A FEASIBILITY STUDY OF PORTABLE SPECTROSCOPY FOR THE ANALYSIS OF MORTAR FROM THE HOUSE OF THE VESTALS

by

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(Under the Direction of Samuel E. Swanson)

ABSTRACT

Mortar samples from the House of the Vestals, in Pompeii, Italy, were examined with traditional analytical techniques, including X-ray fluorescence, X-ray diffraction and thin section analysis. These techniques were used to establish mineralogical and chemical profiles of the samples and to verify the results of experimental field methods. Results showed the lime-based binder was composed of calcite, and the volcanic sand aggregate contained leucite, clinopyroxene, plagioclase, sanidine and olivine crystals. Field analysis of the mortar *in situ* consisted of near-infrared (NIR) reflectance spectrometry with a portable FieldSpec 3 spectroradiometer. Key variances between samples fell within ~2000 – 2200nm and ~2250 – 2375nm, approximately where the major absorption bands appeared in a reference sample of pure calcite. This suggests the binder component of mortar is potentially useful for distinguishing different mortar types, and that this method of non-destructive analysis of the mortar *in situ* shows promise.

INDEX WORDS: Pompeii, construction, mortar; portable, near-infrared, spectroscopy

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CHAPTER 1

INTRODUCTION

The ancient city of Pompeii was preserved by fallen ash and lapilli from an eruption of Mount Somma-Vesuvius in 79CE. The ruins were discovered in the 1590s during construction for an aqueduct in the area, but remained buried until excavations began in 1748 (Ling 2005). One of the earliest city blocks ("*insula*") uncovered was in the northwestern corner of the city, Regio VI.1 (Figures 1.1, 2.1). Most of the damage to the walls throughout the city has occurred since rediscovery. Many fresco wall paintings have been chipped from the walls and moved to museums; ongoing exposure to the elements is weathering the wall stones and mortar. Much of the city, including parts of Regio VI.1, suffered extensive bomb damage during WWII (Descoeudres et al 1994**)**. Given the history of the site, the structures in Pompeii stand in surprisingly good condition, which presents a unique opportunity for archaeologists to study ancient building technologies and techniques on a large, city-wide scale. Architectural studies at ancient sites typically identify the materials used in wall construction and decoration, as well as the sequence of wall construction events throughout a structure's history. Popular techniques and preferences toward specific materials evolved with the city as Pompeii flourished (see Chapter 4), so structures are assessed to understand where they fit within the basic construction style time line as it is understood today. A better understanding of the materials and styles found in a given structure can lend insight, no matter how small, to the wider building economy of Pompeii.

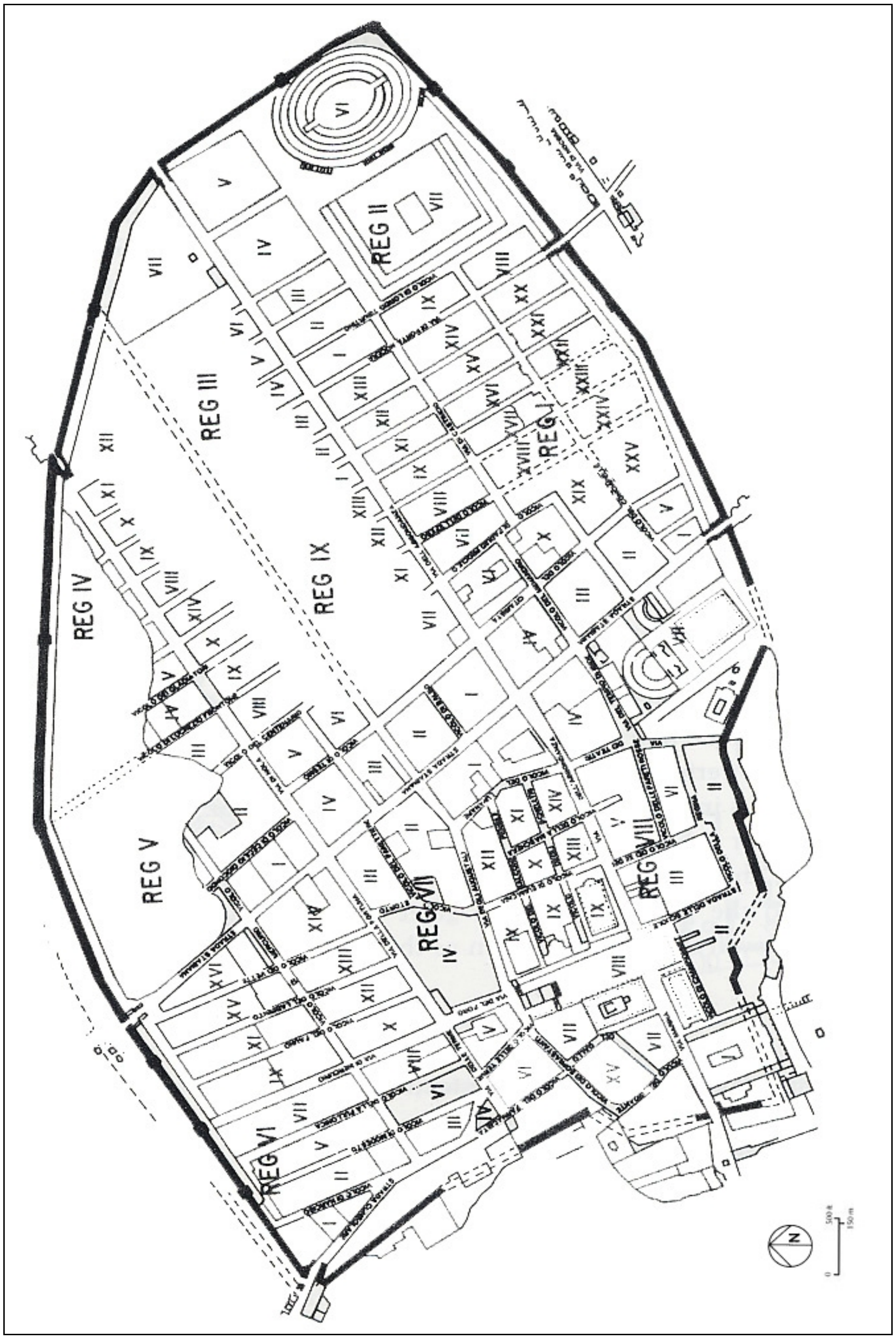

Figure 1.1: Plan-view map of ancient Pompeii. Source: Descoeudres et al (1994) after Eschebach (1970).

The walls of Pompeii were made of stone set in mortar. Construction mortar is a type of cement composed of a binder and an aggregate. The most common types of binder are mud, gypsum, or lime; however, historic mortars in Europe were mostly lime-based (Elsen 2006). For a lime-based mortar, a calcium carbonate ($CaCO_3$) material (e.g. limestone, dolostone) is burned in a kiln, where it is converted to calcium oxide (CaO) then mixed with water and an alumino-silicate aggregate (Figure 1.2; Leslie and Hughes 2002; Orchard 1973). Hydraulic mortars contain an additional pozzolanic material, which is typically volcanic ash that reacts with calcium hydroxide to produce cementitious calcium-silicate-hydrates (Funiciello et al 2006*)*. These compounds are actually minerals that form within the mortar during production, and they improve strength and durability (Taylor 1964).

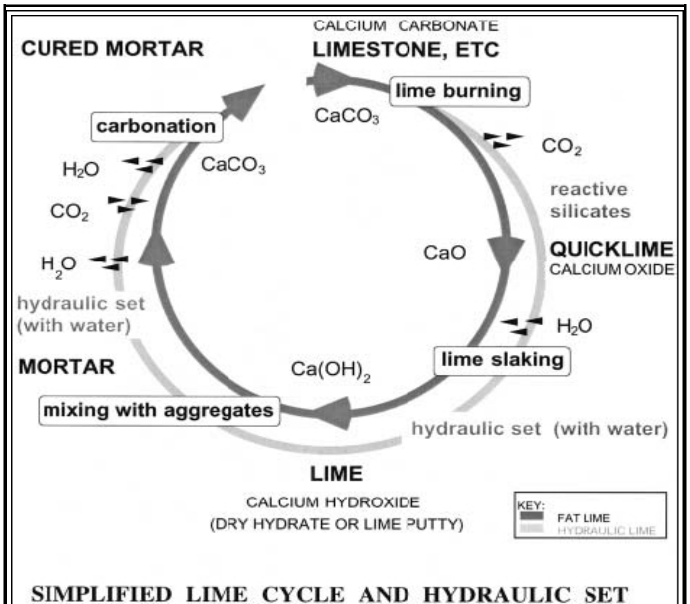

Figure 1.2: The Lime Cycle for pure limestone or calcium carbonate and impure limestones which form hydraulic limes. Source: Leslie and Hughes (2002).

