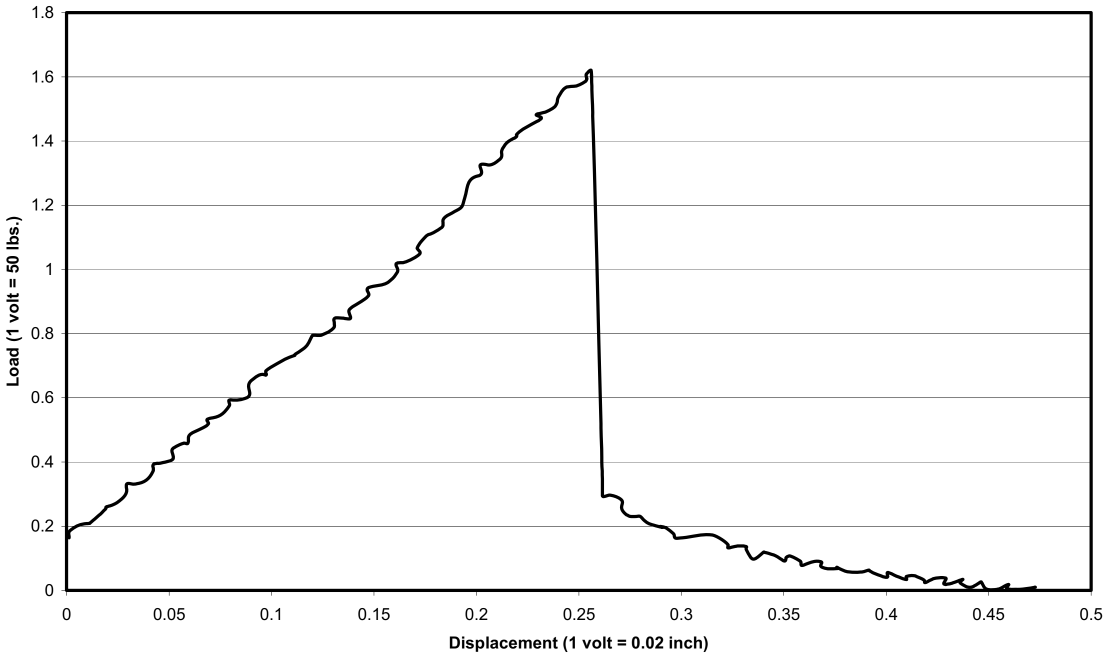
APPENDIX J: MODULUS OF RUPTURE – ASTM D1635



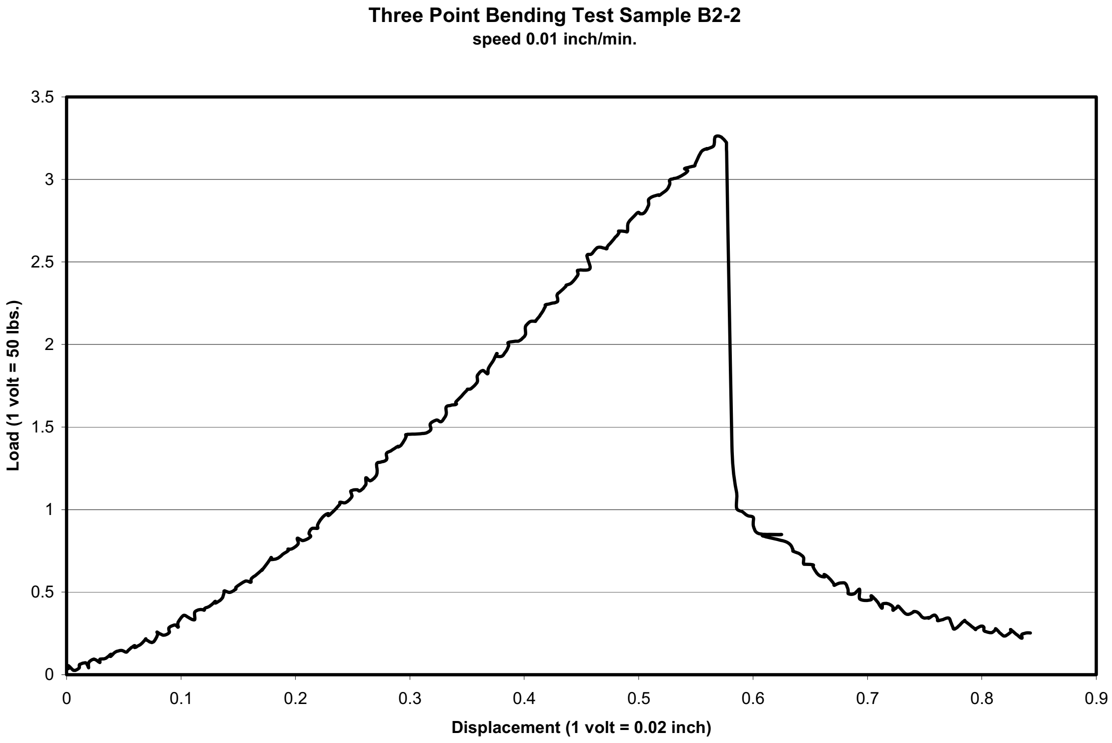


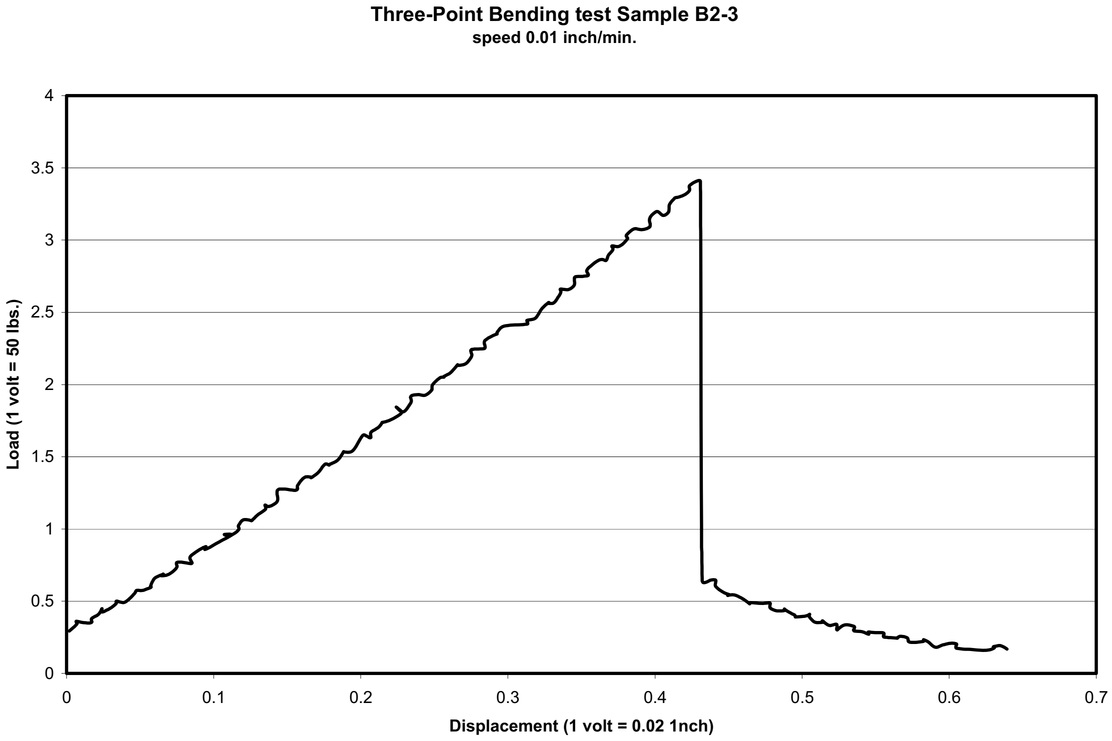
APPENDIX J: MODULUS OF RUPTURE – ASTM D1635


Three-Point Bending Test Sample B1-3
speed 0.01 inch/min


Three-Point Bending Test Sample B2-1
speed 0.02 inch/min.

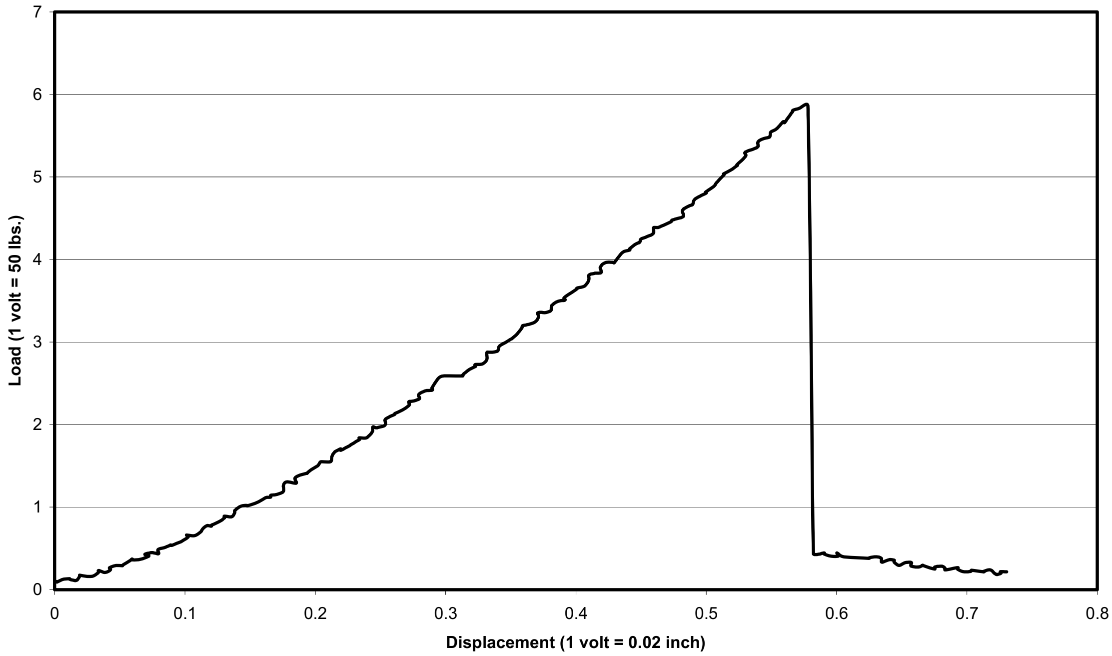
APPENDIX J: MODULUS OF RUPTURE – ASTM D1635



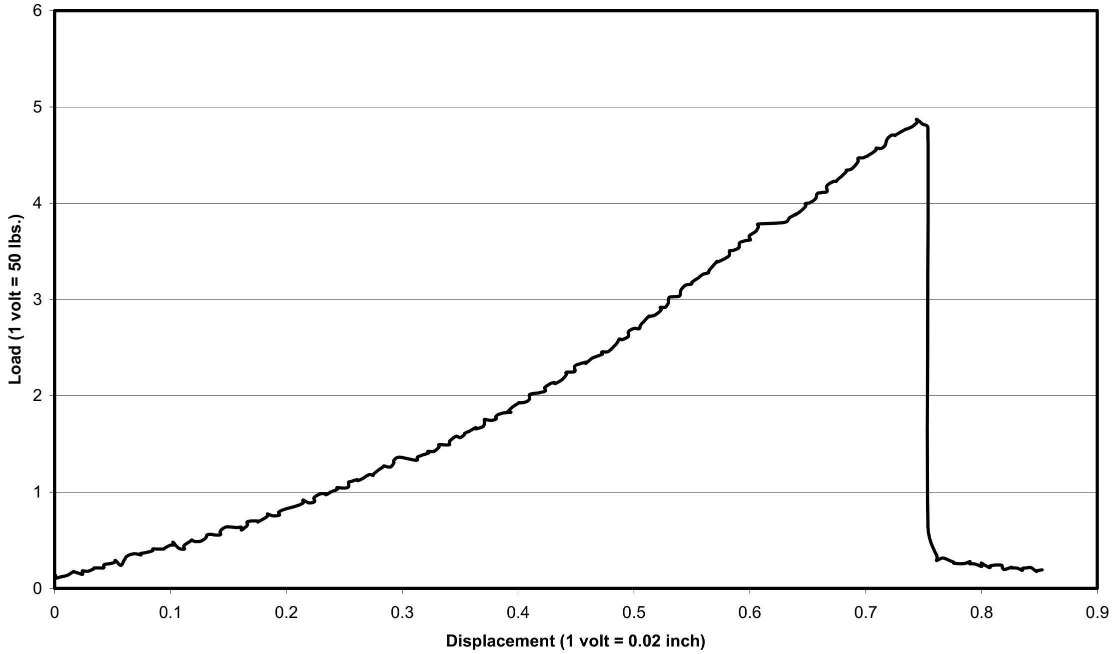


APPENDIX J: MODULUS OF RUPTURE – ASTM D1635

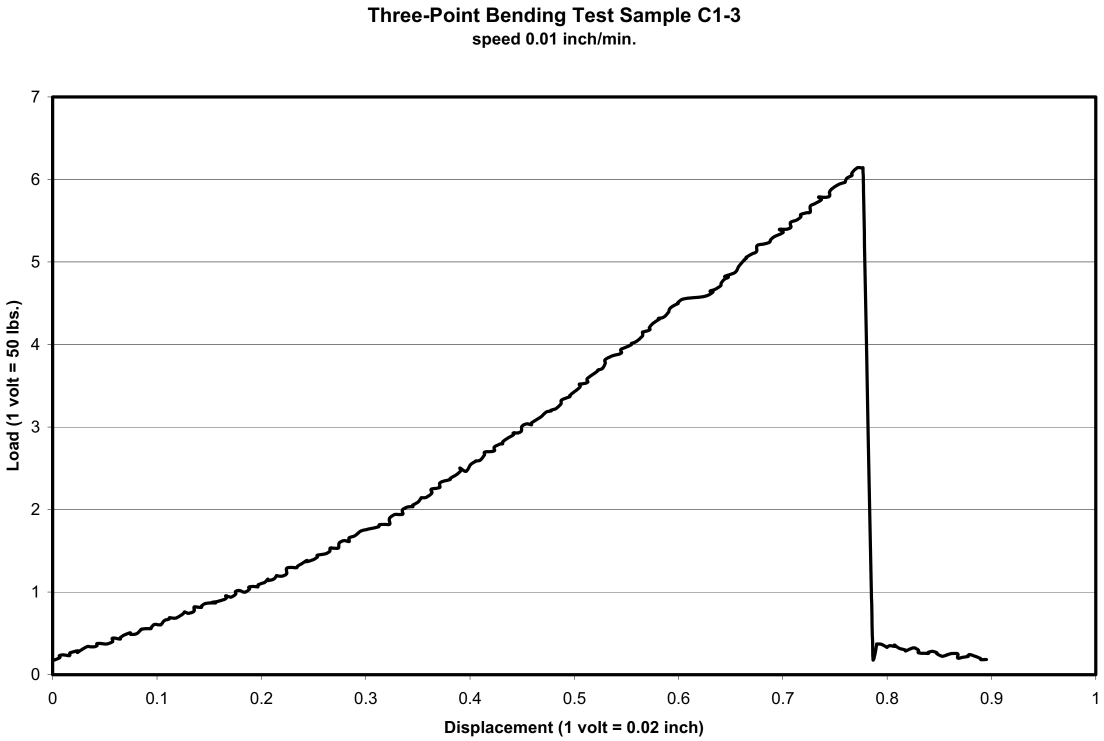
Three-Point Bending Test Sample C1-1
speed 0.01 inch/min.