Archaeometric analysis of binder and aggregate components of the mortar can reveal the nature of materials used in initial construction , as well as the current degree of post-construction decay (Arioglu and Acun 2006). The type, proportion and sorting of aggregate inclusions affect the performance of the mortar (Casadio et al. 2005); therefore, studies focused on these aspects have contributed to the understanding of ancient building technology. Mineralogical studies, including petrography and spectroscopy, are especially important because they can identify source materials (and potentially their provenance) and can detect alteration minerals resulting from weathering and decay (Signorelli et al. 1996). In cases where reconstruction or repointing - applying new mortar directly over the original wall - is intended, similar materials to the original mortar must be used to avoid destructive reactions between incompatible materials (Casadio et al. 2005). Compositional data can help conservators determine ideal materials for use in structure repair and conservation. This project will investigate the binder and aggregate components in mortars from the ancient House of the Vestals in Pompeii, Italy. The intent here is not comprehensive analysis of a complete structure, but rather an investigation of new non-destructive techniques for collecting and interpreting *in situ* data.

CHAPTER 2

A FEASIBILITY STUDY OF PORTABLE SPECTROSCOPY FOR THE ANALYSIS OF MORTAR FROM THE HOUSE OF THE VESTALS

The Anglo-American in Project in Pompeii (AAPP) conducted an excavation of Regio VI.1 from 1993-2007. The project's focus was the development of each of the properties within the unique triangular city block. Regio VI.1 was home to several types of structures, including large houses, industrial workshops, a possible shrine, an inn, and three bars (Figure 2.1). The block was flanked by a city gate to the north and on the south by a public fountain and street shrine. The variety of structure types - public and private, residential and commercial - provided a microcosm of life in ancient Pompeii, and the scale of excavations allowed a full study of the properties as they developed together. Architecture studies composed a large part of the project archive and consist primarily of visual analysis. and documentation of structures and current state of degradation.

The House of the Vestals was an elite house in Regio VI.1 when the eruption buried Pompeii in 79CE. In its final configuration, the house had been coalesced from several more modest structures (Jones and Robinson 2005). The final extent of the property spanned the width of Regio VI.1 and abutted the city walls on its northernmost end (Figure 2.2). Initial architectural study of the early phases of the House of the Vestals has shown pink mortar was used in properties VI.1.24 and VI.1.25[1], which were eventually incorporated into the final expanse of the

1 The addresses mentioned here are the traditional addresses created by archaeologiist Guiseppe Fiorelli in the 1860s (Ling 2005). The nomenclature represents properties in Regio VI, *insula* 1, and doorways 24 and 25. (see Figure 2.1)

elite house (Jones and Robinson 2005). Property VI.1.25 (Figure 2.1; Figure 2.2, Rooms 27-38) retained its basic original layout, but has undergone several reconstructions within the walls themselves. Excavation data and pottery dating information associated with wall construction trenches have shown that the distinctive pink mortar was used in two separate building phases: original construction of the smaller structures in the late 2nd century BCE and a later, Augustan-era (27 BCE - 14 CE) addition of the walls that form Room 35 (DeSena and Ikaheimo 2003).

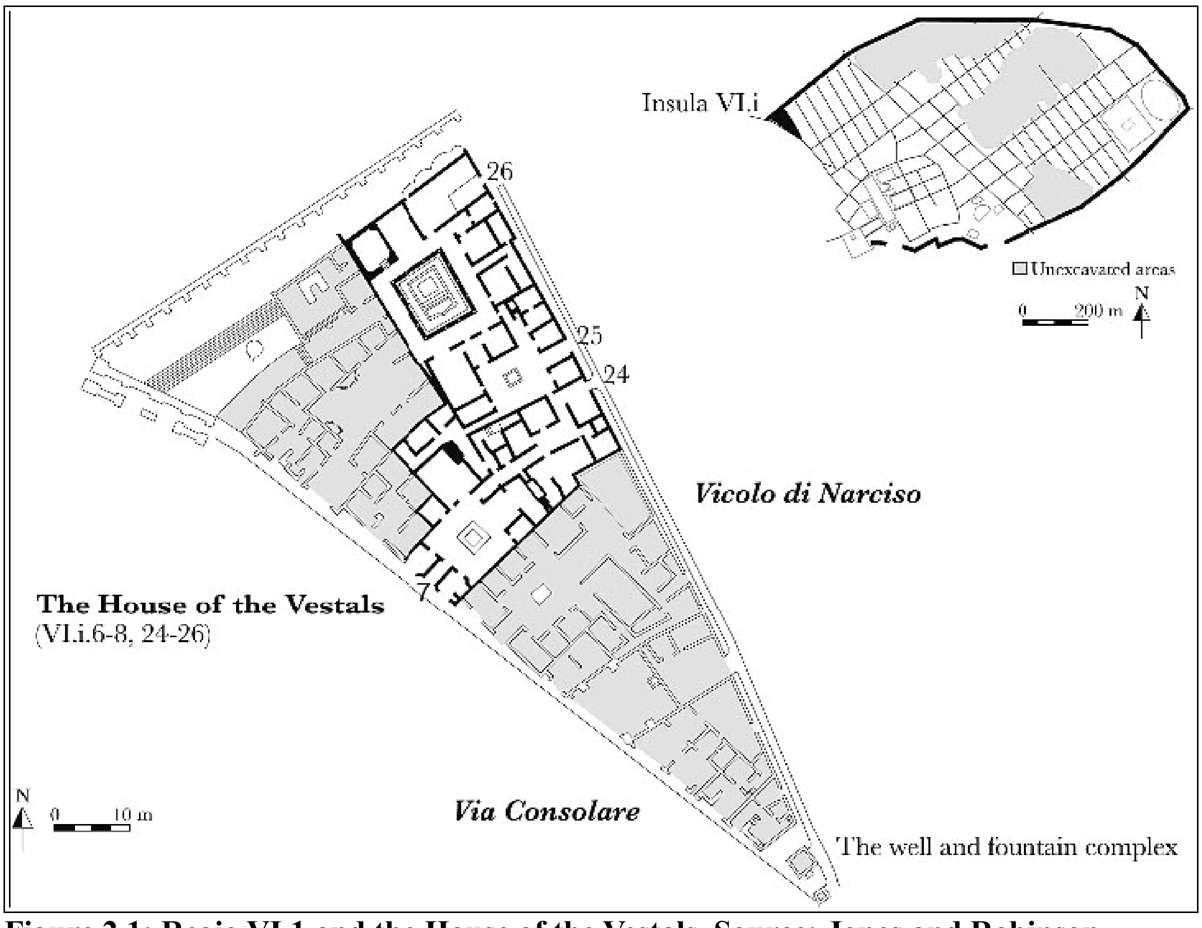

Figure 2.1: Regio VI.1 and the House of the Vestals. Source: Jones and Robinson (2004).