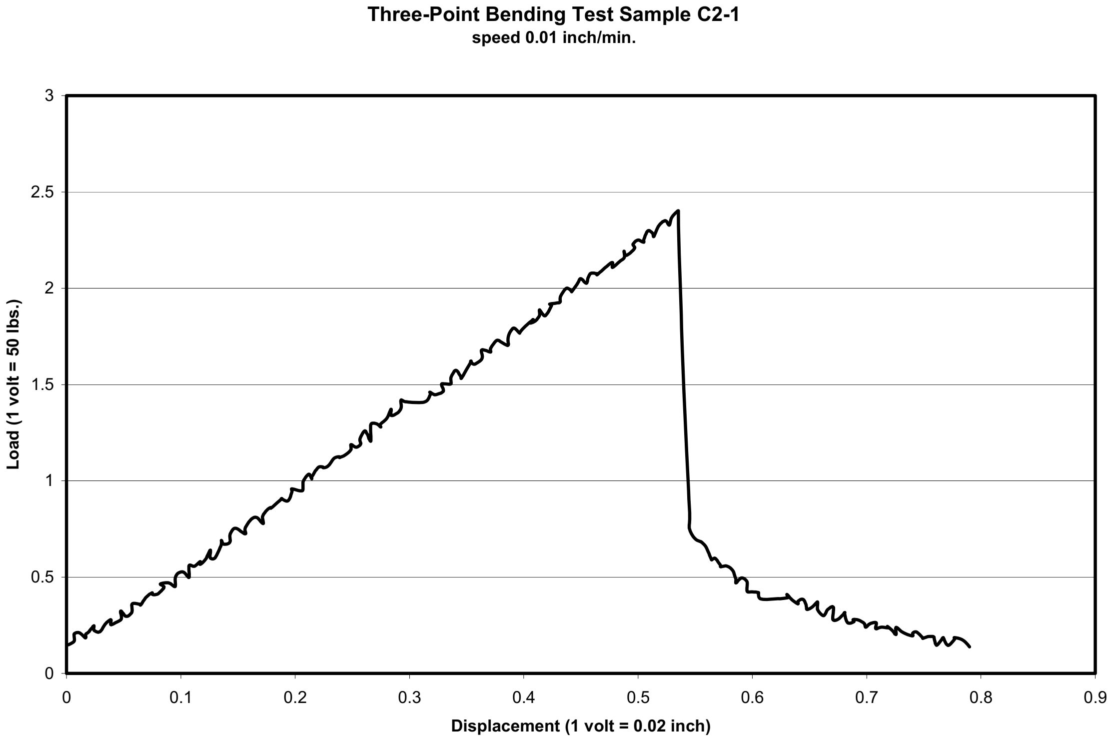


Three-Point Bending Test Sample C1-2
speed 0.01 inch/min.

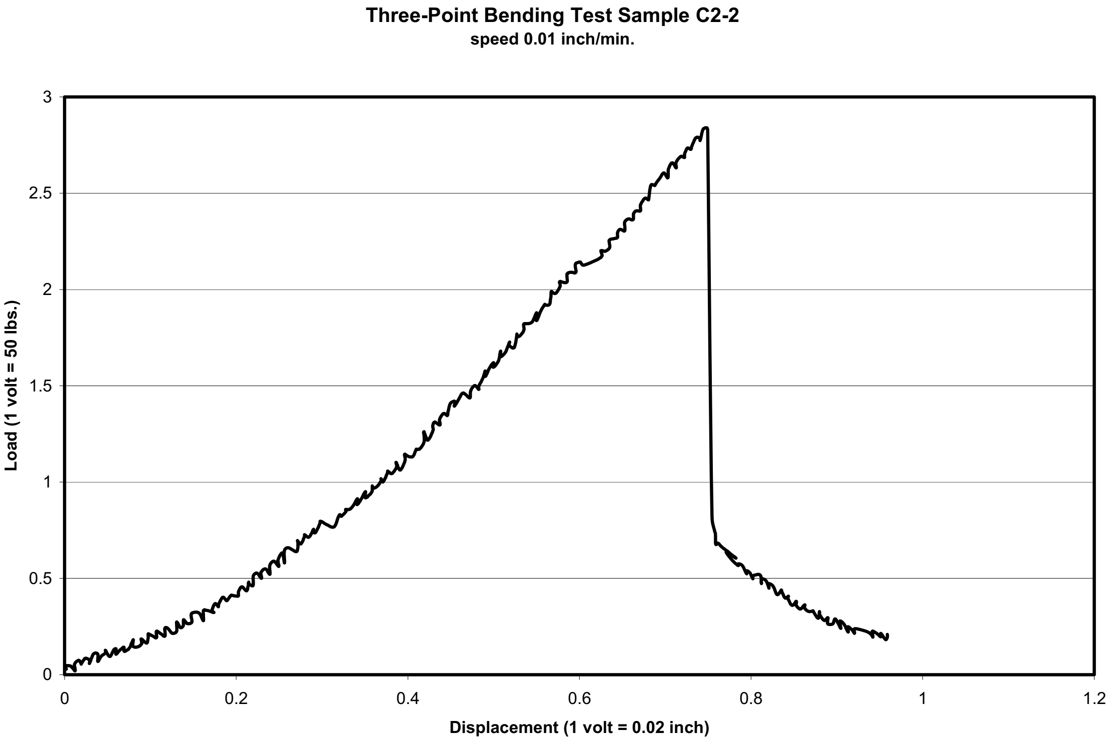


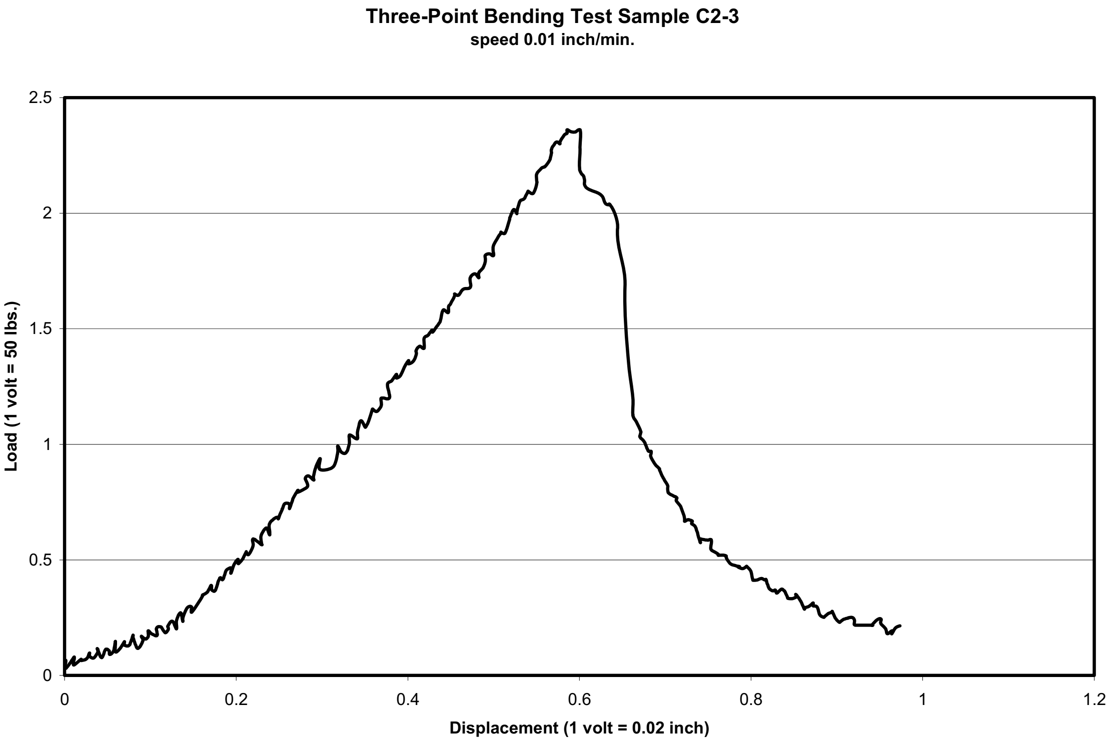
APPENDIX J: MODULUS OF RUPTURE – ASTM D1635





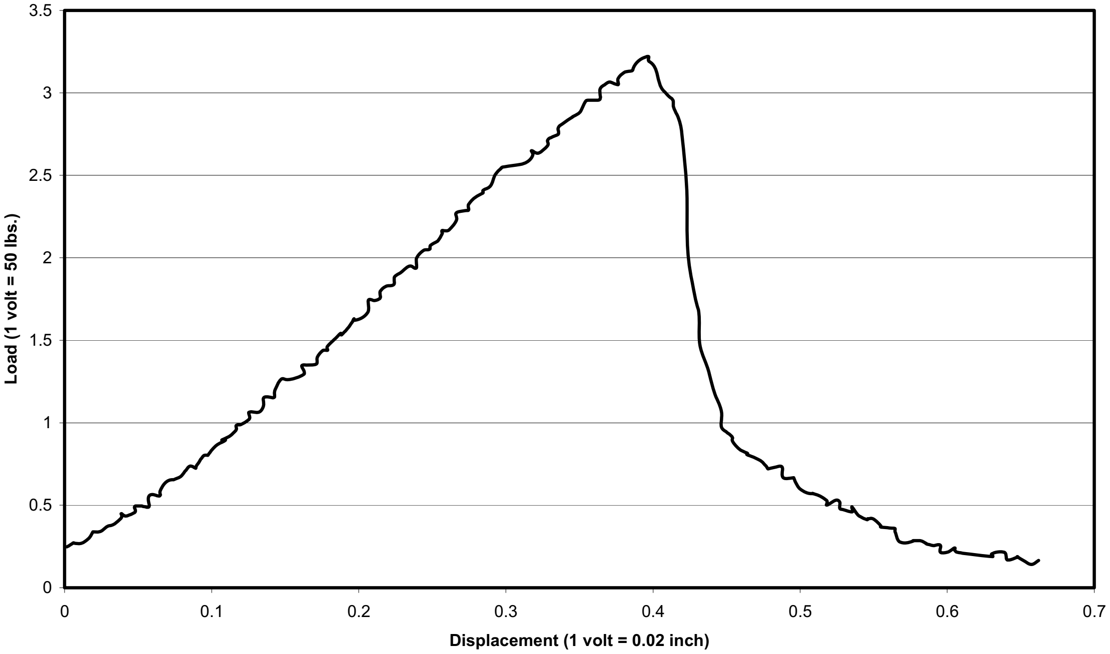
APPENDIX J: MODULUS OF RUPTURE – ASTM D1635



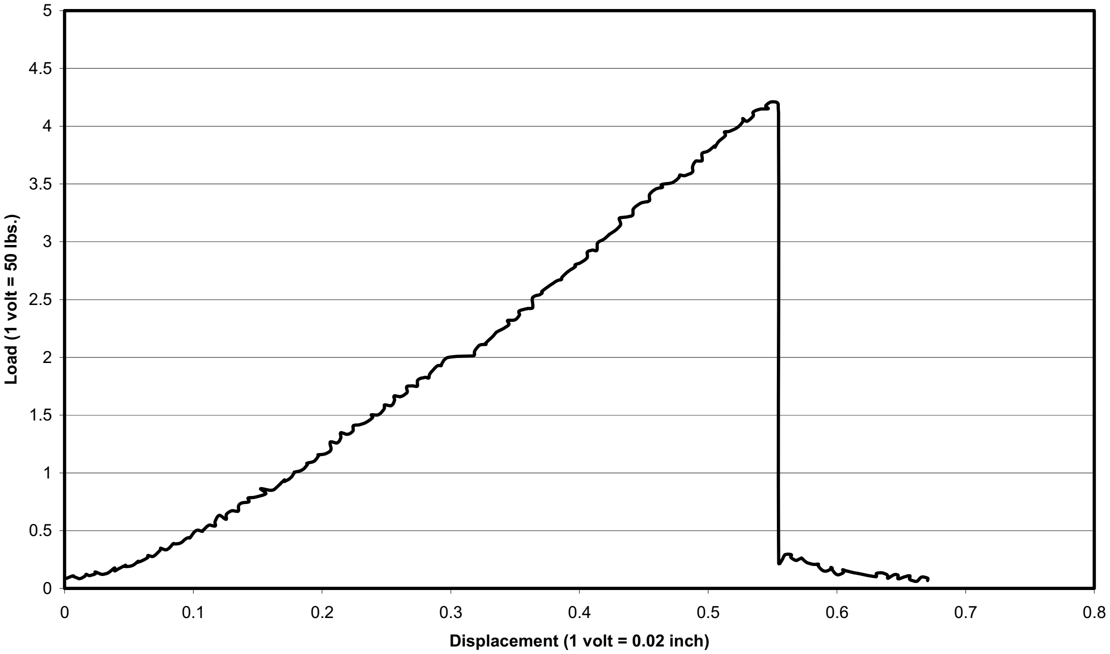


APPENDIX J: MODULUS OF RUPTURE – ASTM D1635

Three-Point Bending Test Sample S1-1
speed 0.01 inch/min.

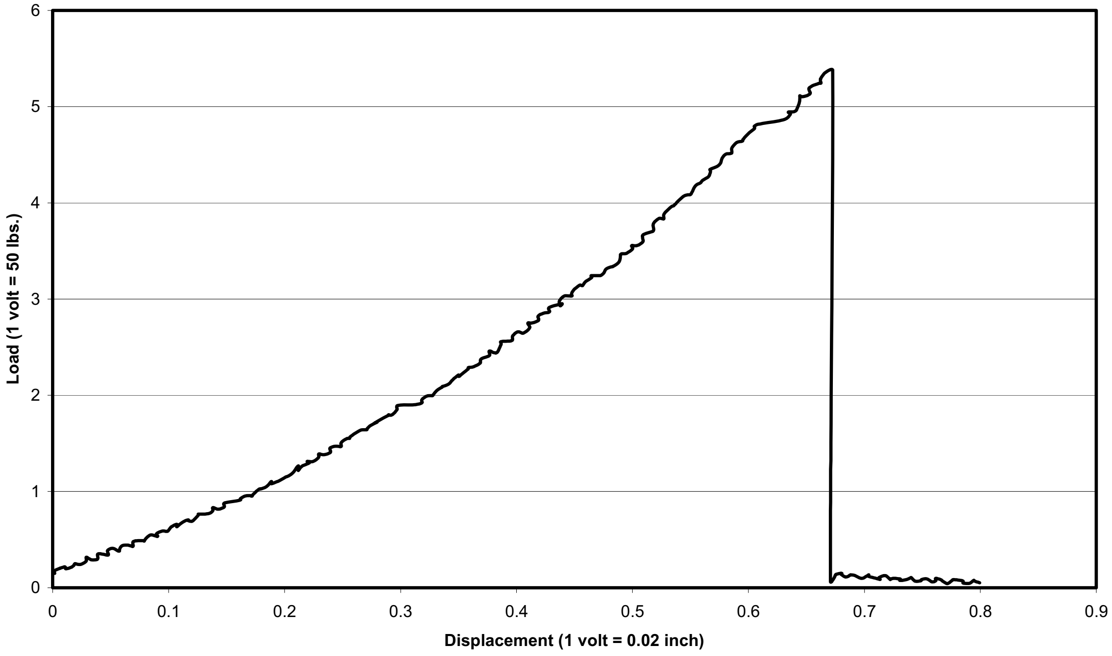


Three-Point Bending Test Sample S1-2
speed 0.01 inch/min.

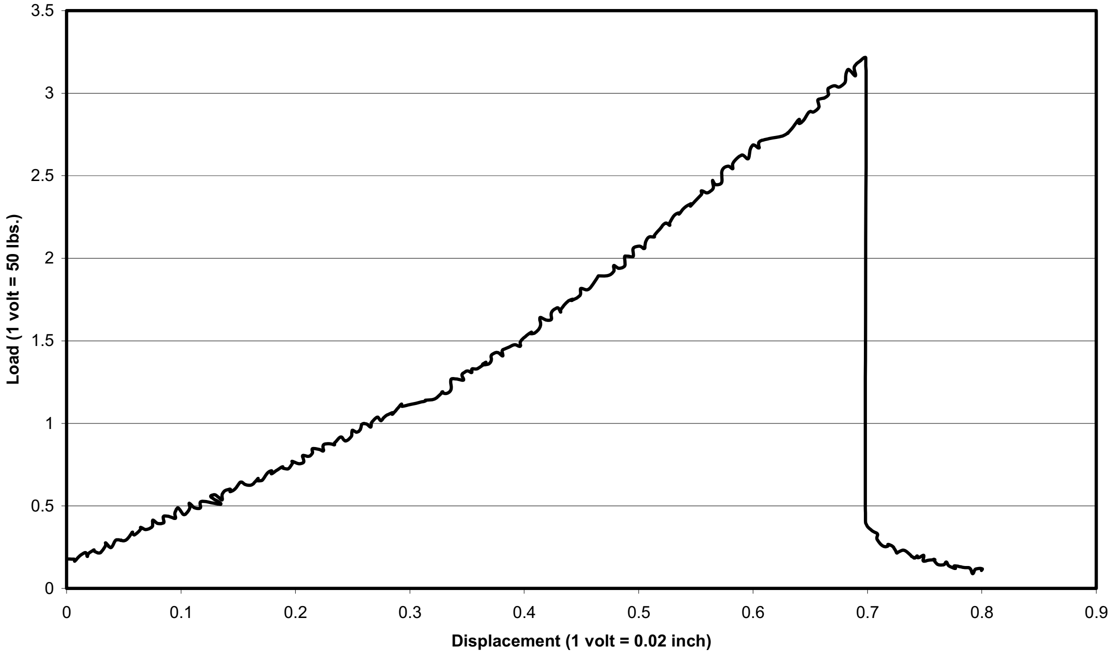


APPENDIX J: MODULUS OF RUPTURE – ASTM D1635

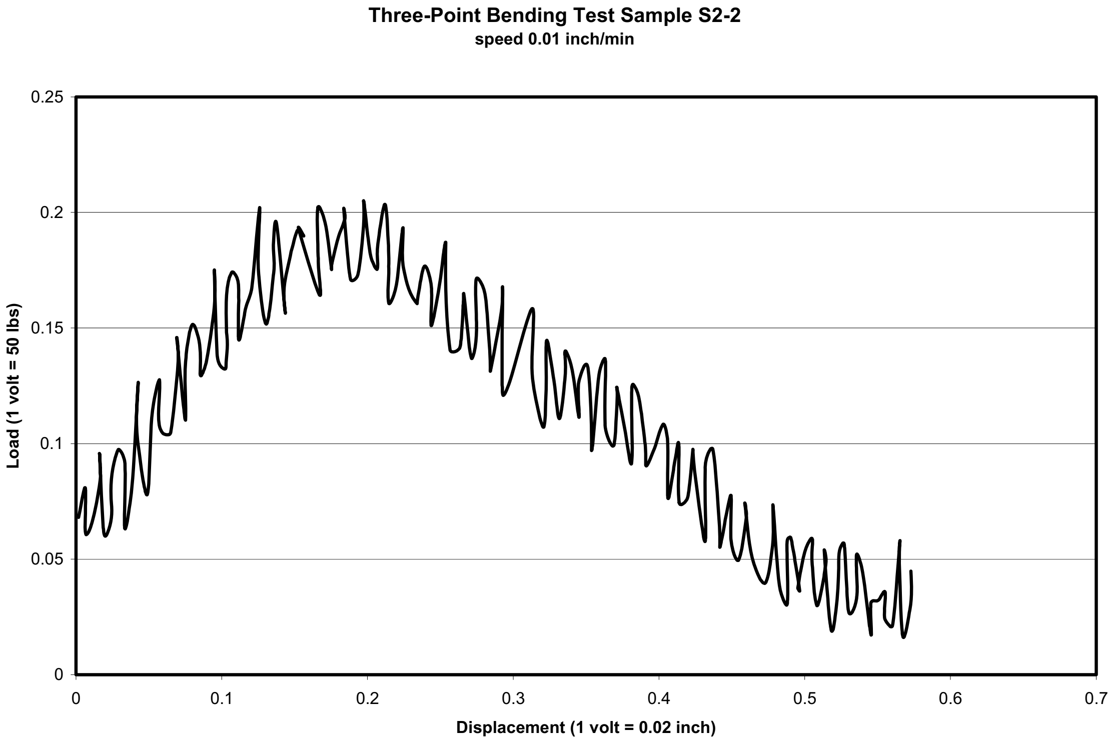
Three-Point Bending Test Sample S1-3
speed 0.01 inch/min.

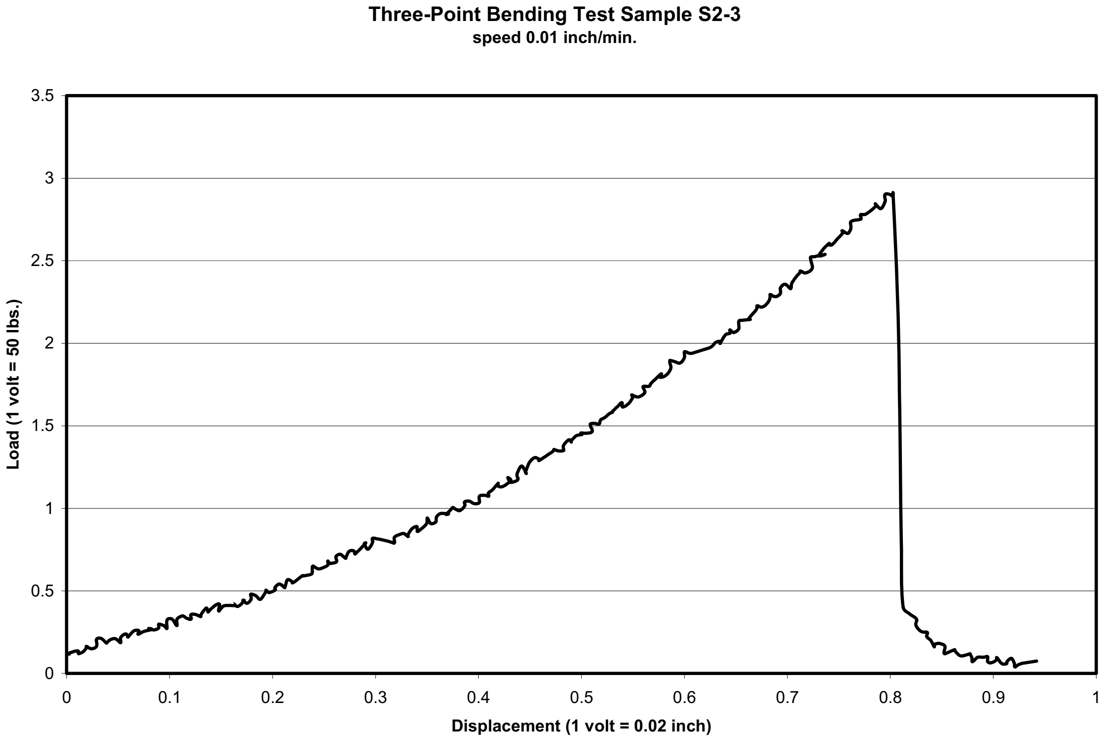


Three-Point Bending Test Sample S2-1
speed 0.01 inch/min.



APPENDIX J: MODULUS OF RUPTURE – ASTM D1635

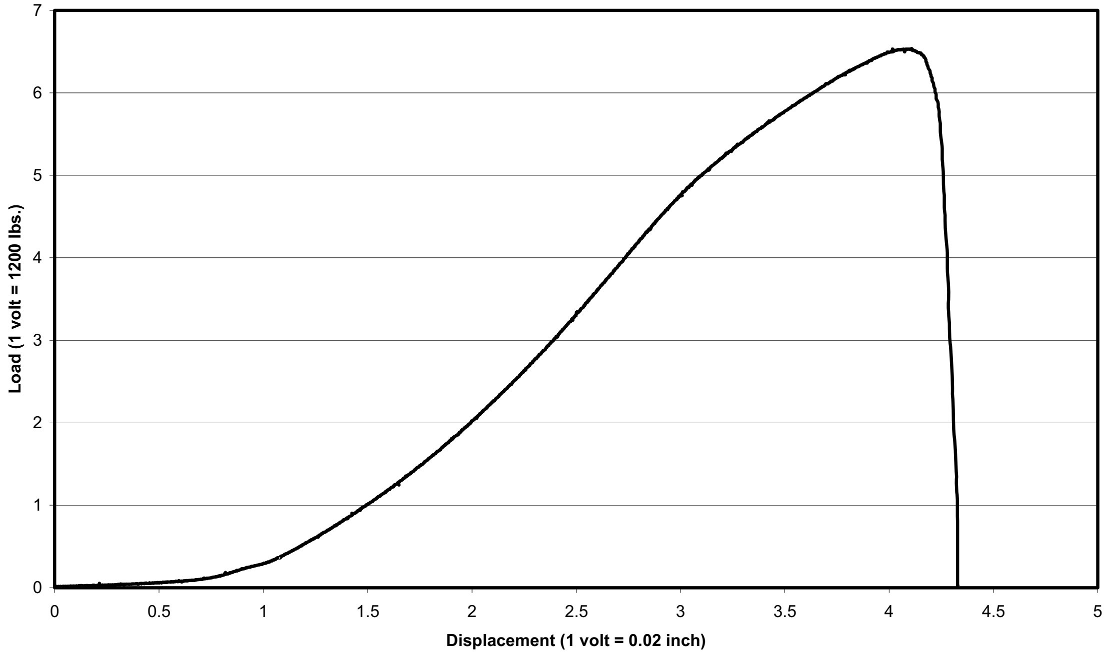




APPENDIX K: SPLITTING TENSILE STRENGTH – ASTM C496-96

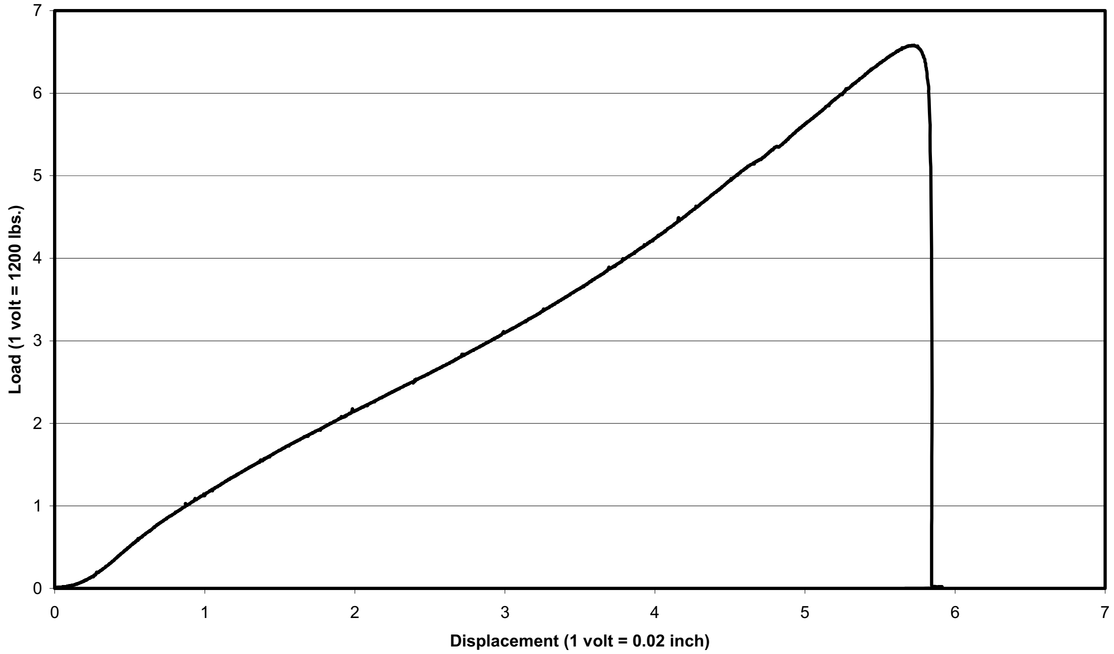
Compression Test Sample B1-1

speed 0.01 inch/min.



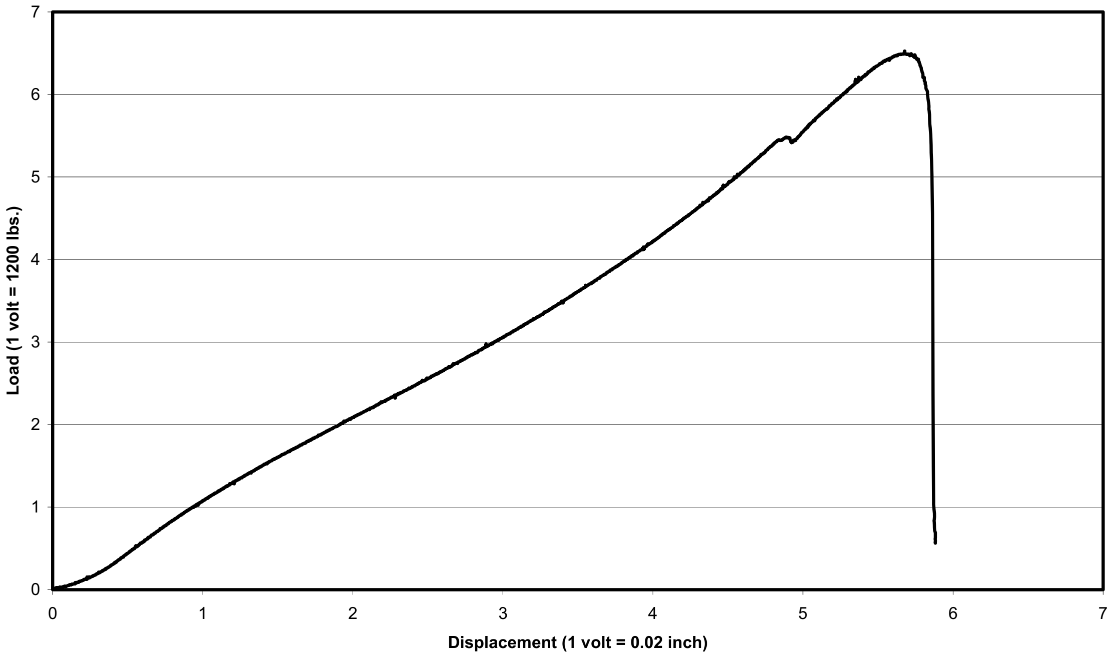
Compression Test Sample B1-2

speed 0.02 inch/min.

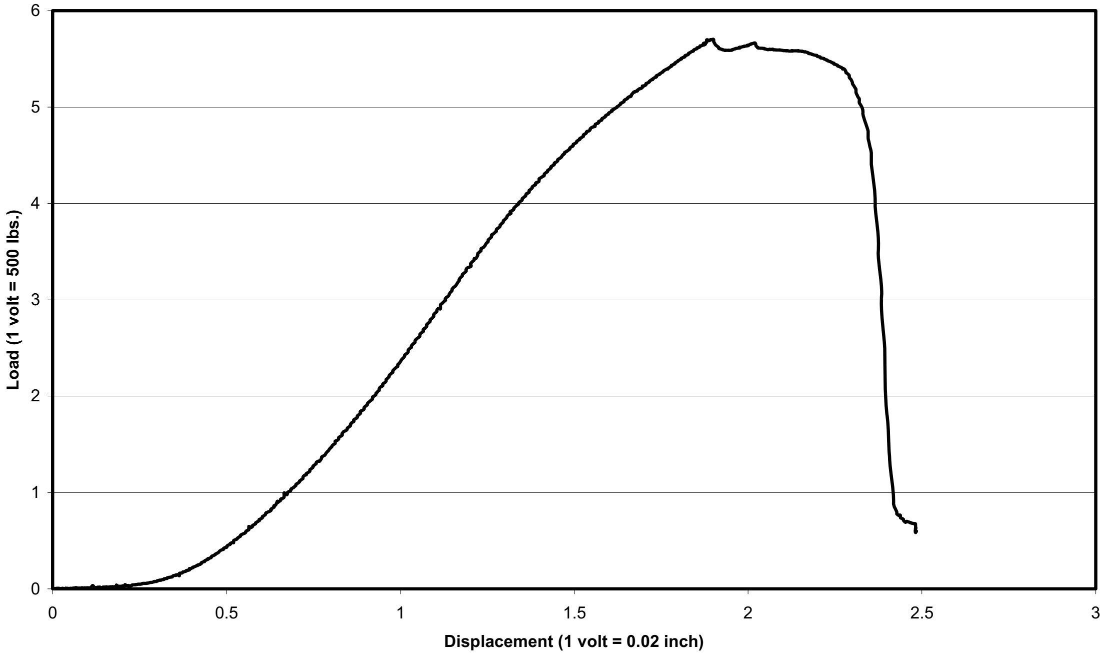


APPENDIX K: SPLITTING TENSILE STRENGTH – ASTM C496-96

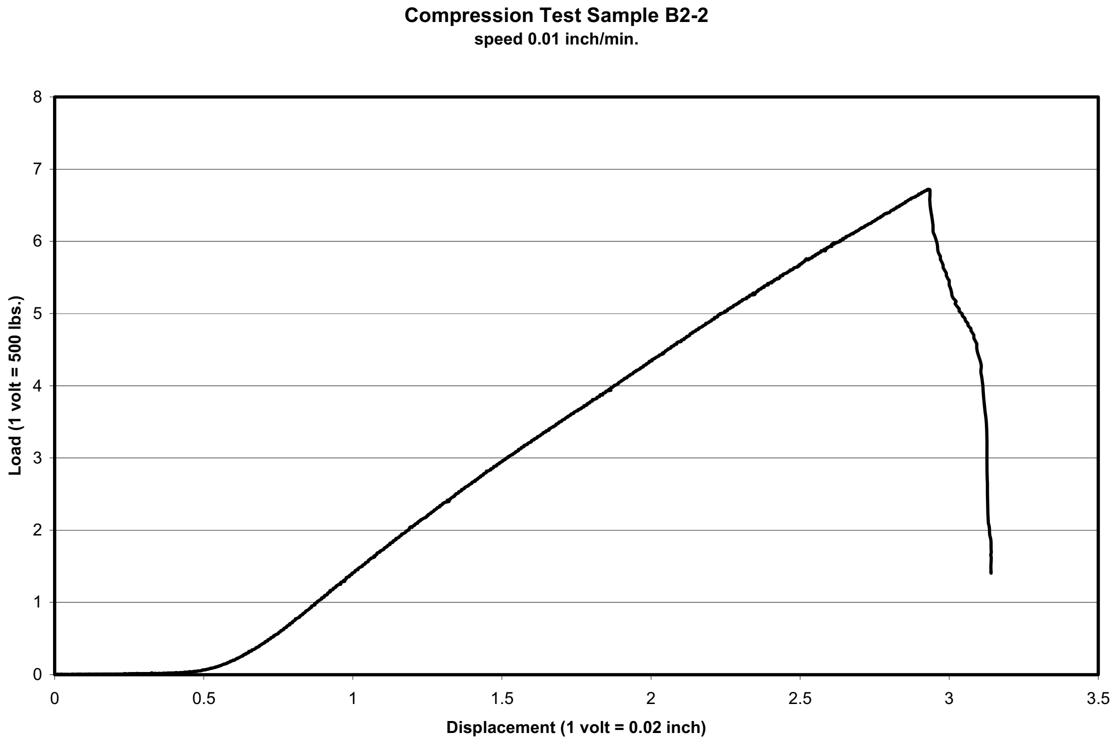
Compression Test Sample B1-3
speed 0.01 inch/min.