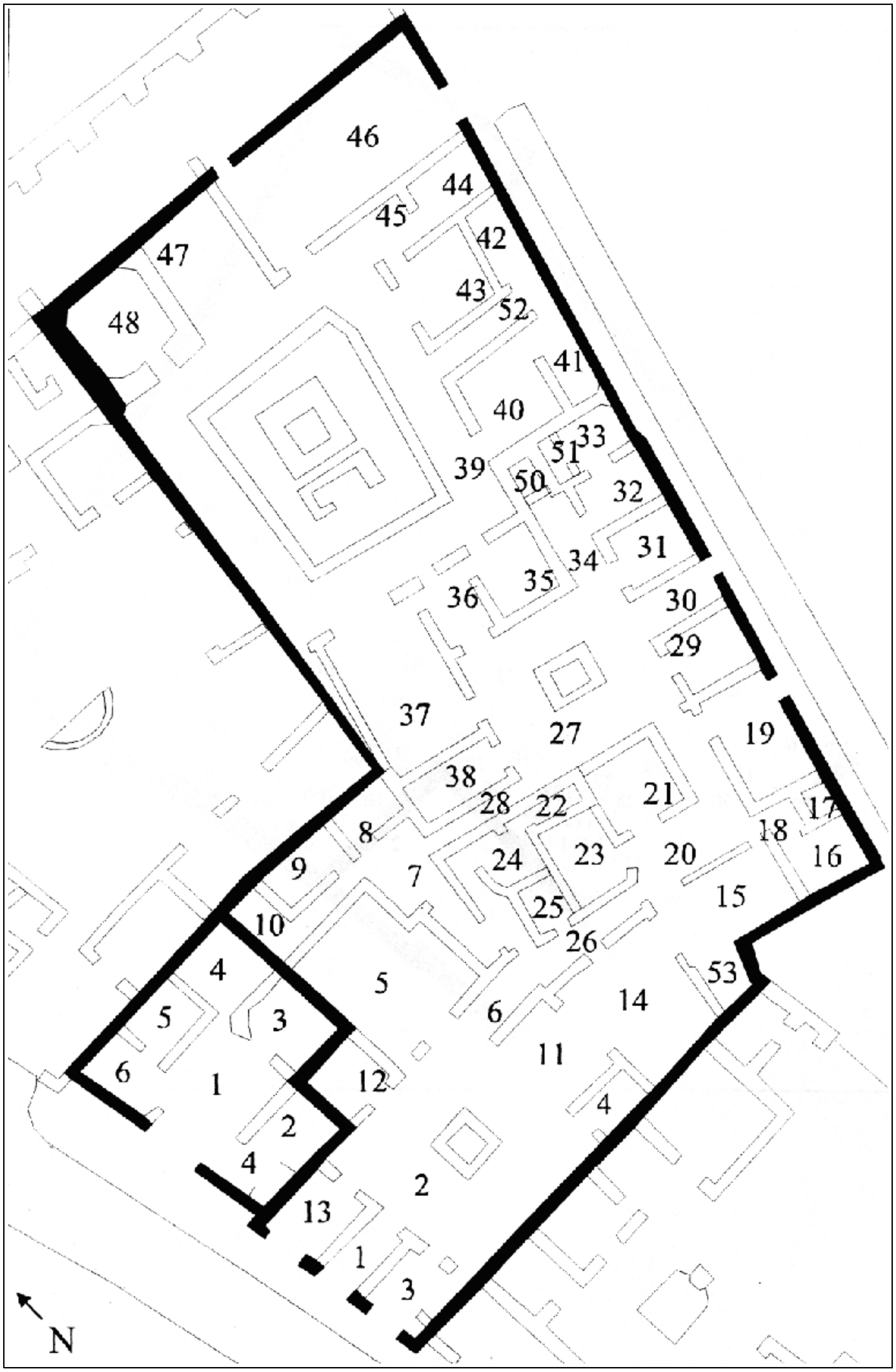

Figure 2.2: The House of the Vestals, with room numbers labeled. Source: AAPP (2005).

Currently, the AAPP is completing post-excavation work with artifact cataloging and analysis. Efforts are ongoing to correlate data from newly analysed material to strengthen and expand the archaeological interpretation of the study site. Researcher Jaye Pont (2007) has recently studied red slip pottery found in Region VI.1 with inductively coupled plasma mass spectrometry, resulting in a reinterpretation of context information for many structures and excavated deposits. The structural history as determined by associated excavation data could be strengthened (or discounted) in face of new information from further analysis of the construction materials. Mortar studies were included in the original research plan, but were given low priority due to time and budget constraints, as well as the potential for irreparable damage to walls during sample collection.

At a fragile monument such as Pompeii, researchers must mitigate potential damage to the site (and the artifacts) before sample selection and collection can begin. This is especially true for the study of standing structures and mortar, where the material under study is actually holding the artifact together, and deteriorating conditions can result in safety hazards. Mineralogical analysis can identify the materials used in mortar production, while binder:aggregate ratios and grain size distribution can reveal the ancient "recipe" of the mortar mixture (Casadio et al. 2005). The most common techniques for these types of analyses consume the sample during preparation, often including mechanical separation of the binder from the aggregate. This is problematic when individual samples are small and multiple analytical techniques are desired. Even the sample collection process damages the wall itself.

A field-based mobile laboratory would allow work to be conducted quickly *in* situ and with no further damage to the walls under study. Portable versions of vibrational spectroscopic equipment have been developed in the earth sciences in recent years for chemical and mineralogical analysis, and these techniques are emerging as useful tools in archaeology. Portable microscopes can peer into the surface of the mortar to illustrate the size and abundance of aggregate materials within the binder. The use of portable equipment could be ideal for non-destructive data collection where traditional consumable sampling techniques are impractical or impossible. Large data sets could be collected in the field, allowing for a more complete sampling of mortar types to account for the greatest amount of variance within a study site.

This project tests field-based methods of data collection for mortar analysis, including portable microscope imaging and portable near-infrared spectroscopy. This study is designed to demonstrate how well these techniques perform in a field setting and whether or not the data they produce are comparable to data collected with traditional techniques. The quality of the field-collected data will be evaluated on how well they reproduce the results expected after traditional laboratory analysis. The hypothesis tested here is that portable microscopy and portable vibrational spectroscopy are useful tools for *in situ* study of ancient structures.

CHAPTER 3

GEOLOGIC AND HISTORIC SETTING

Geologic Setting

The active subduction-related volcanoes along the western coast of Italy are relatively recent formations, less than 2 million years old (Locardi 1985). The Mediterranean Sea sits on convergent plate boundary, which means a section of the earth's crust (the African plate) is moving northward toward another (the European plate). Where they meet, the African plate is subducted under the European plate and down into the mantle. Melting associated with the sinking African plate causes volcanoes to form on the overriding European plate along the coast of Italy. The Appenine Mountains that form the spine of Italy and the Monti Lattari on the Sorrentine peninsula are also new geological features, having been formed from the uplift of Italy on the European plate that accompanies the subduction (Locardi 1985). These are limestone hills full of fresh water springs, which have been piped down to the Campanian plain since the first aqueducts were constructed (Ling 2005).

Pompeii is located in Italy's Campania region, near the Bay of Naples on the Mediterranean Sea (Figure 3.1). Campania is essentially a plain of volcanic material that has been laid down in successive beds as the now dormant Campi Flegrei volcanoes and the still active Mt Somma-Vesuvius have erupted over the millennia (Locardi 1985). The ancient city was settled atop an old lava flow from a Somma-Vesuvian eruption that covered a Bronze Age settlement in the 17th century BCE (Ranieri 1997). This location likely offered a good defensive position as well as useful proximity to the Sarno River (labeled "Sarnus" in Figure 3.1).

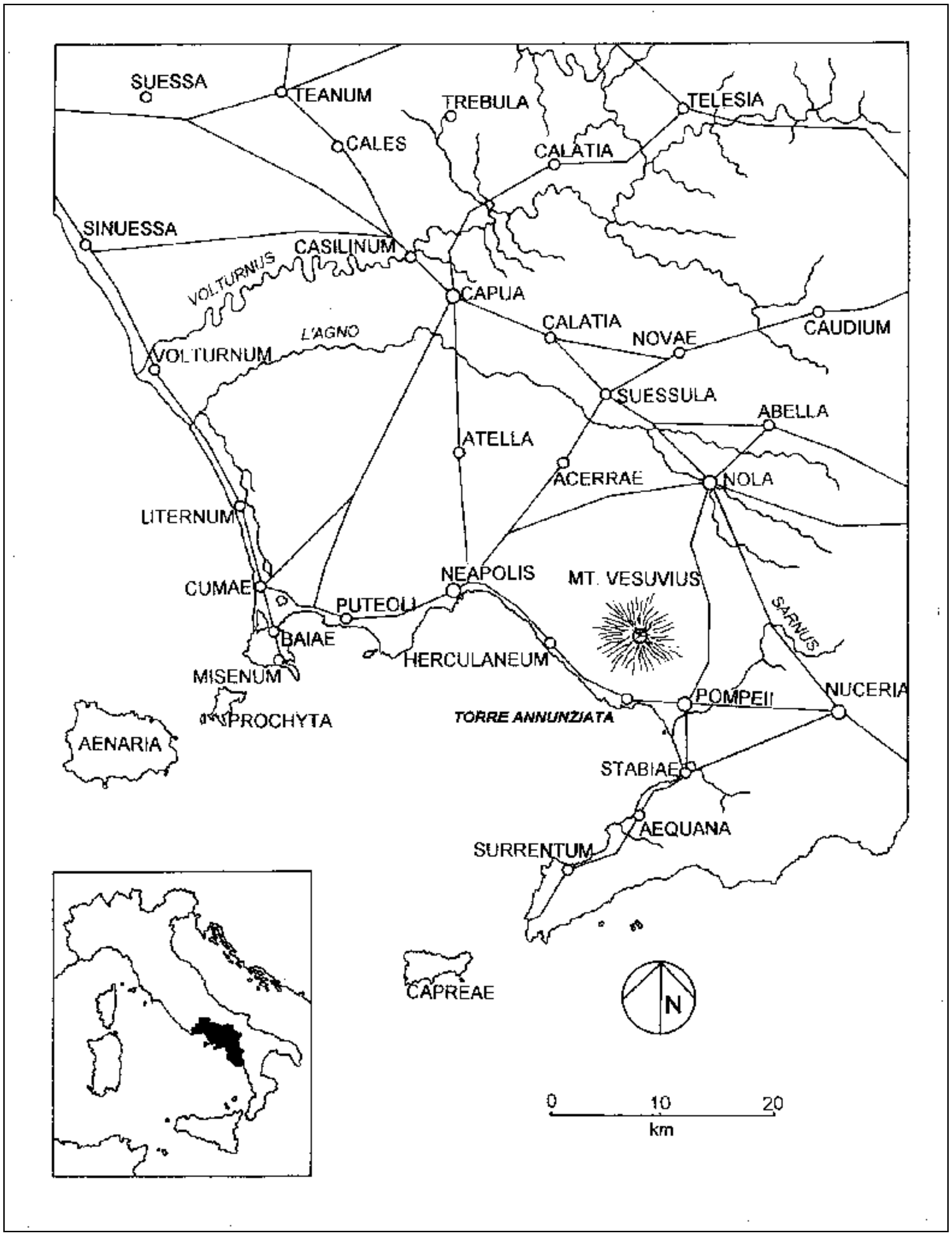

Figure 3.1: Map of Campania, Italy. Source: Descoeudres et al (1994).