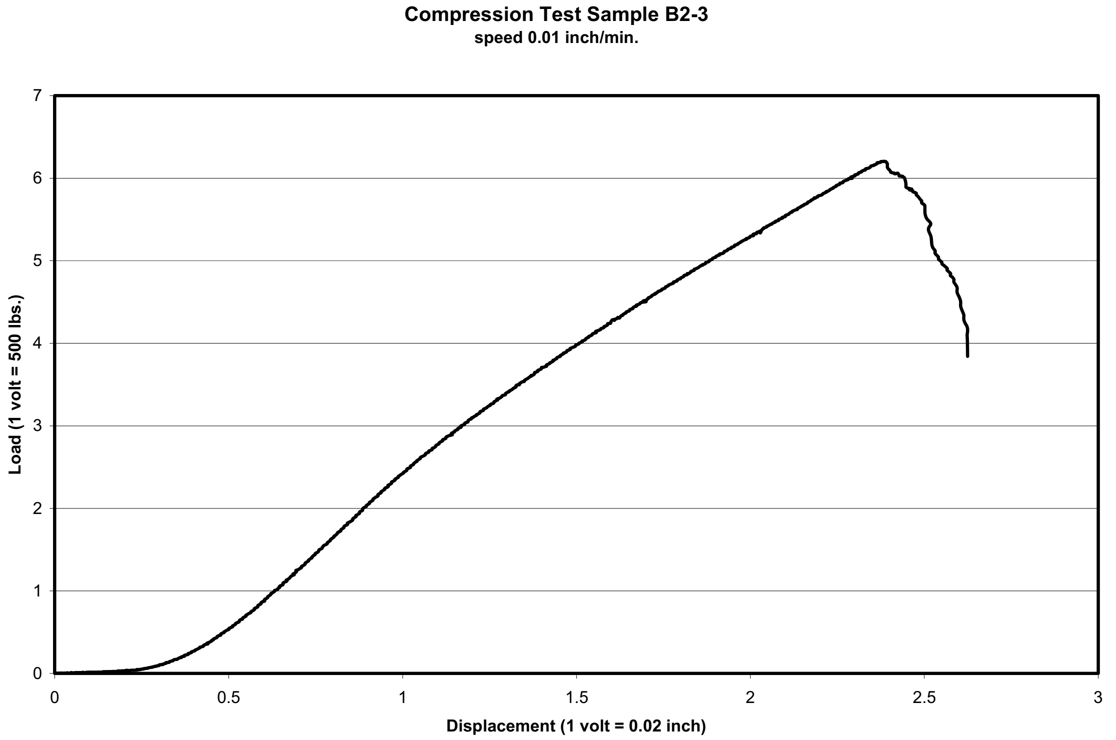
Compression Test Sample B2-1
speed 0.01 inch/min.



APPENDIX K: SPLITTING TENSILE STRENGTH – ASTM C496-96

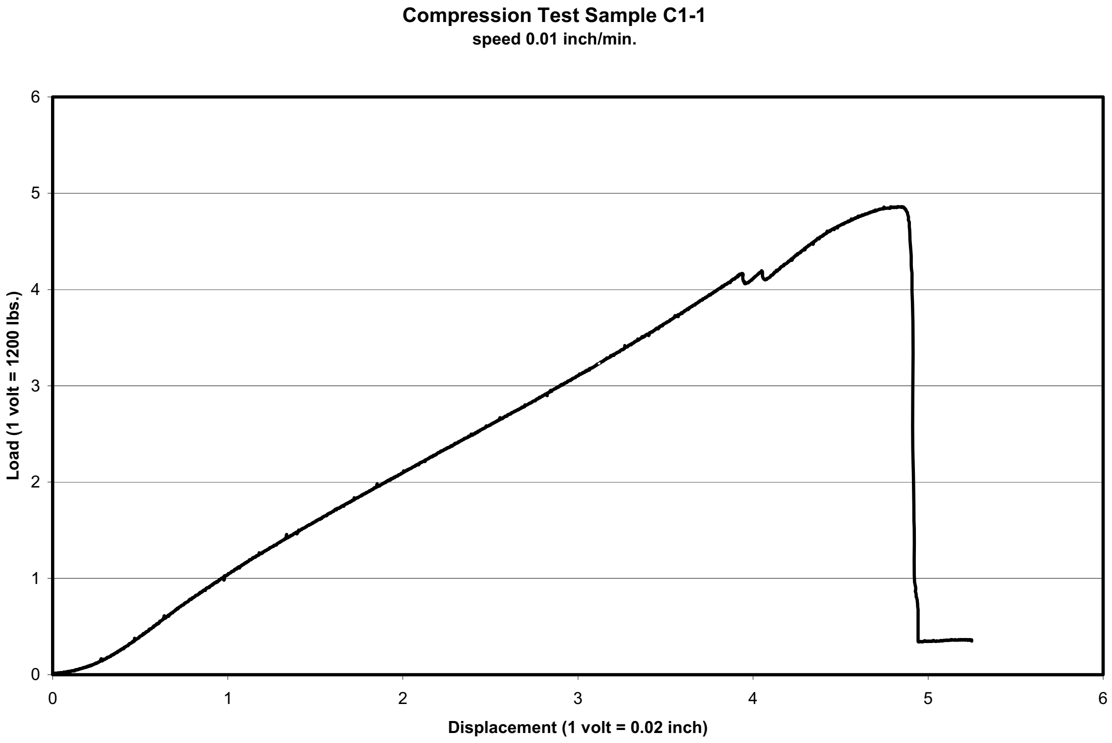

Compression Test Sample B2-2

speed 0.01 inch/min.

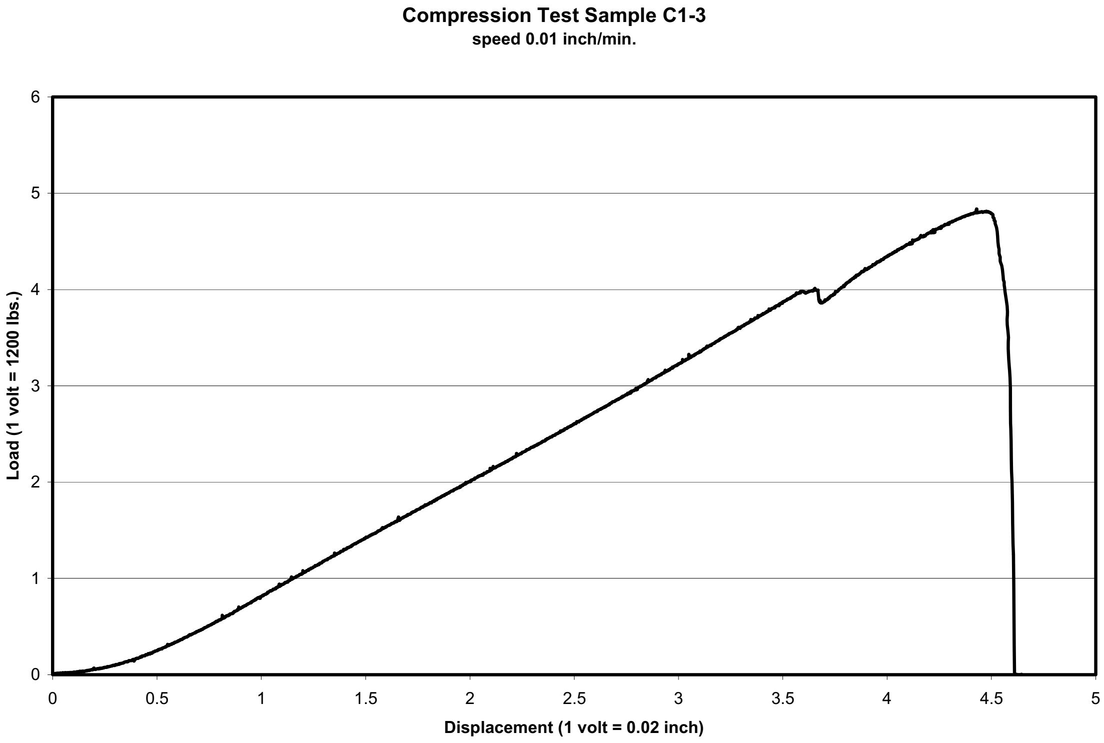

Compression Test Sample B2-3

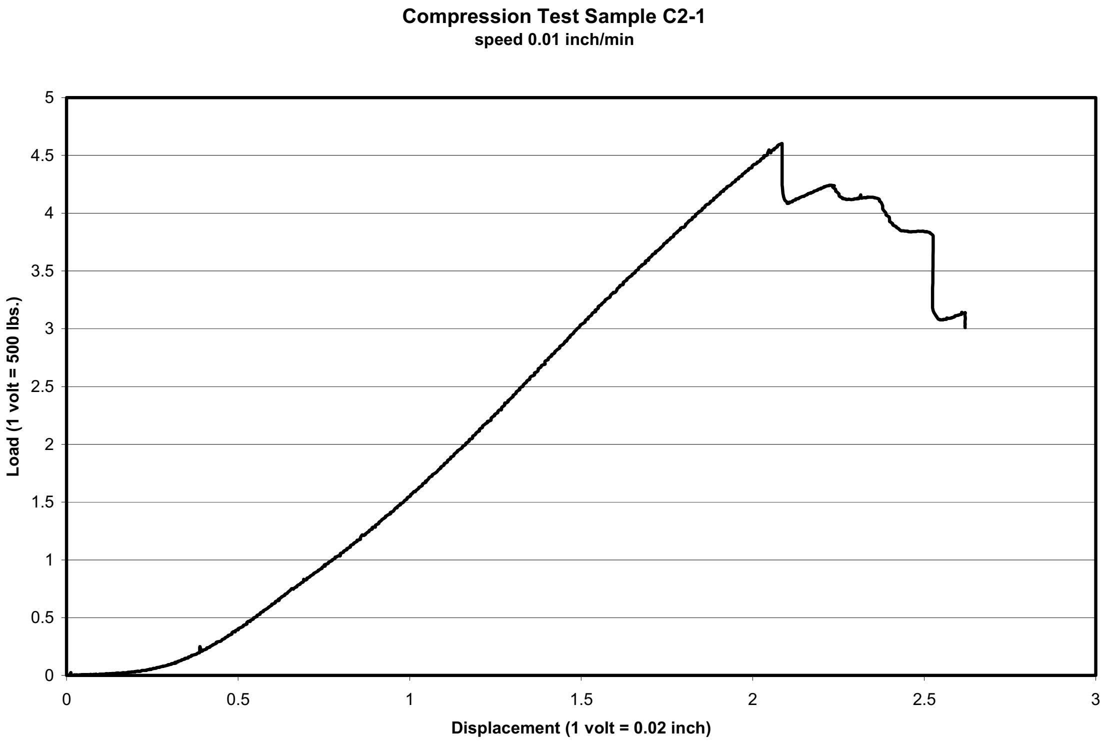
speed 0.01 inch/min.

APPENDIX K: SPLITTING TENSILE STRENGTH – ASTM C496-96



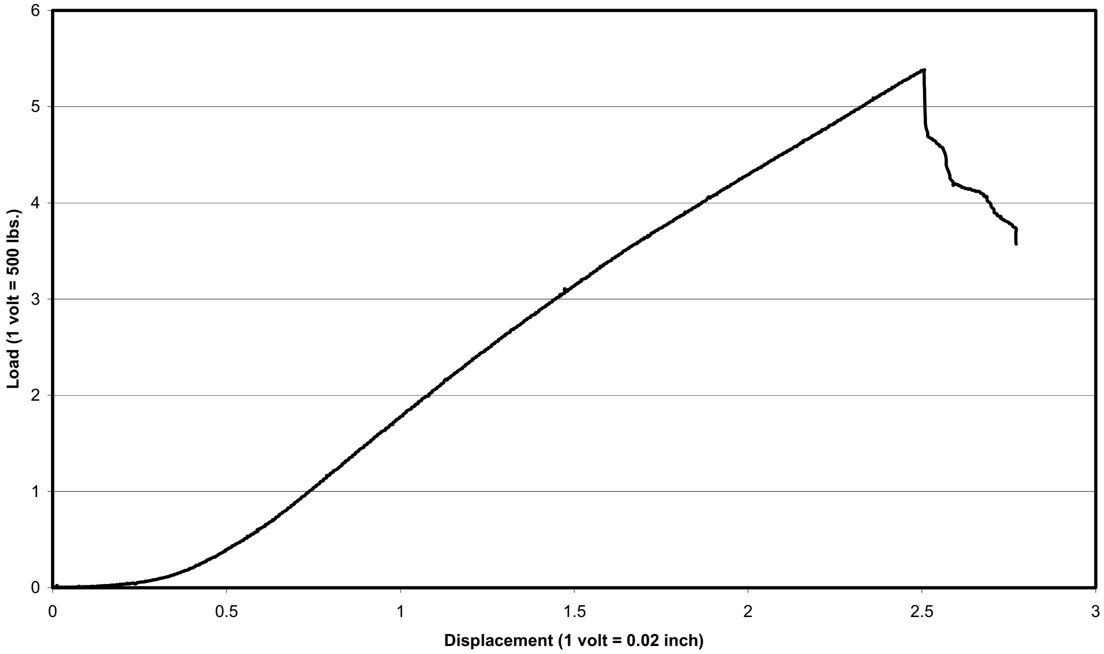
APPENDIX K: SPLITTING TENSILE STRENGTH – ASTM C496-96



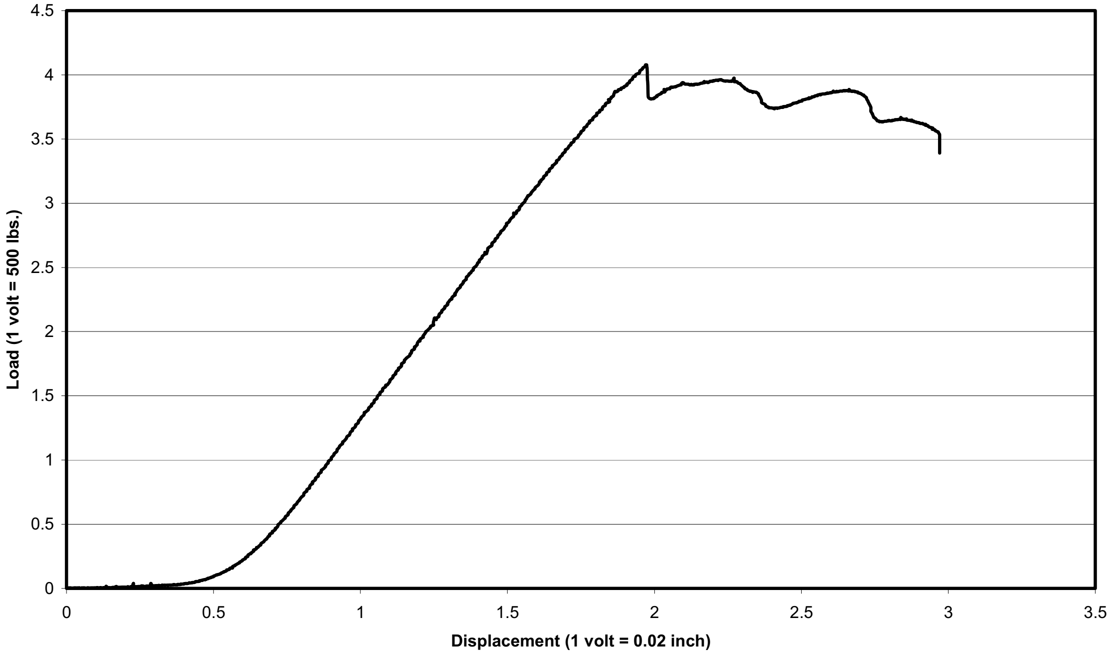


APPENDIX K: SPLITTING TENSILE STRENGTH – ASTM C496-96

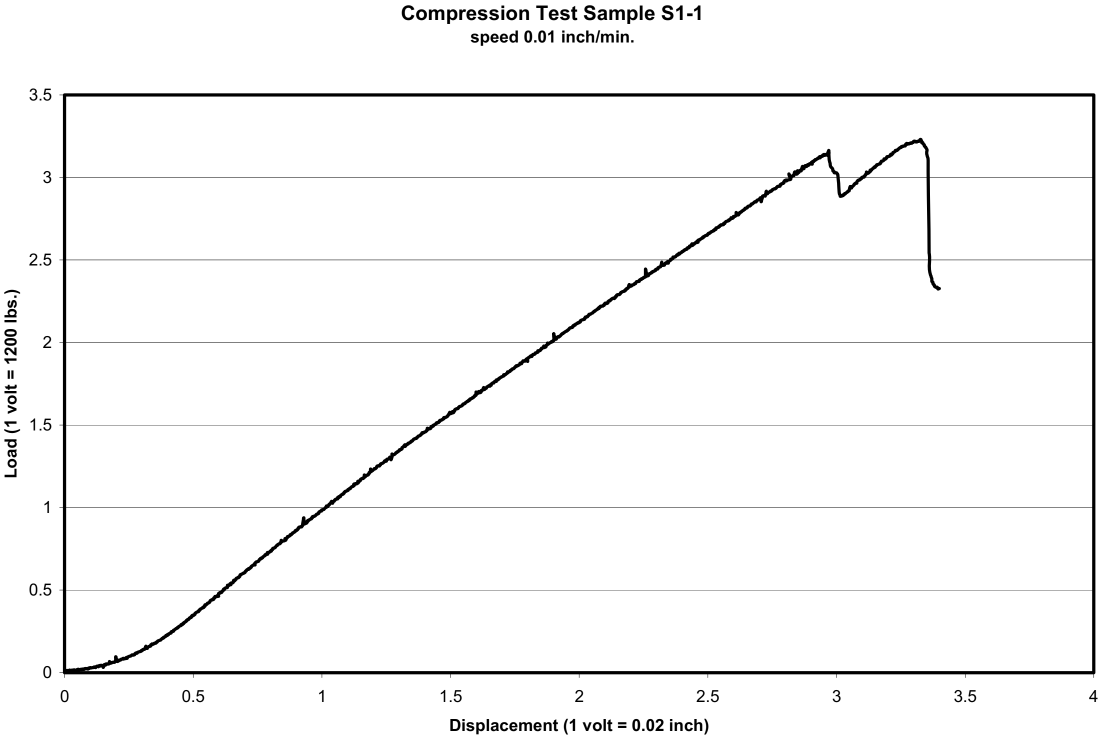
Compression Test Sample C2-2
speed 0.01 inch/min.

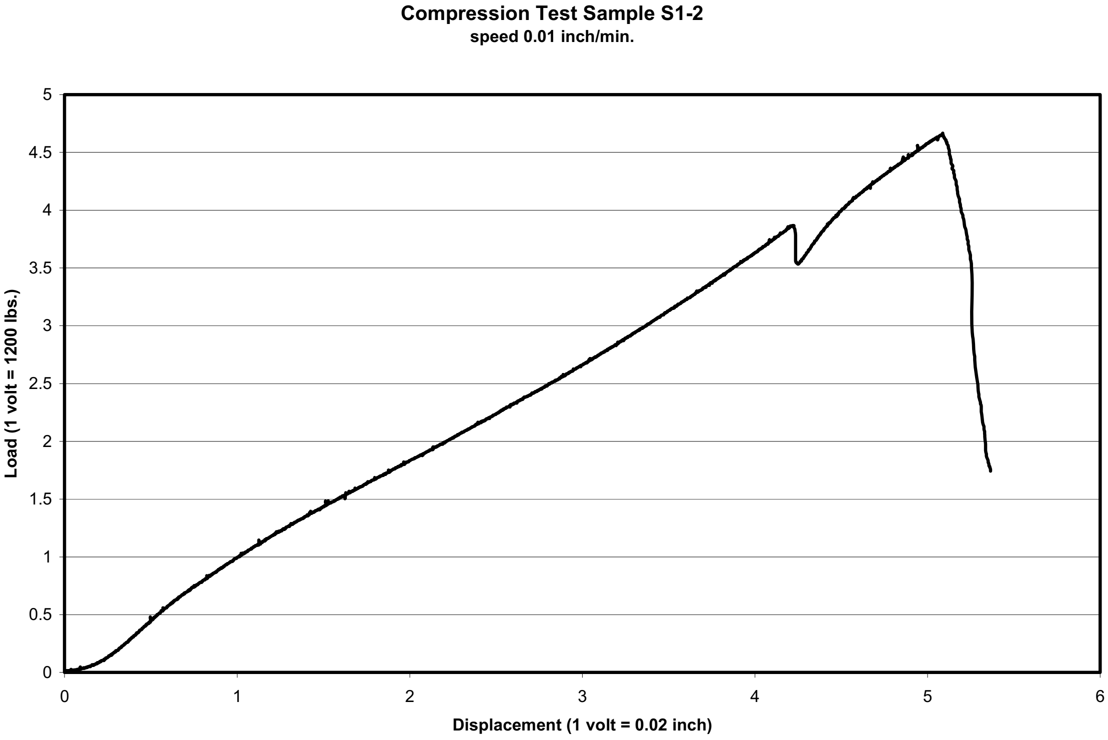


Compression Test Sample C2-3
speed 0.01 inch/min.



APPENDIX K: SPLITTING TENSILE STRENGTH – ASTM C496-96

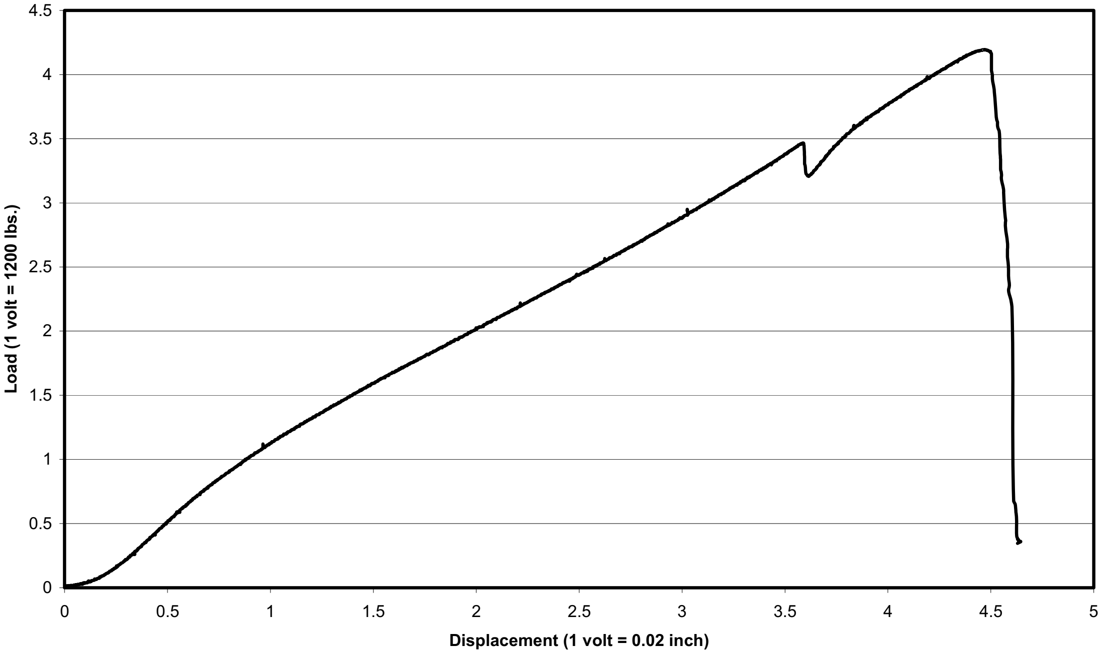




APPENDIX K: SPLITTING TENSILE STRENGTH – ASTM C496-96

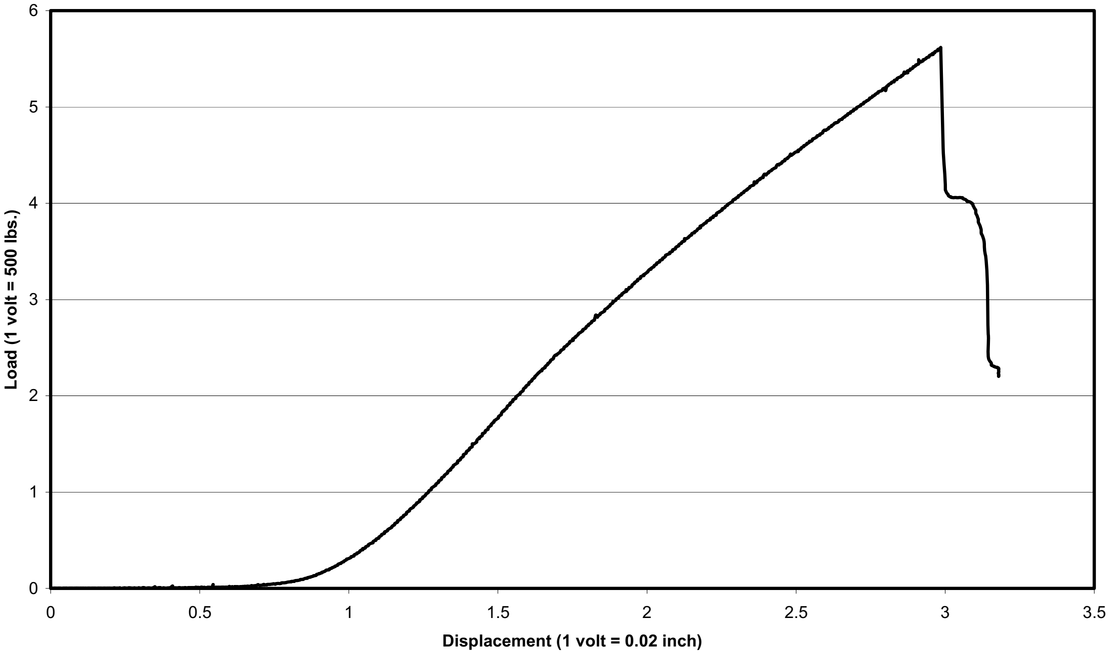
Compression Test Sample S1-3

speed 0.01 inch/min.



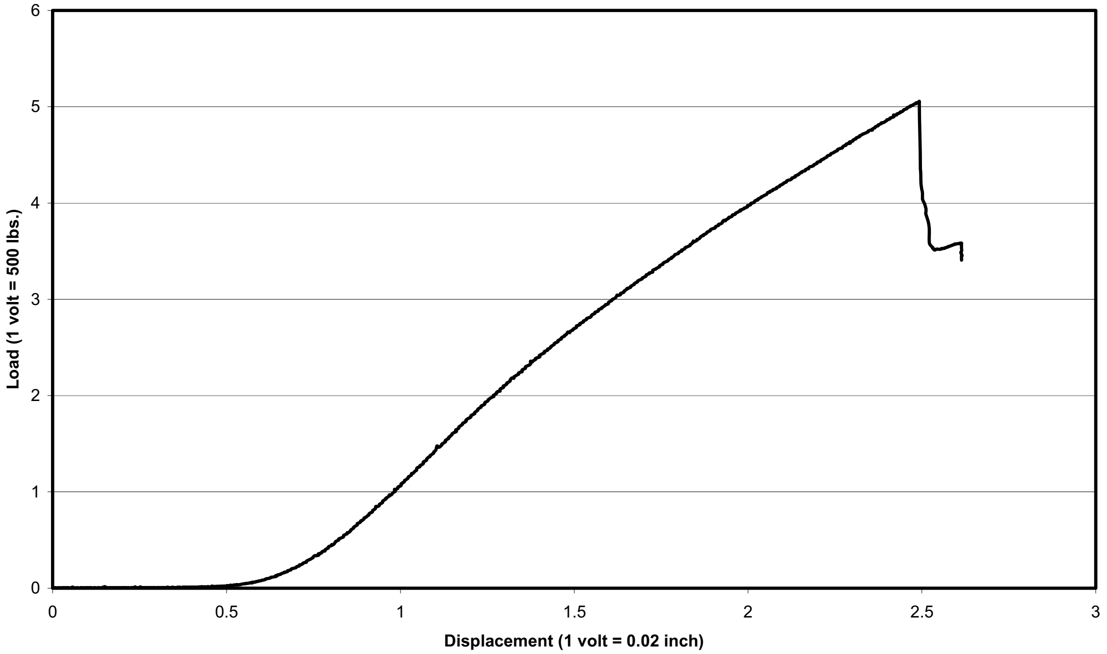
Compression Test Sample S2-1

speed 0.01 inch/min.

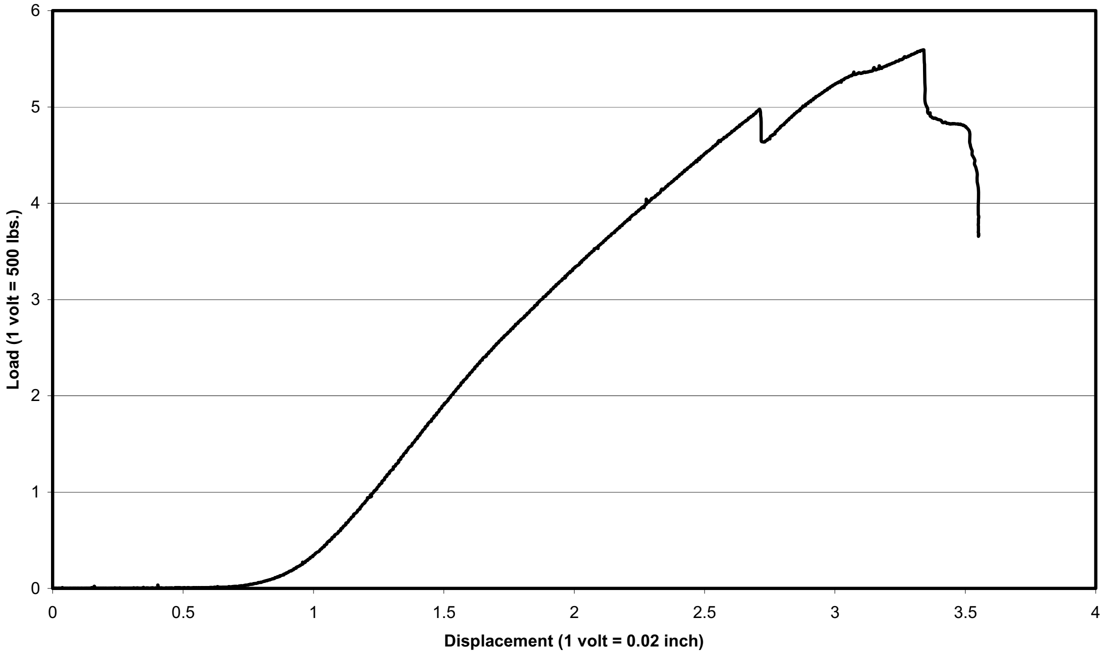


APPENDIX K: SPLITTING TENSILE STRENGTH – ASTM C496-96

Compression Test Sample S2-2
speed 0.01 inch/min.



Compression Test Sample S2-3
speed 0.01 inch/min.