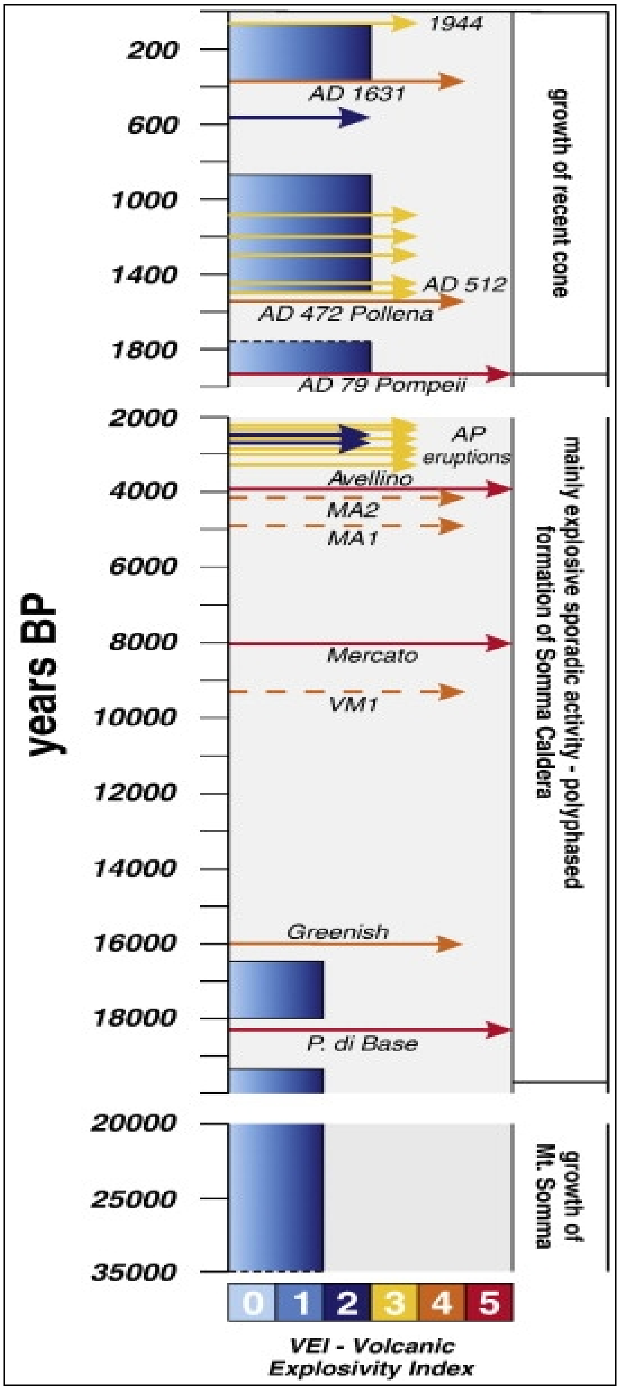

Figure 3.2: Schematic chronogram of Somma-Vesuvius activity. Arrows refer to explosive eruptions, length and colour reflect the estimated VEI. Breaks in the chronogram mark changes of time-scale. Source:Cioni et al 2008.

The eruption history of Somma-Vesuvius is well documented from 35,000 years before present (BP) (Figure 3.2). The initial cone, known as Mt Somma, produced mainly effusive eruptions, though it became more explosive in nature after the Pomici di Base plinian eruption ca 18k BP (Cioni et al 2008). Multiple collapses associated with the explosive events caused a caldera to form at the the summit of Mt Somma; the current cone, Mt Vesuvius, formed after the Pompeii Pumice eruption that buried ancient Pompeii in 79CE(Ciono et al 2008). Somma-Vesuvius is currently active, and its last eruption was a moderately explosive event in 1944 (Figure 3.2; Cioni et al 2008).

The primary igneous rock types in the region of Somma-Vesuvius are trachytes, phonolites, tephrites, and phonolitic-tephrites (Cioni et al 2008; Andronico and Cioni (2002). These rock types are generally com-posed of minerals from the feldspar, pyroxene and feldspathoid groups (Le Maitre 2002). Fragmentation of these lavas during explosive eruptions is responsible for the wide-spread volcanic tuffs in the area. Such a volcanic tuff covered Pompeii in 79CE. Andronico and Cioni (2002) described the mineralogical and chemical composition of volcanic materials deposited in the region with the Somma-Vesuvian events between the Avellino and 79CE Pompeii Pumice eruptions (Figure 3.2). The authors collected 42 core samples from the Somma-Vesuvius fallout region and correlated the stratigraphy of each to six different eruptions. Cores contained the same mineral constituents, including plagioclase, sanidine, clinopyroxene, amphiboles and biotite in a leucitic groundmass. Mortars produced from these local materials should contain mineral phases from these groups.

Historic Setting

The Pre-Roman history of Pompeii and the Campanian region can be summarized as conquest and settlement by a succession of different cultural groups. Some of the earliest known settlements were of Greek origin in the 8th – 7th century BCE (Frederiksen 1984), followed by the Etruscans in the 6th century BCE (Richardson 1988). Even if it was not a fully Greek city, Pompeii was at least under Greek influence, as evidenced by the early Doric temple in the Triangular Forum. As a part of the *ager Nuceria*, Pompeii was under the control of Nuceria (modern Nocera) to the southeast, situated strategically at a narrow pass in the Monti Lattari (Figure 3.3) (Richardson 1988). From this point on, the Sarno river (and its use for shipping) was controlled from Pompeii (Ling 2005).