APPENDIX L: X-RAY DIFFRACTION ANALYSIS

XRD Data for Bandelier Garcia Landscape Materials Blend Soil

```
                       µPDSM Report                    18:07,6/28/5

Input Pattern

HSPV WILLIAM ZINN SOIL B
Peak search on 28-JUN-0513:45:17

     d   [Cor.]       I          d   [Cor.]       I          d   [Cor.]      I
  6.592 [6.512 ]     5.6      2.9404[2.9222]     4.9      1.7842[1.7773]    2.7
  4.541 [4.501 ]     4.3      2.5744[2.5602]     4.0      1.6782[1.6722]    9.3
  4.289 [4.253 ]      23      2.4685[2.4554]      26      1.6640[1.6581]    2.8
  4.086 [4.053 ]     4.7      2.2951[2.2837]      82      1.5464[1.5413]     17
  4.049 [4.016 ]     4.4      2.2460[2.2351]     5.1      1.5123[1.5075]    4.9
  3.808 [3.779 ]      12      2.1373[2.1274]     7.2      1.5078[1.5030]    3.8
  3.369 [3.346 ]     100      2.0896[2.0801]     3.6      1.4651[1.4606]    3.7
  3.249 [3.227 ]      12      1.9889[1.9803]     9.1      1.4571[1.4527]    6.1
  3.215 [3.194 ]      14      1.8555[1.8480]     3.2      1.4164[1.4123]    4.9
  3.187 [3.166 ]      19      1.8250[1.8178]      22      1.3863[1.3824]     12
  3.052 [3.033 ]     6.6      1.8073[1.8002]     3.3      1.3767[1.3728]     30

  33 lines in pattern.

Manual corrections to your pattern were previously specified.

PDF pattern(s) used as correction references: 46-1045
Fiduciary Marks Selected (Input->Corrected)
1.3863->1.3821  1.4571->1.4529  1.5464->1.5415  1.6640->1.6592  1.6782->1.6717
1.8073->1.8017  1.8250->1.8180  1.9889->1.9799  2.1373->2.1277  2.2460->2.2361
2.2951->2.2815  2.4685->2.4569  3.369 ->3.343   4.289 ->4.255


Identified Phases:

 JCPDS#     SI    ML/X   At%   Identity . . .

46-1045*   227    15/0   160   *Silicon Oxide / Quartz, syn = SiO2
          Ierr:50,150      derr:2.0  Bground:2.7    dmax/min:8.842/1.343

84-0752C    82*   15/5    21   Sodium Aluminum Silicate / Albite low - from
                               Cazadero, California, USA = Na(AlSi3O8)
          Ierr:50,150      derr:2.0  Bground:2.7    dmax/min:8.842/1.343


Summary Report:

        Full   Resid   46-1045:160%    84-0752: 21%
  d      I      I        d       I       d        I
6.592   5.6    5.6
                                     <6.3878    2.9>

4.541   4.3    4.3
4.289    23   None   4.2550     26
4.086   4.7    4.7
4.049   4.4   None                    4.0265     15
3.808    12   None                    3.7755    7.0
                                     <3.6821    4.5>
                                     <3.6569    8.0>

3.369   100   None   3.3435    160
```

APPENDIX L: X-RAY DIFFRACTION ANALYSIS

XRD Data for Bandelier Garcia Landscape Materials Blend Soil (contd.)

```
3.249     12  None                  3.2145    12
3.215     14  None                  3.1939    19
 "  "     "                         3.1873    21
3.187     19  None                  3.1698   7.2
 "  "     "                         3.1484   6.4
3.052    6.6   6.6
                                   <2.9638   4.1>
                                   <2.9552   4.3>
2.9404   4.9  None                  2.9268   4.5
2.5744   4.0  None                  2.5603   3.1
2.4685    26    12  2.4569     14
2.2951    82    69  2.2815    13*
2.2460   5.1  None  2.2361    6.4
2.1373   7.2  None  2.1277    9.6  [2.1249   1.6]
2.0896   3.6   2.4                  2.0756   1.2
1.9889   9.1  None  1.9799    6.4
1.8555   3.2  None                  1.8493   1.6
 "  "    "                          1.8427   1.0
1.8250    22  None  1.8180     21  [1.8230   1.8]
 "  "    "                         [1.8185   2.3]
1.8073   3.3  None  1.8017    1.6  [1.8123   1.0]
 "  "    "                         [1.8026   1.2]
1.7842   2.7   2.7
1.6782   9.3  None  1.6717    6.4
1.6640   2.8  None  1.6592    3.2  [1.6668   0.8]
 "  "    "                         [1.6531   0.2]
1.5464    17  None  1.5415     14
1.5123   4.9   4.9
1.5078   3.8   3.0                  1.5012   0.8
1.4651   3.7  None                  1.4639   1.0
 "  "    "                          1.4587   0.8
1.4571   6.1  None  1.4529    3.2  [1.4555   1.0]
1.4164   4.9   4.9
1.3863    12  None  1.3821    9.6
1.3767    30    11  1.3750     11
 "  "    "          1.3719    8.0
          * = Obscured    <..> = Missing     [..] = Previously Removed
```

APPENDIX L: X-RAY DIFFRACTION ANALYSIS

XRD Data for Salinas Mountainair Local Quarry Soil

```
                      μPDSM Report                    14:00,6/28/5


Input Pattern

HSPV WILLIAM ZINN SOIL S
Peak search on 28-JUN-0513:27:29

   d       I    d       I    d       I    d       I    d       I    d       I
6.371    2.2 3.746    3.3 3.181  -  5.6 2.5780   2.9 2.0903   2.5 1.5404   9.4
4.446    3.2 3.664    2.3 3.143    2.6 2.5602   2.9 1.9768   6.6 1.4518   1.9
4.239     32 3.582    2.2 3.009    3.9 2.4529    11 1.8157    11 1.3716   7.7
4.025    3.0 3.468    3.5 2.9817   2.2 2.2784   6.6 1.7990   2.3
3.834    2.5 3.340    100 2.9123   2.2 2.2333   4.3 1.6710   3.5
3.786    3.6 3.223     13 2.6071   2.2 2.1242   6.0 1.6572   3.6

  33 lines in pattern.

Identified Phases:

 JCPDS#     SI   ML/X  At%  Identity . . .

46-1045*   221   15/1  112  *Silicon Oxide / Quartz, syn = SiO2
         Ierr:50,150    derr:2.0  Bground:1.9   dmax/min:8.842/1.343

71-1151C    99   13/3   12  Sodium Aluminum Silicate / Albite high =
                            Na(AlSi3O8)
         Ierr:50,150    derr:2.0  Bground:1.9   dmax/min:8.842/1.343

83-1604C    47*  10/3  8.3  Potassium Aluminum Silicate / Microcline - from
                            Kungnat, SW Greenland = KAlSi3O8
         Ierr:50,150    derr:2.0  Bground:1.9   dmax/min:8.842/1.343

74-0345C     5    3/0  3.7  Potassium Aluminum Silicate Hydrate / Muscovite =
                            KAl2(Si3Al)O10(OH)2
         Ierr:50,150    derr:2.0  Bground:1.9   dmax/min:8.842/1.343


Summary Report:

       Full  Resid  46-1045:112%   71-1151: 12%   83-1604:  8%   74-0345:  4%
  d     I     I      d        I     d       I      d        I     d        I
6.371   2.2  None                 6.4354   2.3
 "  "   "                         6.3675   1.0
4.446   3.2  None                                               4.4811   0.70
 "  "   "                                                       4.4477    2.1
4.239    32     9  4.2550     18                4.2551    5.3
4.025   3.0  None                 4.0485    10
                                 <3.8848   2.3>
3.834   2.5  None                                               3.8624    1.8
3.786   3.6  None                 3.7667   3.7  [3.7774   3.7]
3.746   3.3  None                 3.7514   5.2  [3.7560   3.9]  [3.7295   1.6]
3.664   2.3  None                 3.6556   3.2
3.582   2.2  None                                3.5997  0.91   [3.5919  0.19]
 "  "   "                                        3.5653  0.66
3.468   3.5  None                 3.4739   1.0   3.4641   3.8   [3.4760   2.0]
3.340   100  None  3.3435    112                [3.3341   4.6]  [3.3450   1.9]
 "  "   "                                                       [3.3357   2.7]
                                                <3.3146   4.9>
```

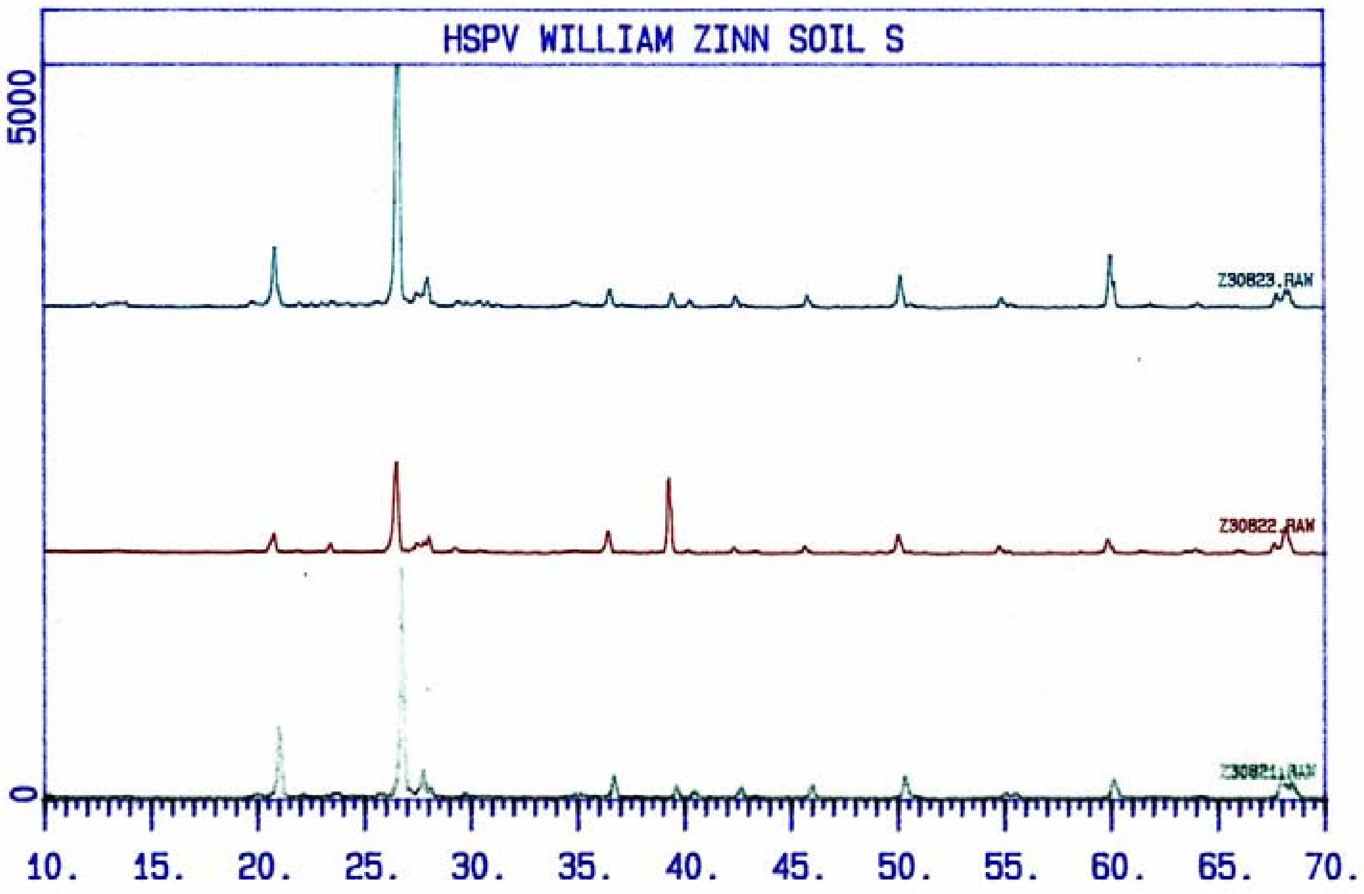
APPENDIX L: X-RAY DIFFRACTION ANALYSIS

XRD Data for Salinas Mountainair Local Quarry Soil (contd.)

```
                                                 <3.2971    5.1>
3.223     13  None                 3.2126     12  [3.2245    8.3]  [3.2153    2.1]
3.181    5.6  None                 3.1837    9.0
3.143    2.6  None                 3.1447    3.2
3.009    3.9  None                 3.0106    1.7
2.9817   2.2  None                              2.9914    2.6  [2.9902    1.9]
 "  "    "                                      2.9791    3.1
                                  <2.9447   2.0>
2.9123   2.2  None                 2.9251    1.5
 "  "    "                         2.9157    1.5
                                                 <2.8906    2.2>
2.6071   2.2  None                              2.6158    1.4
2.5780   2.9  None                              2.5822    1.6  [2.5871    1.4]
2.5602   2.9  None                              2.5656    1.7  [2.5574    3.7]
 "  "    "                                      2.5483   0.66
                                  <2.5262   2.3>
2.4529    11  None  2.4569     10                                [2.4553  0.63]
2.2784   6.6  None  2.2815    9.0
2.2333   4.3  None  2.2361    4.5                                [2.2405  0.15]
2.1242   6.0  None  2.1277    6.7 [2.1183    0.9] [2.1294   0.75] [2.1330    1.2]
2.0903   2.5   2.5
1.9768   6.6  None  1.9799    4.5                [1.9734   0.50]
1.8157    11  None  1.8180     15
1.7990   2.3  None  1.8017    1.1 [1.7993    0.5] [1.7967    1.6]
1.6710   3.5  None  1.6717    4.5
1.6572   3.6  None  1.6592    2.2 [1.6602    0.4]                [1.6563  0.67]
1.5404   9.4  None  1.5415     10
1.4518   1.9  None  1.4529    2.2
                   <1.3821    6.7>
1.3716   7.7  None  1.3750    7.8
 "  "    "          1.3719    5.6
          * = Obscured    <..> = Missing    [..] = Previously Removed
```