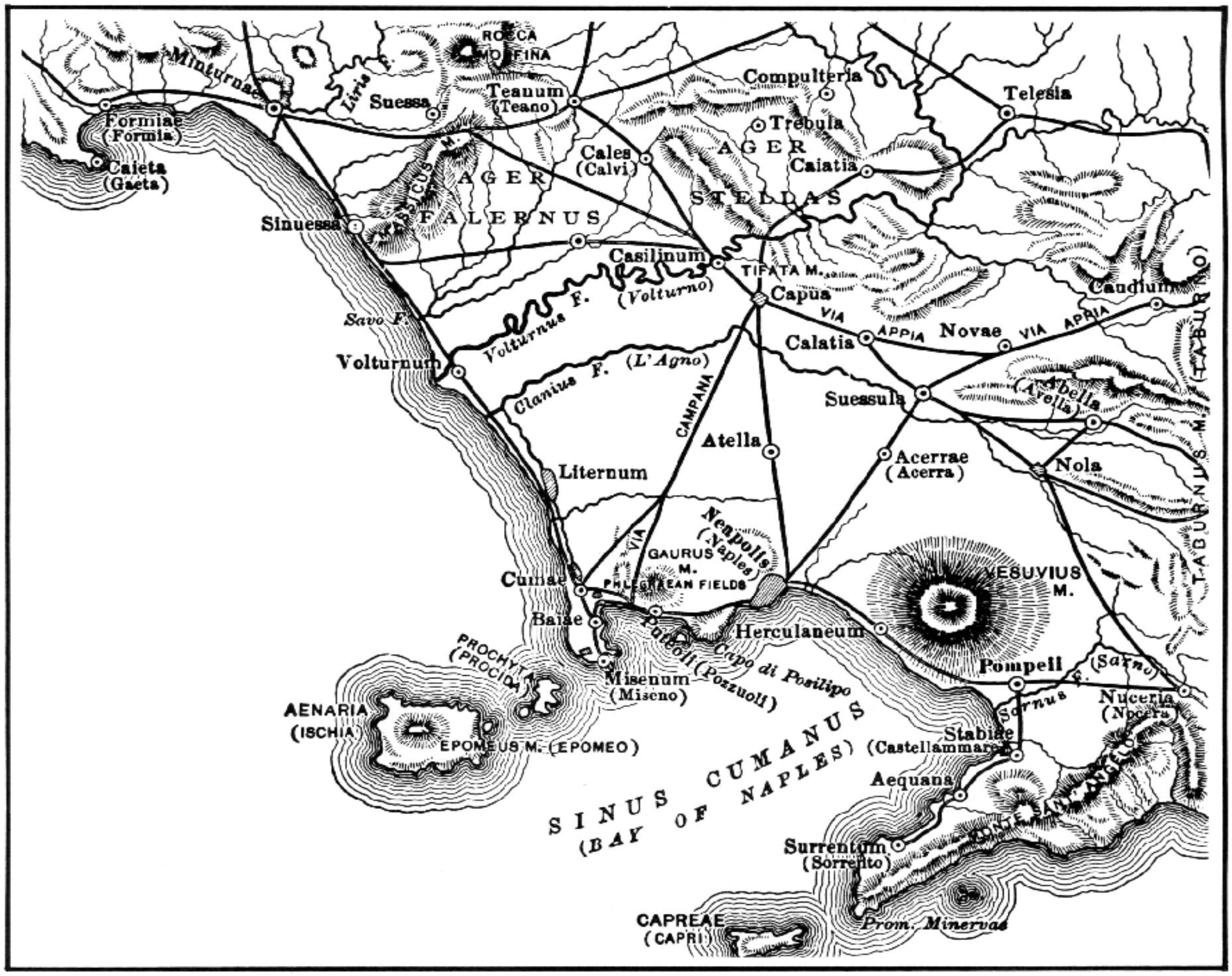

Figure 3.3: Map of ancient cities and road systems. Source: Mau 1899

By the 5th century BCE, the Greeks had been supplanted in southern Italy by the Oscans and Samnites (Frederiksen 1984). These groups were Italic tribes who lived along the coast and in the hills, respectively. They shared a language, Oscan, which survived in Pompeii in the form of inscriptions until the city's demise in 79CE (Cooley and Cooley 2004). Between the 5th and 3rd century BCE, the Samnites became fully entrenched in Pompeii, expanding the city to its full extent and current city layout, which grew outward from the *altstadt* ("old city") in the southwest (Ling 2005). This was a period of widespread reconstruction of both domestic and civic architecture. August Mau referred to this period as the "Period of the Limestone Atriums." This title refers to the construction of large houses with atria built in the *opus quadratum* style, also known as ashlar masonry, which utilized large blocks of limestone laid in horizontal courses (Mau 1899). Rome's influence during this time had expanded south to Capua, an important city located inland on the Via Appia (Frederiksen 2005). This may have been the impetus for a reinforcement of Pompeii's city walls in the 3rd century BCE (Richardson 1988).

A second city-wide expansion occurred in the 2nd century BCE, known as the "Tufa Period," so named for the introduction of a new type of building stone that Mau called "Nucerian Tufa" (Mau 1899). This period also saw the introduction of the *opus incertum* building style, again in both domestic and public architecture (Mau 1899). The city's expansion at this time apparently followed a growth in Pompeii's economy. The impetus for this economic boom is uncertain, but hypotheses include the growth of Pompeii as a trade port where the Sarno River met the Mediterranean and the birth of a ship-building industry for the burgeoning Roman navy (Richardson 1988). What is certain, however, is that by this time Pompeii had liberated itself from the control of Nuceria. Oscan inscriptions indicate the city was operating with fully autonomous local governmental and religious systems (Cooley and Cooley 2004).

From the 3rd BCE, Rome's influence continued to spread and strengthen throughout Campania, with several cities named as *coloniae* of Rome, though not all cities surrendered peacefully (Frederiksen 1984). Roman generals met with resistance at Pompeii, resulting in a siege by Lucius Cornelius Sulla in 89 BCE (Cooley and Cooley 2004). Sulla's attack left its mark on the city walls and properties located near the outermost edges of the city, especially those near the Herculaneum Gate (Jones and Robinson 2004). Sulla successfully conquered Pompeii, and in 80 BCE, a colony for Roman veterans was established in Pompeii by his nephew

Publius Cornelius Sulla (Cooley and Cooley 2004). Cicero, in his *Pro Sulla,* suggested the relationship between Samnites in Pompeii and new colonists was less than harmonious, and Roman influence was almost certainly felt (Cic. *Sul.60-62*). Electoral graffiti and funerary inscriptions from this time show that Romans had usurped public offices from Samnite families (Cooley and Cooley 2004). The Romans in Pompeii also imported 2nd Style wall paintings and the new construction styles *opus quasi-reticulatum* and *opus reticulatum* (Carrington 1933).

The Augustan era in Pompeii (27 BCE – 14 CE) saw the addition of still more Roman influence in the form of the Imperial Cult and its associated temples and shrines (Richardson 1988). Several structures were added to the Forum in a large-scale public building event, which included the Eumachia building, the macellum, and four (maybe five) “monumental arches” (Richardson 1988).t Brick work was first introduced during this period, most often used as doorway quoins in smaller structures (Carrington 1933). Still another city-wide reconstruction event occurred after a large earthquake rocked the city in 62 CE. The quake damaged many buildings, including much of the forum and adjacent structures. Yet another construction style, *opus mixtum*, was introduced during this time of massive repairs, which utilized both brick and stone (Carrington 1933). Reconstruction was still underway in some public and domestic structures when Mount Vesuvius erupted in 79CE, burying the city for nearly 2000 years (Ling 2005).

CHAPTER 4

CONSTRUCTION MATERIALS IN POMPEII

Italic stone masons developed an ingenious quarrying technique that allowed access to the stone while preserving arable land well above the quarry site (Adam 1994). The top layers of soil and weathered stone were removed to expose usable building stones. The quarry was terraced on the way down to a vertical face, and this stair-stepping provided small rubble and pebble-sized material. Stonecutters then moved inward, continuing underground, where large blocks of stone were cut from the "working face." A pillar of stone was left to provide support for the rock ceiling above. Volcanic tuffs (composed mostly of solidified ash) in Campania were perfect for this type of extraction, because these materials are relatively soft and easy to harvest. While this was not the only technique, it was very common, and the remains of these quarries can be found below modern cities like Naples (Funiciello *et al* 2006). The types of stone used for construction in Pompeii from the 2nd century BCE through the 1st century CE are described below.

Travertine

Travertine (Figure 4.1) is formed in the Sarno River valley, where lime-rich water flows from the Appenine Mountains into the lower volcanic plain (see Figure 3.1). Here, the river is warmed by volcanic springs, which causes the lime to precipitate and collect along the riverbed (Richardson 1988). The stone is lightweight and soft yet durable, and therefore easily quarried and cut to shape, though it is unsuitable for decorative carving or sculpting. This material, still quarried today, is believed to have been used in the earliest defensive stone walls of Pompeii (Richardson 1988), which Mau dates to roughly the 6th century BCE (Mau 1899). The city walls, and some early Pompeiian houses, utilized the *opus quadratum* construction technique, in which large blocks of travertine were laid in horizontal courses and bonded with mud or clay (Mau 1899). Another example of its early use is in the capitals of the Doric temple in the Triangular Forum (Richardson 1988).

Figure 4.1: Travertine. Photo by Damian Robinson.

The use of travertine, traditionally known as "Sarno limestone," was prevalent during Mau's Period of the Limestone Atriums (Mau 1899). This period started sometime after the beginning of the 5th century BCE, lasting until the end of the 3rd century BCE, the early period of Samnite occupation in Pompeii (Frederiksen 1984). Exterior walls and facades typically were constructed in the opus quadratum style, while the interior walls were constructed with limestone framework filled with rubble-sized fragments (Mau 1899). In the later phases of the city, travertine often was utilized in corners and doorways or as buried foundation stones. This material was later frequently reused, either as large blocks or broken into smaller brick- or rubble-sized fragments; therefore, it is difficult to assign reliable dates to a structure based solely on the presence of travertine (Mau 1899).

Lapis pompeianus

Lapis pompeianus ("stone of Pompeii") first came into use during the Tufa Period of 200-80 BCE as rubble-sized fill and foundation stones in *opus incertum* walls (Richardson 1988). This was a relatively peaceful and prosperous period in Pompeii's history that saw a substantial city-wide expansion (Ling 2005). *Lapis pompeianus* was used widely throughout the northwestern part of Regio VI, but it occurs throughout the city (Kawamoto and Tatsumi 1992). As noted above, the stone was primarily used as rubble fill, but was also utilized for curbstones, paving stones, threshold stones, and grain mills (Richardson 1988).

Figure 4.2: *Lapis pompeianus*. Left: Clinopyroxene phyric lava; Right: phonolitic lava

Lapis pompeianus was probably quarried on the slopes of Vesuvius, based on comparative analysis of this stone and beds of volcanic material in situ (Kawamoto and Tatsumi 1992). However, the quarry site has not been found, as it likely has been covered by subsequent eruptions (Kawamoto and Tatsumi 1992). This material is solidified lava, cooled slowly, which allowed it to form large crystals. Two types were used together and are often equated in the literature, however, they each have a distinct appearance and mineral assemblage (Carrington 1933; Mau 1899). Clinopyroxene phyric lava stone contains mostly black clinopyroxene crystals, while phonolitic lava stone contains white leucite crystals in addition to clinopyroxene (Figure 4.2; Kawamoto and Tatsumi 1992).

Nucerian "tufa"

Nucerian tuff, what Mau called "Nucerian tufa," (Mau 1899) is a much utilized igneous rock composed of volcanic ash and rock fragments that have been cemented together by clay or zeolite minerals (Fisher *et al* 2006). This fine-grained grey stone was quarried near the ancient city of Nuceria (modern Nocera) at an opening of the Monti Lattari (see Figure 3.3) (Kawamoto and Tatsumi 1992). This material erupted from the Campi Flegrei region near Puteoli (modern Pozzuoli) about 30,000 years ago. The provenience of this stone was first identified by Mau in 1899 and later confirmed with chemical analysis by Kawamoto and Tatsumi (1992). Vitruvius recognized this stone, or at least something similar, as a viable building stone. In his *De Architectura (VII.1.5),* he recommended that soft stones and tuffs should be quarried in summer and left to dry for 2 years before use. This advice was in fact quite appropriate, because tuff can absorb enough water to compromise its structural integrity in a wall (Vaniman 2006).

The exploitation of Nucerian tuff in Pompeii began in earnest during what Mau labeled the Tufa Period, from 200 BCE – 80 BCE (Mau 1899; Richardson 1988). During this time, the material was utilized in large blocks for impressive structural features such as building facades and quoining (Figure 4.3), and tombs, impluvia, and altars, as well as threshold stones and curbstones (Richardson 1988). The stone is soft, friable, and suitable for carving. Its presence as rubble in *opus incertum* is uncommon, but does occur (Figure 4.3).

Figure 4.3: Nucerian tuff - left: rubble sized chunk in opus incertum wall (House of the Surgeon); right: large blocks used for doorway quoin (the Soap Factory, photo ©Soprintendenza di Pompeii).

Scoria

At the top of a lava flow, residual gas bubbles rise to the surface and are released as the lava cools which results in porous, friable material called scoria (Fisher et al 2006). The Italian word for scoria is "cruma," and the ancient Pompeiians may have quarried it from the volcanic bed directly below Pompeii (Kawamoto and Tatsumi 1992). Local scoria contains the same type of clinopyroxene and leucite crystals as *lapis pompeianus* and is typically a dark red to black color. This material was used as rubble-fill in *opus incertum* walls and was crushed for use as aggregate in mortar. (Figure 4.4). The date of its use is unclear, as it seems to survive mostly in wall repairs or doorway and window fills.

Figure 4.4: Red scoria in a wall repair in the House of the Vestals.

Yellow tuff

Yellow tuff is solidified volcanic ash from an eruption in the Campi Flegrei region 11,000 years ago (Kawamoto and Tatsumi 1992). Chemical analysis has confirmed that this stone, sometimes called "Neapolitan tuff," was quarried from the region of Puteoli (modern Pozzuoli) (see Figure 3.3) (Richardson 1988). It was quarried with the tunnel method, though typically was used as smaller brick-sized blocks, rather than in large blocks (as in Nucerian tuff or Sarno limestone). Yellow tuff was often found in walls of the *opus mixtum* construction style or in reconstructions and door or window blocking fills in *opus incertum* walls (Figure 4.5). Carrington describes a "yellow tufa" (which is a sedimentary rock, also under Pompeii), primarily used in the *opus mixtum* construction style, dating to the 1st century CE (Carrington 1933). This may be a confusion caused by Mau's misidentification of tuff as tufa, but it is not clear if he was referring to the sedimentary tufa or volcanic tuff, which appears about this time.

Figure 4.5: Reconstructed bar counter, Bar of Phoebus. Yellow tuff is on right side of photo.

White limestone

White limestone, also called "Caserta stone," was quarried at the foot of the Appenines to the north of Vesuvius, near the major inland city of Capua (see Figure 3.3) (Richardson 1988). This is a "fine-grained white limestone with very few veins or flaws," which gives it added strength and integrity (Richardson 1988). The first known use was in decorative flooring elements before mosaics were common (Richardson 1988). This limestone was utilized more often for decorative or finishing elements (such as inscriptions, thresholds, impluvia, and cistern heads) than in weight bearing walls (Richardson 1988). Caserta stone was the only imported stone that required a land route. This likely made it an expensive stone, which may account for its limited use. It was used for the bright white colonnade in the Forum, constructed in the 1st century CE, in temples, and famously, the weight standards table – the *mensa ponderaria* of Samnite origin – in the forum (Mau 1899; Richardson 1988). Caserta stone was generally replaced by marble for inscriptions at the onset of the Augustan period, but was still used for thresholds and pavement stones until the destruction of Pompeii (Richardson 1988).

Figure 4.6: White limestone used as rubble fill in opus incertum wall.

Roman Mortar Studies

Writing in the first century CE, Vitruvius claimed in *De Architectura* (*II.VI.1*) that lime-based mortar mixed with a pozzolano binding agent and rubble aggregate was ideal in terms of water resistance and compressive strength. This particular mortar mixture is long believed to have come into use in ancient Pompeii before the end of the third century BCE (Carrington 1933). The lime source was commonly limestone or dolostone which reduce upon heating to a white block the same size and shape of the original source, only much less dense (Leslie and Hughes 2002). This made it easy to transport, so lime kilns would have been located close to the source, rather than near the building site (Adam 1994).

Pozzolana is a material that when added to hydrated lime reacts to acquire cementitious properties (Eslen 2006); it is commonly volcanic pumice or tuff, both abundant in the Bay of Naples (Orchard 1973). Vitruvius called this material pit sand, and preferred its use to river sand (II.IV.1). Where natural volcanic pozzolanas were unavailable, ceramics such as crushed pottery or brick dust were often substituted (Carrington 1933; Elsen 2006); these were often a pink color (Elsen 2006). Experimental archaeological tests have indeed shown that lime mortar mixed with brick dust acting as a pozzolana increases the compressive strength of mortar compared to that of sand mixtures (Teutonico et al. 1993). Orchard (1973) claims this is because the pozzolanic material "reduces the leaching of soluble compounds" which can compromise the mortar. Pozzolanic mortars are hydraulic because of the reaction of aluminum, iron hydrated oxides and lime, and so were used as lining for water-holding structures like cisterns, drains or aqueducts (Genestar et al. 2006). Pozzolanic material is abundant near Pompeii and throughout Campania. Chemical analysis of ancient hydraulic concrete from the Roman harbor at Santa Liberata has shown the tested samples contained pozzolana additives from the Naples area, suggesting a trade area of this material that extended north beyond Rome (Gotti et al 2008).

In their studies of 30 samples of lime mortars from the Roman town of Pollentia (Balearic Islands, Spain), Genestar et al (2006) found that pozzolanic mortars were in use at this site from the first century BCE until the third century CE. The authors determined that different size aggregate inclusions correlated to function. Flooring mortar contained "descending distribution" of grain size and high binder/aggregate ratios, whereas lining and plaster mortars contained "symmetrical distribution" and lower per weight ratios (Genestar et al 2006). Fourier-transform infrared analysis identified three types of binder materials: calcium carbonate with silicates; carbonates, silicates, and iron oxides; and carbonates with a low amount of silicates (Genestar et al 2006). After analysis of the aggregate, four types were apparent: artificial pozzolanic mortars, hydraulic mortars with siliceous aggregate, hydraulic mortars with calcareous aggregate, and "typical lime mortars" which were non-hydraulic. Genestar et al have illustrated the variability of mortar possible across a single site; however, the authors do not assign binder and aggregate types to individual samples. It is not possible to correlate samples to discrete construction events with the available data, so there is no evidence to illustrate the variability within a single structure or individual wall.