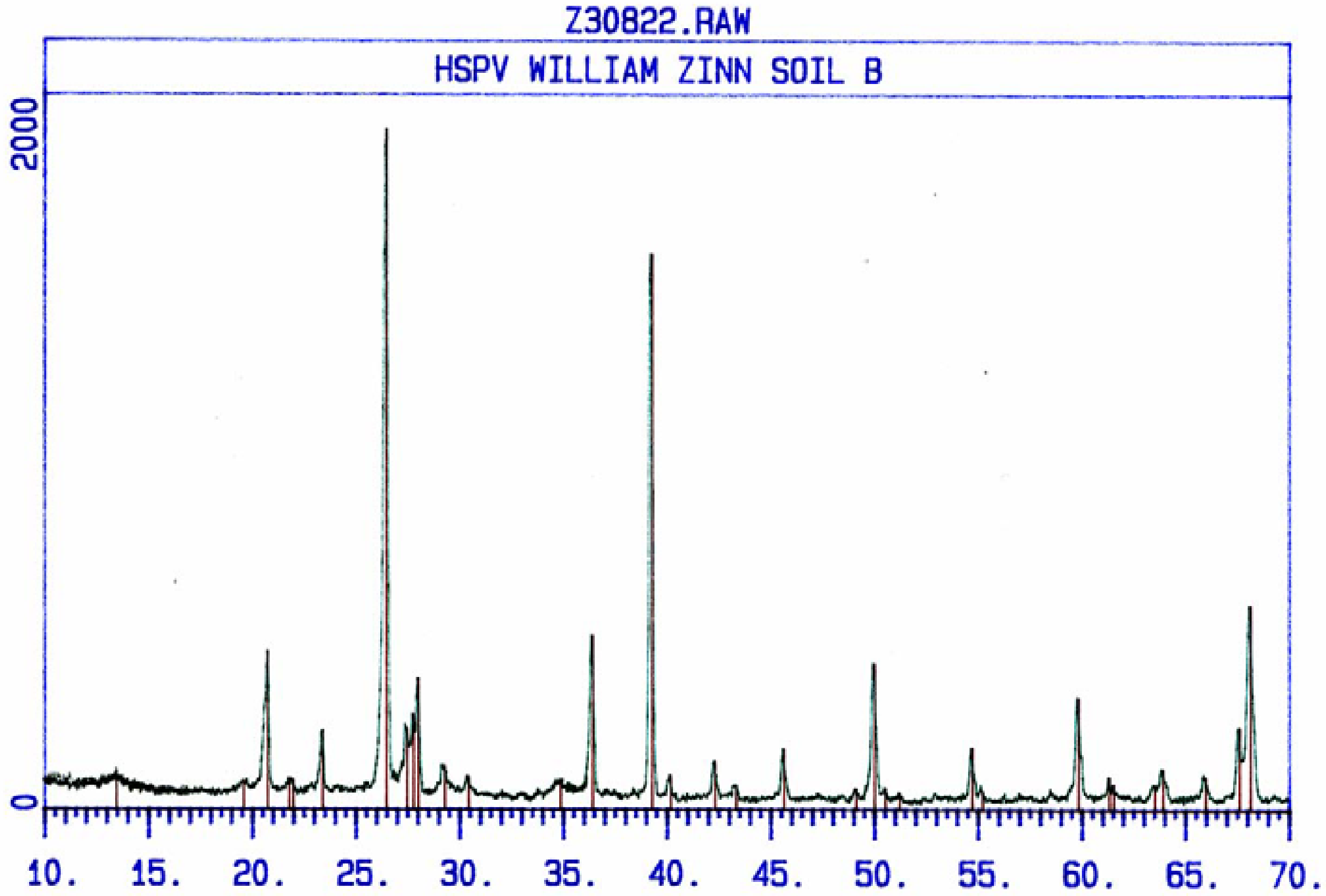
APPENDIX L: X-RAY DIFFRACTION ANALYSIS

Combined XRD Results for Soils from; Chaco-Top, Bandelier-Middle, Salinas-Bottom



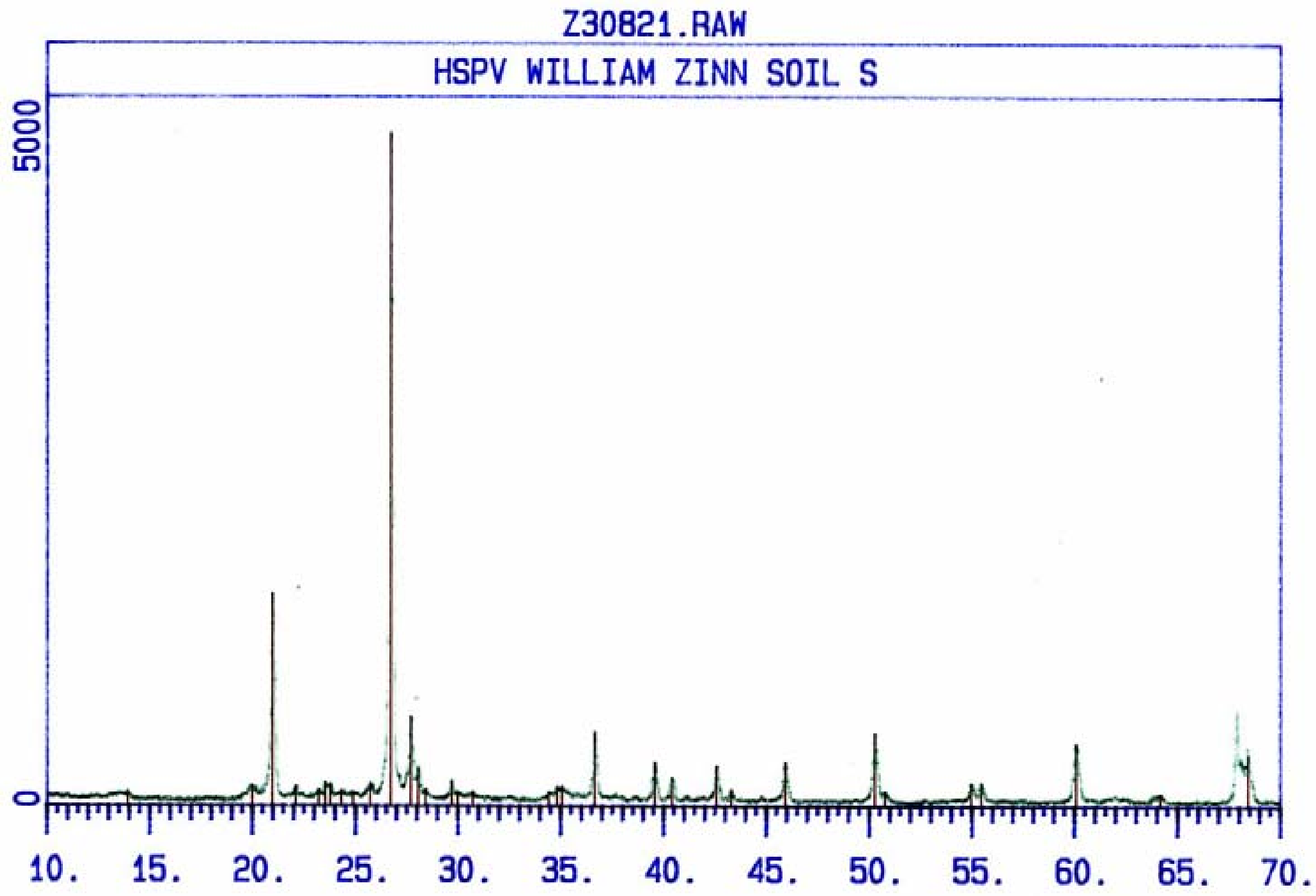
APPENDIX L: X-RAY DIFFRACTION ANALYSIS

XRD Results for Bandelier Garcia Landscape Materials Blend Soil



APPENDIX L: X-RAY DIFFRACTION ANALYSIS

XRD Results for Salinas Mountainair Local Quarry Soil



APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Bandelier National Monument

SOIL TEST RESULTS		Bandelier National Monument						
Test Type	**Test Description**	2 Alamo Bottoms	3 Alamo Bottoms	5 Frijolito Ruin	6 Frijolito Ruin	9 Tsankawi Ruin	12 Tsankawi Ruin	13 Tsankawi Ruin
Particle Size Distribution	**Hydrometer Analysis:**							
	% Sand (0.2-0.05 mm)	76.0	72.5	75.0	64.5	59.0	55.5	54.5
	% Silt (0.05-0.002 mm)	11.0	6.0	5.0	12.5	3.0	11.5	10.0
	% Clay (<0.002 mm)	13.0	21.5	20.0	23.0	38.0	33.0	35.5
	Total %	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Sand Sieve Analysis:							
	% very coarse (2.0-1.0 mm)	13.36	6.26	16.04	14.65	14.73	6.80	7.94
	% coarse (1.0-0.5 mm)	32.58	23.16	28.97	27.17	29.33	20.05	20.33
	% medium (0.5-0.25 mm)	22.54	21.40	18.41	21.48	18.85	19.09	15.02
	% fine (0.25-0.10 mm)	18.76	26.61	18.67	19.88	20.45	26.18	17.47
	% very fine (0.10-0.05 mm)	12.76	22.57	17.91	16.82	16.64	27.88	39.25
	Total %	100.00	100.00	100.00	100.00	100.00	100.00	100.01
Chemical (General)	**pH of Soil Paste**	7.7	8.2	8.1	7.1	7.1	8.3	7.2
	$CaCO_3$ (lime) Equivalent %	2.75	11.40	1.15	1.18	0.93	2.88	0.8
	Cation Exchange Capacity (me/100g)	15.23	13.49	14.79	18.71	12.18	17.40	16.1

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Bandelier National Monument

SOIL TEST RESULTS		**Bandelier National Monument**						
Test Type	**Test Description**	2 Alamo Bottoms	3 Alamo Bottoms	5 Frijolito Ruin	6 Frijolito Ruin	9 Tsankawi Ruin	12 Tsankawi Ruin	13 Tsankawi Ruin
Chemical (Soil-Water Extract)	**Electroconductivity (mmho)**	3.14	0.35	0.20	0.12	9.31	0.23	0.19
	Soluble Salts (ppm)	1302.0	200.9	127.1	150.8	5684.0	147.7	133.1
	pH of Soil Paste	7.0	8.1	7.4	7.3	7.1	7.7	7.2
	Ion Concentrations:							
	Calcium (mg/l or ppm)	520.0	13.0	10.0	5.0	2300.0	7.0	23.0
	Magnesium (mg/l or ppm)	25.3	0.9	0.7	1.1	89.6	0.9	2.0
	Sodium (mg/l or ppm)	196.0	23.0	4.6	4.3	260.0	3.5	17.3
	Chlorine (mg/l or ppm)	190.0	17.0	5.0	25.0	460.0	10.0	10.0
	Sulfate (mg/l or ppm)	267.0	60.0	41.0	78.0	228.0	44.0	45.0
	Bicarbonate (mg/l or ppm)	34.2	83.0	63.4	34.2	68.3	80.5	34.2
	Carbonate (mg/ml or ppm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Nitrate (mg/ml or ppm)	69.6	4.0	2.4	3.2	2278.0	1.8	1.6

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Bandelier National Monument

SOIL TEST RESULTS		Bandelier National Monument						
Test Type	**Test Description**	2 Alamo Bottoms	3 Alamo Bottoms	5 Frijolito Ruin	6 Frijolito Ruin	9 Tsankawi Ruin	12 Tsankawi Ruin	13 Tsankawi Ruin
Clay Mineralogy by x-ray Diffraction								
Montmorillonite	Tendency to Crack (hi/med/lo)	hi	hi	hi	hi	hi	hi	hi
	Amt: None (0)-Dominant (5)	3	0	1	1	NA	1	2
Mica (Illite)	Tendency to Crack (hi/med/lo)	lo	lo	lo	lo	lo	lo	lo
	Amt: None (0)-Dominant (5)	3	2	3	3	NA	4	3
Vermiculite	Tendency to Crack (hi/med/lo)	med	med	med	med	med	med	med
	Amt: None (0)-Dominant (5)	2	2	3	2	NA	1	3
Chlorite	Tendency to Crack (hi/med/lo)	lo	lo	lo	lo	lo	lo	lo
	Amt: None (0)-Dominant (5)	0	1	0	1	NA	0	0
Kaolinite	Tendency to Crack (hi/med/lo)	lo	lo	lo	lo	lo	lo	lo
	Amt: None (0)-Dominant (5)	2	2	3	3	NA	3	3
Interstratified	Tendency to Crack (hi/med/lo)	lo-med	lo-med	lo-med	lo-med	lo-med	lo-med	lo-med
	Amt: None (0)-Dominant (5)	2-3	4	3	2	NA	1	2

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Bandelier National Monument

SOIL-CEMENT TEST RESULTS		Bandelier National Monument						
Test Type and Description		2 Alamo Bottoms	3 Alamo Bottoms	5 Frijolito Ruin	6 Frijolito Ruin	9 Tsankawi Ruin	12 Tsankawi Ruin	13 Tsankawi Ruin
Strength			a		b		c	d
Unconfined Compressive Strength (psi) by Soil-to-Cement Ratio								
Ratio = 4:1 ,	**Compressive Strength =**	NA	802	NA	658	NA	722	777
Ratio = 6:1 ,	**Compressive Strength =**	NA	326	NA	348	NA	480	317
Ratio = 10:1 ,	**Compressive Strength =**	NA	169	NA	125	NA	264	122
Unconfined Compressive Strength (psi) by % of Sand Added to a 6:1 Soil-Cement								
% Sand = 0	**, Compressive Strength =**	NA	326	NA	348	NA	480	317
% Sand = 20	**, Compressive Strength =**	NA	297	NA	332	NA	273	304
% Sand = 40	**, Compressive Strength =**	NA	296	NA	310	NA	277	275
% Sand = 60	**, Compressive Strength =**	NA	259	NA	226	NA	241	264
Capillary Water Rise								
Capillary Rise (feet) by Soil-to-Cement Ratio								
Ratio = 1:0 ,	**Capillary Water Rise =**	NA	14.7	NA	11.6	NA	5.9	10.1
Ratio = 10:1 ,	**Capillary Water Rise =**	NA	24.1	NA	19.9	NA	27.6	21.0
Ratio = 6:1 ,	**Capillary Water Rise =**	NA	27.1	NA	23.8	NA	27.6	22.4
Ratio = 4:1 ,	**Capillary Water Rise =**	NA	28.9	NA	27.4	NA	28.1	27.5
Capillary Rise (feet) by % of Sand Added to a 6:1 Soil-Cement								
% Sand = 0	**, Capillary Water Rise =**	NA	27.1	NA	23.8	NA	27.6	22.4
% Sand = 20	**, Capillary Water Rise =**	NA	19.5	NA	18.4	NA	19.4	16.9
% Sand = 40	**, Capillary Water Rise =**	NA	12.4	NA	11.2	NA	14.1	14.8
% Sand = 60	**, Capillary Water Rise =**	NA	7.5	NA	8.1	NA	6.7	12.1

The added sand had the following origins: clean silica (a), Bandelier-7/Frijolito (b), Bandelier-10/Tsankawi (c), and Bandelier-14/Tyuounyi (d).

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Bandelier National Monument

STONE TEST RESULTS	Bandelier National Monument						
Test Type and Description	2 Alamo Bottoms	3 Alamo Bottoms	5 Frijolito Ruin	6 Frijolito Ruin	9 Tsankawi Ruin	12 Tsankawi Ruin	13 Tsankawi Ruin
Source of Stone	NA	Bandelier Alamo Bottoms	NA	Bandelier Frijolito Ruin	NA	Bandelier Frijolito Ruin	Tyuounyi Ruin
Description of Stone	NA	WVT (Weathered volcanic tuff)	NA	WVT	NA	1) Highly welded VT 2) Highly WVT	1) Highly welded VT 2) WVT
Compressive Strength (psi)	NA	840	NA	970	NA	1) 10,350 2) 440	1) 13,340 2) 970
Estimated Capillary Rise Potential (feet)	NA	57	NA	50.6	NA	1) impervious 2) >70	1) 9.9 2) 22.6
Comments	NA	High capillarity, readily transmits H_2O.	NA	High capillarity, readily transmits H_2O.	NA	Two stone types were analyzed separately.	Two stone types were analyzed separately.

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Bandelier National Monument

COMMENTS: Bandelier National Monument
USEFULNESS OF SOIL AS UNAMENDED MUD MORTAR OR PLASTER

2 Alamo Bottoms	Particle Size Distribution[1]	**Though somewhat high in sand and low in clay, the distribution would likely work.**
	Sand Size Distribution[2]	Sand size distribution is **suitable, favoring coarse**.
	Clay Mineral Composition[3]	The level of swelling clays, montmorillonite and vermiculite, is **excessive**.
	Soluble Salts[4]	The content of soluble salts is **excessively high, exceeding** 1000 ppm.
	Liquid Limit: % Water[5]	The limit for the water content of this soil is **not available**.
	Summary	**Marginal: Excessive swelling clays and soluble salts will likely lead to cracking.**
3 Alamo Bottoms	Particle Size Distribution[1]	**The clay-sand-silt distribution of this soil is in the ideal range.**
	Sand Size Distribution[2]	Sand size is >49% fine and very fine; **still usable despite reduced strength**.
	Clay Mineral Composition[3]	The level of swelling clays is **acceptably low**.
	Soluble Salts[4]	The content of soluble salts is **acceptable being well below** 1000 ppm.
	Liquid Limit: % Water[5]	The limit for the water content of this soil is **25%**.
	Summary	**Useful: Soil should work very well as an unamended mortar.**
5 Frijolito Ruin	Particle Size Distribution[1]	**The clay-sand-silt distribution of this soil is in the ideal range.**
	Sand Size Distribution[2]	Sand size distribution is **very suitable, favoring coarse**.
	Clay Mineral Composition[3]	The level of swelling clays is **moderate, resulting in a slight tendency for cracking**.
	Soluble Salts[4]	The content of soluble salts is **acceptable being well below** 1000 ppm.
	Liquid Limit: % Water[5]	The limit for the water content of this soil is **not available**.
	Summary	**Useful: Soil should work well as an unamended mortar.**
6 Frijolito Ruin	Particle Size Distribution[1]	**The clay-sand-silt distribution of this soil is in the favorable range.**
	Sand Size Distribution[2]	Sand size distribution is **very suitable, favoring coarse**.
	Clay Mineral Composition[3]	The level of swelling clays is **acceptably low**.
	Soluble Salts[4]	The content of soluble salts is **acceptable being well below** 1000 ppm.
	Liquid Limit: % Water[5]	The limit for the water content of this soil is **27%**.
	Summary	**Useful: Soil should work very well as an unamended mortar.**

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Bandelier National Monument

COMMENTS: Bandelier National Monument **USEFULNESS OF SOIL AS UNAMENDED MUD MORTAR OR PLASTER**		
9 **Tsankawi** **Ruin**	Particle Size Distribution[1]	**Sand content is low and clay high. Add coarse masonry sand in sand:soil ratio 1:3.**
	Sand Size Distribution[2]	Sand size distribution is **very suitable, favoring coarse**.
	Clay Mineral Composition[3]	**Data on clay mineral composition are not available.**
	Soluble Salts[4]	The content of soluble salts is **excessively high, greatly exceeding** 1000 ppm.
	Liquid Limit: % Water[5]	The limit for the water content of this soil is **not available**.
	Summary	**Unacceptable: Soluble salts ~6 times recommended limits will lead to cracking.**
12 **Tsankawi** **Ruin**	Particle Size Distribution[1]	**Sand content is low and clay high. Add coarse masonry sand in sand:soil ratio 1:3.**
	Sand Size Distribution[2]	Sand is **54% fine/very fine**. Adding coarse masonry sand will greatly improve size distribution.
	Clay Mineral Composition[3]	The level of swelling clays is **acceptably low**.
	Soluble Salts[4]	The content of soluble salts is **acceptable being well below** 1000 ppm.
	Liquid Limit: % Water[5]	The limit for the water content of this soil is **28%**.
	Summary	**Useful: Soil should work very well as unamended mortar with sand added as above.**
13 **Tsankawi Ruin** **Ruin**	Particle Size Distribution[1]	**Sand content is low and clay high. Add coarse masonry sand in sand:soil ratio 1:3.**
	Sand Size Distribution[2]	Sand is **54% fine/very fine**. Adding coarse masonry sand will greatly improve size distribution.
	Clay Mineral Composition[3]	The level of swelling clays is **moderate, resulting in a slight tendency for cracking**.
	Soluble Salts[4]	The content of soluble salts is **acceptable being well below** 1000 ppm.
	Liquid Limit: % Water[5]	The limit for the water content of this soil is **not available**.
	Summary	**Useful: Soil with sand added as above should be a very good unamended mortar.**

[1] Optimum distribution: 20-25% clay, 60-70% sand, 0-10% silt. Low silt is best because of low strength and poor blending with clay.

[2] Coarse sand is superior to fine sand because properties of fine sand resemble those of silt.

[3] High montmorillonite or vermiculite in clay causes cracking from excessive shrinking/swelling with water desorption/absorption.