Sanchez-Moral et al (2005) studied lime:pozzolano mortar samples from the Saint Callistus and Domitilla catacombs outside the walls of Rome. Here, mortar was used to cover the cubicles which held family tombs. It was composed of two or three layers of decreasing thickness outward, separated by small voids. The inner layers contained coarser aggregate grains than the smooth external layer. Microscopy with polarizing microscope and environmental scanning electron microscope showed variable binder: aggregate ratios (1:0.5 – 1:1.1). Porosity studies of the samples showed that “larger pores are empirically linked to coarser grains and imply higher CO_2 diffusion and faster calcinization,” which increases mortar strength (Sanchez-Moral et al 2005). Electron microprobe, X-ray diffraction, and atomic absorption spectroscopy tests determined the aggregate consisted of “vitreous volcanic rock,” present as small tephra fragments containing pyroxene phenocrysts, sanidine, biotite, analcime, feldspars and calcite (Sanchez-Moral et al 2005). The calcite present as aggregate represented under-processed lime, indicating low water content during the slaking process (Sanchez-Moral et al 2005). The authors found that the mortar contained similar chemical composition to the volcanic tuff out of which the catacombs were cut, suggesting local materials were exploited for mortar production.

Bendetti et al. (2004) analyzed a single sample of plaster mortar from the Villa of Pollio Felice in Sorrento, Italy, on the bay of Naples. This sample consisted of four layers of lime mortar, each of different composition and of descending thickness from the interior to the outermost layer. The authors also found that lime percentage increased toward the external surface of the sample, as sand content decreased in the same direction. The aggregate in this sample included both volcanic lithic fragments and crushed ceramics, presumably “to achieve better hydraulic and mechanical properties” (Benedetti et al. 2004). The mineral phases of the aggregate inclusions identified by XRD (powder samples) included sanidine, hematite, quartz, diopside, dolomite, biotite, and serandite. X-ray microdiffraction of “as-received” samples further identified aragonite, graphite, muscovite, periclase, analcime, labrodorite, calcite, and pyrope (Benedetti et al. 2004). This mortar sample contained many of the markers of Vesuvian pozzolana, with a conspicuous absence of leucite.

CHAPTER 5

METHODS

Mortar Sample Collection

Different construction phases throughout the House of the Vestals are traditionally identified by visual analysis, relying largely on mortar color and the types of visible inclusions (eg. crushed rock fragments, visible mineral grains, ceramic fragments). Several mortars of different colors have been found within property VI.1.25, including three different ancient mortars (pink, grey, and yellow), one historic brown mortar, and one modern grey mortar. The "ancient" mortars were believed to pre-date the 79CE eruption because they are inset in the wall and surround - rather than cover - the wall stones. The historic and modern mortars have been identified as repointed mortar, which covers the wall as a way to strengthen the structure and prevent further deterioration.

One objective of this mortar study was to determine the degree of compositional variance that exists throughout VI.1.25, as well as within a single construction phase. Sample locations were selected to best represent where those differences occur. The following criteria were used when selecting sample locations and subsequent comparisons:

- **Pink mortar vs. non-pink mortar.** The distinctive pink mortar within structure VI.1.25 has been identified as the original construction phase in the House of the Vestals because it was located along the lowest portions of the walls, including buried foundations (Jones and Robinson 2005). Mortars of different colors were used for later reconstructions within the structure, and these may exhibit some variation in chemical or mineral composition.

- **Original phase vs. later phase pink mortar.** According to current archaeological interpretation, a small room was added to what was originally open courtyard space during an Augustan-era reconstruction of the House of the Vestals (D. Robinson, pers. comm 2007). The pink mortar used for these walls, constructed more than a century after the original pink mortar walls, may also exhibit some degree of chemical or mineral variation from the samples attributed to the original construction phase.
- **Interior walls vs. exterior walls.** Walls were designated as either "interior" or "exterior" according to whether the wall faces were constructed as part of enclosed rooms (interior) or as property boundary walls (exterior), intended to be exposed to the elements. There may be some variation in the mortar used for these different purposes. There may also be different alteration and decay products.
- **Inner core vs. wall face samples.** Mortar samples from different parts of a wall may vary in composition or decay products. Evaluating these reveal the degree of variation.
- **Samples from both faces of a single wall.** Multiple samples from the same wall can help elucidate the degree of chemical, mineral, or morphological variation of samples from a single construction event.
- **In situ mortar vs. re-used mortar.** Throughout the House of the Vestals, fragments of pink mortar have been reused along with recycled wall stones in numerous wall repairs. Reused mortar samples may have retained composition information from the original

mortar production, in which case, it may be possible to determine from which walls the reused samples were taken.

- **Opposite ends of a single wall that was divided** in a later reconstruction phase. Excavation evidence suggested that walls 151 and 125 were initially a single wall that was opened with a new door and subsequent repairs to either side of the doorway. Comparing samples from both walls may help evaluate the range of variation to be expected from a single construction phase.
- **Pink wall mortar vs. pink flooring mortar** excavated from the House of the Surgeon. Excavation revealed a bed of mortar in the House of the Surgeon that was similar in color to the wall mortar from the House of the Vestals. Evaluating this type of mortar may reveal variation in mortar used for different purposes.

A total of 25 samples were collected, including nineteen ancient pink mortars, one grey and one yellow ancient mortar, one large ancient lime lump, one possibly Bourbon-era mortar, one modern grey mortar and one ancient pink flooring mortar sample (Figure 5.1, Appendix B).

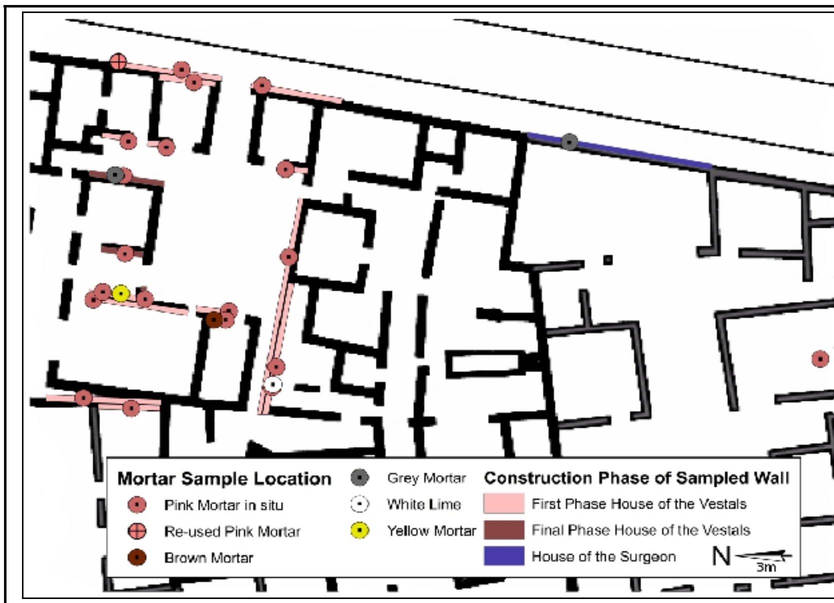

Figure 5.1: Location of all mortar samples collected July 2007

Wall samples were carefully cut away from the wall with a Marshalltown trowel and stored in 4-mil archival polyethylene bags labelled with the wall number, sample ID number, and the date. The ID numbering system is consistent with that established for the original sample set, which includes structure plot number, wall number, and successive sample number (i.e. W7-125-1, W6-118-24). Sample numbers on graphs and illustrations have been abbreviated to the last number in the sequence (i.e. 1, 24). During collection, sample description forms were used to consistently record the details of wall construction type, techniques and materials, sample location, preliminary assessment of the mortars' mineral assemblage and additional descriptive information (Appendix A). Detailed notes on wall construction phasing, as well as sketches of each wall (with approximate sample locations marked), were recorded in a field notebook along with general observations and additional research questions. The flooring mortar (sample X701-2-20) was collected from the House of the Surgeon during trench excavation by Area Supervisor Ian Sumpter and stored in a 4-mil archival polyethylene bag. Figure 5.2 displays the location of samples by sample number.