[4] Excessive (>1000 ppm) soluble salts can result in a mortar that is weakened by efflorescence and attraction of moisture.

[5] Maintaining water content of the soil at or near the liquid limit for the soil is recommended for mixing a mud mortar.

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Bandelier National Monument

COMMENTS: Bandelier National Monument

USEFULNESS OF SOIL IN SOIL-CEMENT MIXTURES

2 Alamo Bottoms	NA
3 Alamo Bottoms	This soil at a 4:1 soil:cement ratio is nearly the strength of the stone.[6] **Use a 5:1 or 6:1 ratio.**
	The capillary potential of all soil-cement mixes **fails** to exceed that of the stone[7], which is very high in this case.
	Do not add sand.[8] It effects compressive strength of the soil-cement little & further lowers capillary potential.
5 Frijolito Ruin	NA
6 Frijolito Ruin	This soil at all soil:cement ratios has strength less than that of the stone,[6] **meeting the criterion.**
	The capillary potential of all soil-cement mixes **fails** to exceed that of the stone[7], which is very high in this case.
	Do not add sand.[8] Soil's compressive strength compared to rock is low, & sand further lowers capillary potential.
9 Tsankawi Ruin	NA
12 Tsankawi Ruin	**Stone 1) All** soil:cement ratios **meet strength criterion**. Stone **2) Only** soil:cement = **10:1 meets strength criterion.**
	Stone 1) All soil:cement ratios meet capillary rise criterion. Stone 2) All soil-cements fail capillary rise criterion.
	Stone 1 ONLY) Add coarse masonry **sand in sand:soil ratio of 1:4** to meet strength criterion **for 4:1 or 6:1 soil-cements.**
13 Tsankawi Ruin Ruin	This soil at all soil:cement ratios has strength less than that of either stone 1 or 2,[6] **meeting the criterion.**
	Stone 1) All soil:cement ratios meet capillary rise criterion. Stone 2) Soil-cements of ratio >6:1 meet criterion.
	Do not add sand.[8] Soil's compressive strength compared to rock is low, & sand further lowers capillary potential.

---

[6] The strength of a soil-cement should be weaker than that of the stone.

[7] A soil-cement should have a greater capillary potential than the stone.

[8] Adding sand reduces the strength and capillary rise of the soil-cement mortar.

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Chaco Culture National Historic Park (Chaco Canyon)

SOIL TEST RESULTS		Chaco Canyon National Monument					
Test Type	**Test Description**	55.5 Chettro Kettle	Kin Bineola	55 Kin Ya'a	58.5 Pueblo Alto	Trash Pit	Tzin Kletzin
Particle Size Distribution	**Hydrometer Analysis:**						
	% Sand (0.2-0.05 mm)	74.0	55.5	87.0	77.0	74.0	83.5
	% Silt (0.05-0.002 mm)	13.0	27.5	7.0	10.5	11.0	9.5
	% Clay (<0.002 mm)	13.0	17.0	6.0	12.5	15.0	7.0
	Total %	100.0	100.0	100.0	100.0	100.0	100.0
	Sand Sieve Analysis:						
	% very coarse (2.0-1.0 mm)	2.50	0.94	0.46	0.92	1.33	0.27
	% coarse (1.0-0.5 mm)	6.39	5.33	1.33	3.83	6.40	2.64
	% medium (0.5-0.25 mm)	12.16	19.75	9.30	6.23	18.45	3.82
	% fine (0.25-0.10 mm)	58.50	48.39	70.07	61.42	62.19	64.46
	% very fine (0.10-0.05 mm)	20.46	25.59	18.84	27.59	11.60	28.81
	Total %	100.01	100.00	100.00	99.99	99.97	100.00
Chemical (General)	**pH of Soil Paste**	7.9	8.3	7.7	7.9	8.1	7.9
	$CaCO_3$ (lime) Equivalent %	3.98	2.03	0.80	2.50	1.78	1.18
	Cation Exchange Capacity (me/100g)	13.49	15.66	4.68	8.27	9.14	6.20

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Chaco Culture National Historic Park (Chaco Canyon)

SOIL TEST RESULTS		Chaco Canyon National Monument					
Test Type	**Test Description**	55.5 Chettro Kettle	Kin Bineola	55 Kin Ya'a	58.5 Pueblo Alto	Trash Pit	Tzin Kletzin
Chemical (Soil-Water Extract)	**Electroconductivity (mmho)**	0.96	0.18	0.09	0.57	0.26	0.09
	Soluble Salts (ppm)	557.0	98.5	78.9	293.7	111.3	55.8
	pH of Soil Paste	7.3	7.5	7.3	7.6	7.3	7.4
	Ion Concentrations:						
	Calcium (mg/l or ppm)	169.0	9.0	8.0	54.0	27.0	7.0
	Magnesium (mg/l or ppm)	7.2	0.5	11.0	8.6	5.3	0.9
	Sodium (mg/l or ppm)	86.0	19.7	4.3	60.0	11.2	2.5
	Chlorine (mg/l or ppm)	49.0	7.0	7.0	55.0	6.0	4.0
	Sulfate (mg/l or ppm)	168.0	6.0	3.0	45.0	6.0	5.0
	Bicarbonate (mg/l or ppm)	39.0	48.8	43.9	43.9	53.7	34.2
	Carbonate (mg/ml or ppm)	0.0	0.0	0.0	0.0	0.0	0.0
	Nitrate (mg/ml or ppm)	39.0	7.5	1.7	27.2	2.0	2.2
Clay Mineralogy by x-ray Diffraction							
Montmorillonite	Tendency to Crack (hi/med/lo)	hi	hi	hi	hi	hi	hi
	Amt: None (0)-Dominant (5)	4	5	1	0	4	0
Mica (Illite)	Tendency to Crack (hi/med/lo)	lo	lo	lo	lo	lo	lo
	Amt: None (0)-Dominant (5)	3	3	3-4	3	3	3
Vermiculite	Tendency to Crack (hi/med/lo)	med	med	med	med	med	med
	Amt: None (0)-Dominant (5)	3	3	NA	2-3	4	2
Chlorite	Tendency to Crack (hi/med/lo)	lo	lo	lo	lo	lo	lo
	Amt: None (0)-Dominant (5)	2	0	0	1	0	1
Kaolinite	Tendency to Crack (hi/med/lo)	lo	lo	lo	lo	lo	lo
	Amt: None (0)-Dominant (5)	3	2	3-4	4	3	4
Interstratified	Tendency to Crack (hi/med/lo)	lo-med	lo-med	lo-med	lo-med	lo-med	lo-med
	Amt: None (0)-Dominant (5)	1	0-1	2-3	2-3	1	2-3

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Chaco Culture National Historic Park (Chaco Canyon)

SOIL-CEMENT TEST RESULTS		Chaco Canyon National Monument					
Test Type and Description		55.5 Chettro Kettle	Kin Bineola	55 Kin Ya'a	58.5 Pueblo Alto	Trash Pit	Tzin Kletzin
Strength		e	f	f	f	f	f
Unconfined Compressive Strength (psi) by Soil-to-Cement Ratio							
Ratio = 4:1 ,	**Compressive Strength =**	447	338	336	414	380	444
Ratio = 6:1 ,	**Compressive Strength =**	153	320	224	293	286	310
Ratio = 10:1 ,	**Compressive Strength =**	144	176	188	158	145	133
Unconfined Compressive Strength (psi) by % of Sand Added to a 6:1 Soil-Cement							
% Sand = 0	**, Compressive Strength =**	153	320	224	293	286	310
% Sand = 20	**, Compressive Strength =**	126	308	198	275	282	286
% Sand = 40	**, Compressive Strength =**	112	258	192	289	250	258
% Sand = 60	**, Compressive Strength =**	108	266	180	239	201	259
Capillary Water Rise							
Capillary Rise (feet) by Soil-to-Cement Ratio							
Ratio = 1:0 ,	**Capillary Water Rise =**	14.8	6.6	2.5	3.7	NA	13.6
Ratio = 10:1 ,	**Capillary Water Rise =**	17.9	14	4.4	16.9	17.4	13.7
Ratio = 6:1 ,	**Capillary Water Rise =**	20.9	15.7	5.7	23.8	16.7	14.2
Ratio = 4:1 ,	**Capillary Water Rise =**	26.7	19.1	8.7	28.8	17.4	17.3
Capillary Rise (feet) by % of Sand Added to a 6:1 Soil-Cement							
% Sand = 0	**, Capillary Water Rise =**	20.9	15.7	5.7	23.8	16.7	14.2
% Sand = 20	**, Capillary Water Rise =**	14.6	10	3.6	17.3	11.4	7.1
% Sand = 40	**, Capillary Water Rise =**	13.1	8.3	3.3	13.1	7.9	5.1
% Sand = 60	**, Capillary Water Rise =**	9.8	7	2.7	10.9	4.8	2.9

The added sand had the following Chaco Canyon origins: Chettro Kettle (e), and Big Wash (f).

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Chaco Culture National Historic Park (Chaco Canyon)

STONE TEST RESULTS	Chaco Canyon National Monument					
Test Type and Description	Chettro Kettle	Kin Bineola	Kin Ya'a	Pueblo Alto	Trash Pit	Tzin Kletzin
Source of Stone	Chaco Chettro Kettle	Chaco Rock Pit	Chaco Rock Pit	Chaco Pueblo Alto	Rock Pit, Chettro Kettle, Pueblo Alto	Chaco Rock Pit
Description of Stone	Well cemented sandstone	Relatively friable fine-grained sandstone	Relatively friable fine-grained sandstone	Friable fine-grained sandstone	See corresponding cells at left.	Relatively friable fine-grained sandstone
Compressive Strength (psi)	17,790	2210	2210	1290	See corresponding cells at left.	2210
Estimated Capillary Rise Potential (feet)	5.4	63	63	70	See corresponding cells at left.	63
Comments	Strong hard sandstone resists moisture.	No stone submitted from Kin Bineola.	No stone submitted from Kin Ya'a.	Weak, poorly cemented, readily transmits H_2O.	See corresponding cells at left.	No stone submitted from Tzin Kletzin.

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Chaco Culture National Historic Park (Chaco Canyon)

COMMENTS: Chaco Canyon National Monument **USEFULNESS OF SOIL AS UNAMENDED MUD MORTAR OR PLASTER**		
55.5 **Chettro** **Kettle**	Particle Size Distribution^1	**This low-clay, high-silt soil has relatively low compressive strength.**
	Sand Size Distribution^2	Sand is **74% fine/very fine**. This is not good for strength and erosion-resistance.
	Clay Mineral Composition^3	The level of swelling clays, montmorillonite and vermiculite, is **excessive**.
	Soluble Salts^4	The content of soluble salts is **acceptable being below** 1000 ppm.
	Liquid Limit: % Water^5	The limit for the water content of this soil is **24%**.
	Summary	**Unacceptable: Low clay content and excessive swelling clays promote cracking.**
Kin **Bineola**	Particle Size Distribution^1	**This low-sand, low-clay, high-silt soil has relatively low compressive strength.**
	Sand Size Distribution^2	Sand is **fine/very fine**. This is not good for strength and erosion-resistance.
	Clay Mineral Composition^3	The level of swelling clays, montmorillonite and vermiculite, is **excessive**.
	Soluble Salts^4	The content of soluble salts is **acceptable being well below** 1000 ppm.
	Liquid Limit: % Water^5	The limit for the water content of this soil is **25%**.
	Summary	**Unacceptable: Low clay content, swelling clays promote cracking, high silt weakens.**
55 **Kin** **Ya'a**	Particle Size Distribution^1	**This low-clay, high-sand soil will make a very weak mortar.**
	Sand Size Distribution^2	Sand in this 87%-sand soil is **89% fine/very fine**, greatly reducing strength/erosion-resistance.
	Clay Mineral Composition^3	The level of swelling clays is **acceptably low**.
	Soluble Salts^4	The content of soluble salts is **acceptable being well below** 1000 ppm.
	Liquid Limit: % Water^5	The limit for the water content of this soil is **21%**.
	Summary	**Unacceptable: Soil has very low clay content and dominance of fine sand.**

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Chaco Culture National Historic Park (Chaco Canyon)

COMMENTS: Chaco Canyon National Monument **USEFULNESS OF SOIL AS UNAMENDED MUD MORTAR OR PLASTER**		
58.5 Pueblo Alto	Particle Size Distribution[1]	**Soil will make a suitable mortar despite slightly low clay and high sand content.**
	Sand Size Distribution[2]	Sand in this 77%-sand soil is **89% fine/very fine**. This reduces strength/erosion-resistance.
	Clay Mineral Composition[3]	The content of swelling clays is **acceptably low**.
	Soluble Salts[4]	The content of soluble salts is **acceptable being well below** 1000 ppm.
	Liquid Limit: % Water[5]	The limit for the water content of this soil is **20%**.
	Summary	**Useful: Soil should probably work as unamended mortar despite high fine sand.**
Trash Pit	Particle Size Distribution[1]	**Clay content is slightly low & silt high but close enough to ideal limits to use soil.**
	Sand Size Distribution[2]	Sand is **74% fine/very fine**. This reduces strength/erosion-resistance.
	Clay Mineral Composition[3]	Content of swelling clays, montmorillonite/vermiculite, is **excessive, raising risk of cracking**.
	Soluble Salts[4]	The content of soluble salts is **acceptable being well below** 1000 ppm.
	Liquid Limit: % Water[5]	The limit for the water content of this soil is **20%**.
	Summary	**May be Unacceptable: Use alternative soil if test adobe fails by cracking.**
12 Tzin Kletzin	Particle Size Distribution[1]	**Clay content of only 7% is too low for optimum mortar strength.**
	Sand Size Distribution[2]	Sand is 93**% fine/very fine**. This greatly reduces strength/erosion-resistance.
	Clay Mineral Composition[3]	The content of swelling clays is **acceptably low**.
	Soluble Salts[4]	The content of soluble salts is **acceptable being well below** 1000 ppm.
	Liquid Limit: % Water[5]	The limit for the water content of this soil is **25%**.
	Summary	**Unacceptable: Very high-/fine-sand and low-clay cause easily weathered mortars.**

[1] Optimum distribution: 20-25% clay, 60-70% sand, 0-10% silt. Low silt is best because of low strength and poor blending with clay.

[2] Coarse sand is superior to fine sand because properties of fine sand resemble those of silt.

[3] High montmorillonite or vermiculite in clay causes cracking from excessive shrinking/swelling with water desorption/absorption.

[4] Excessive (>1000 ppm) soluble salts can result in a mortar that is weakened by efflorescence and attraction of moisture.

[5] Maintaining water content of the soil at or near the liquid limit for the soil is recommended for mixing a mud mortar.

APPENDIX M: Data from Previous Research Conducted by D. Fenn (1978)
Chaco Culture National Historic Park (Chaco Canyon)

COMMENTS:	Chaco Canyon National Monument USEFULNESS OF SOIL IN SOIL-CEMENT MIXTURES
55.5 Chettro Kettle	This soil at all soil:cement ratios tested has strength less than that of the stone,[6] **meeting the criterion.**
	The capillary potential of all soil-cement mixes exceeds that of the stone[7], **meeting the criterion**.
	Do not add sand.[8] The soil already contains 74% sand.
Kin Bineola	This soil at all soil:cement ratios tested has strength less than that of the stone,[6] **meeting the criterion.**
	The capillary potential of all soil-cement mixes **fails** to exceed that of the stone[7], which is very high in this case.
	Do not add sand.[8] The addition of sand is acceptable but unnecessary.
55 Kin Ya'a	This soil at all soil:cement ratios tested has strength less than that of the stone,[6] **meeting the criterion.**
	The capillary potential of all soil-cement mixes **fails** to exceed that of the stone[7], which is very high in this case.
	Do not add sand.[8] The soil already contains 87% sand.
58.5 Pueblo Alto	This soil at all soil:cement ratios tested has strength less than that of the stone,[6] **meeting the criterion.**
	The capillary potential of all soil-cement mixes **fails** to exceed that of the stone[7], which is very high in this case.
	Do not add sand.[8] The soil already contains 77% sand.
Trash Pit	This soil at all soil:cement ratios tested has strength less than that of the stone,[6] **meeting the criterion.**
	Capillary potential of soil-cements **meets criterion for Chettro Kettle but not Rock Pit or Pueblo Alto stone**.
	Do not add sand.[8] The soil already contains 74% sand.
12 Tzin Kletzin	This soil at all soil:cement ratios tested has strength less than that of the stone,[6] **meeting the criterion.**
	The capillary potential of all soil-cement mixes **fails** to exceed that of the stone[7], which is very high in this case.
	Do not add sand.[8] The soil already contains 84% sand.

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[6] The strength of a soil-cement should be weaker than that of the stone.

[7] A soil-cement should have a greater capillary potential than the stone.

[8] Adding sand reduces the strength and capillary rise of the soil-cement mortar.

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