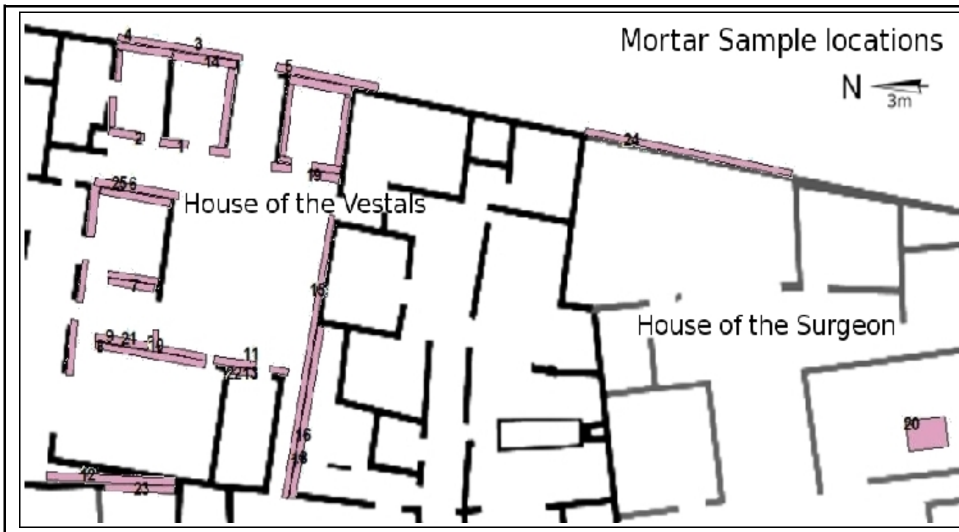

Figure 5.2: Mortar sample locations in the House of the Vestals and the House of the Surgeon

The sample description forms were created and utilized to maintain consistency of visually assessed information about each sample (Appendix A). To that end, standards were defined for attributes that required some estimation. Aggregate inclusion size was listed as "large" or "small," indicating either >5mm or <5mm, respectively. Inclusion density was listed as low (0-30%), medium (30-60%) or high (60-100%), and referred to the estimated abundance of aggregate within the binder. The percentages of individual aggregate inclusions were listed as the percentage of total aggregate, and thus should total 100%. Construction technique and wall composition information referred to the building phase and materials (i.e. wall rocks) associated with the mortar sample, though most walls contained multiple construction events and mortar types or colors. Also, the structure plot, room and wall numbers recorded on the forms were identical to those used by the AAPP throughout the excavation of insula VI.1.

Photography

Digital pictures were taken of whole walls and individual sample locations using a Nikon D70s digital camera (Appendix B). The photo collection provides both site specific and full structure context for each sample. The images were processed in Adobe® Photoshop® (adjusting only auto-levels) and cropped for size. It should be noted here that the north arrows shown in the photo identification boards for each wall depict the site north used for all excavation and wall photos in each field season of the AAPP; this is the general northern direction for the triangle-shaped insula VI.1, but is not true north.

Portable Microscopy

Following sample collection, a Bodelin ProScope HR USB digital microscope connected to a laptop computer was used to acquire digital images of the mortar surface and of the visible inclusions in each sampled wall. During the pre-season lab test of the ProScope, the 100x lens provided the best detail of the lime and small aggregate inclusions in the original samples, so only this level of magnification was used in the field. Images were collected in the early morning and late afternoon to minimize glare and protect the equipment from heat. Again, auto-levels were adjusted in each image with Adobe® Photoshop®.

Data Management and GIS

Data from the field forms, photographs and digital microscope images of each sample were entered into a Microsoft Excel worksheet. A catalogue of the sample set and collected data has been generated with the database software and included here as Appendix B. Additionally, the data were entered into a GIS system using ArcGIS 9 to easily display sample locations and to test the framework for future GIS studies of the samples. The House of the Vestals portion of an Auto Cad map of Pompeii created by the Soprintendenza was used as a base map. Pink mortar walls were highlighted and tagged with Wall Number and construction phase; individual samples were plotted in their approximate locations on the sampled walls. Each sample was further assigned attributes including wall number, archaeological phase, mortar color, and visible aggregate inclusions, including identifiable mineral phases and their relative abundance. These data and maps of individual sample locations are included in Appendix B. Additional maps included a plot of each sample by mortar color; a plot of high, medium and low inclusion densities; and individual plots of each inclusion type by visually estimated percentage.

Thin Section Petrography

Six samples were chosen for thin section preparation and analysis, including three pink mortar samples from the original construction phase, two from the Augustan phase pink mortar reconstruction, and one brown mortar from a historic-era repointing. The nature of thin section preparation required relatively large, solid fragments that would likely maintain cohesion throughout the preparation process. The selected samples were not overly friable and large enough to obtain a standard size thin section (26mm X 46mm). Each was sliced to obtain a fragment approximately 1/2 inch thick that was smooth on both sides. These sliced samples were submitted to Vancouver Petrographic for epoxy impregnation and standard thin section preparation, ~30µm thick and covered with a 20mm X 40mm cover slip.

Identification of the mineral phases present in each sample was conducted on a Leica polarizing microscope. Mineralogical data and morphological observations about the binder and aggregate components of each sample were recorded in analysis forms created for this project (Appendix C). Data collected from each sample included mineral phase identification, estimated abundance, color and birefringence ranges for each mineral present. Sample drawings of identified minerals were also included. Photomicrographs were collected with a digital camera attached to the microscope's eyepiece.

Sample Preparation

After thin section preparation, all samples were prepared for submission for X-ray analyses. Solid chunks of each sample were gently crushed with a porcelain mortar and pestle. To avoid over-representation of the aggregate fraction, care was taken to separate the binder material without pulverizing the rock fragments and mineral crystals. The crushed samples were sieved to separate the material into large and small fractions, using a No. 20 US Standard sieve with 841µm mesh. At this size fraction, no rock fragments or mineral crystals were obvious to the naked eye but were visible under the microscope at 20X power. A minimum of four grams of each sample was further ground to 10µm in a McCrone mill with corundum pellets and ethyl alcohol. The mortar solution was placed in a low temperature (~120°C) drying oven until all ethyl alcohol was evaporated. The dried powder was collected, stored, and labelled for analysis.

X-ray Diffraction

The six samples selected for thin section analysis were also subjected to X-ray diffraction analysis. A minimum of 0.10g of dry powder was mixed with 1ml of ethyl alcohol to produce a liquid solution that was transferred to a glass slide with a glass pipette. The solution air dried for approximately an hour. Bulk analysis of randomly oriented slide mounted samples was conducted on a Scintag X-ray diffractometer at the Savannah River Ecology Lab. The diffractometer utilized CuKα radiation (1.540562λ), with the current set to 45kV, 40mV. The goniomter scanned from 2-60º 2Θ, with a step size of 0.05º 2Θ and a scan rate of 1º 2Θ per minute.

Diffraction patterns were processed and analyzed with the Scintag DMSNT software. Data processing included automated and manual peak finding and peak profile fitting. Major mineral phases were identified by comparing patterns to spectral data in the Powder Diffraction File published by the International Center for Diffraction Data and by comparing numerical data to additional published diffraction data (Chen 1977, Downs and Hall-Wallace 2003).

X-ray Fluorescence

All but one of the separated and milled binder samples were submitted for wavelength dispersive X-ray fluorescence and loss on ignition analysis (LOI) to the Center for Stable Isotope Studies at the University of Georgia. Sample, W7-126-19, was too small to produce the minimum four grams of 10µm powder necessary for major element analysis. No sample was large enough to produce the ten grams of powder necessary for trace element analysis. Powders were crushed to pass a 100 mesh (149µm) screen. LOI was determined by roasting sieved powders for 45 minutes at 925°C and comparing pre-roast and post-roast weights. Roasted powders were prepped for analysis with borate fusion in a 50:50 $Li_2B_4O_7$:$LiBO_2$ flux at 1050°C. Fused glass disks were analyzed for major element content with a Philips (Panalytical) 2.4 kW sequential spectrometer, equipped with flow detectors, PE 002, PX1, LiF 200 and Ge 111 crystals, and appropriate collimators. Concentrations were determined on calibration curves derived from 12-15 international reference materials (U.S. Geological Survey, National Institute of Standards and Technology, and Japanese Geological Survey). Data were reported as weight percent oxide for the following major elements: sodium, magnesium, aluminum, silicon, phosphorous, potassium, calcium, titanium, manganese, and iron. Raw totals of all elements were added to LOI and normalized to 100% for further analysis. Statistical analyses including descriptive statistics, principal components analysis (PCA), and factor analysis were conducted using the XLSTAT statistical package add-in for Ms Excel.

Portable Near-infrared Spectroscopy (NIR)

Objectives for near-infrared analysis in VI.1.25, July 2008, were defined to optimize data collection logistics and adequately sample the range of variation within the structure. These objectives included:

- Analyze mortar at locations where samples were collected in July 2007
- Systematically analyze of mortar from all walls in property VI.1.25
- Collect spectra from each type of wall stone stone used in VI.1.25, as well from unprocessed lime lumps and red scoria fragments present as aggregate

- Collect comparative spectra on multiple days
- Conduct portable NIR analysis of mortar samples collected July 2007

Portable near-infrared analysis was conducted with a FieldSpec®3 portable spectroradiometer, manufactured by Analytical Spectral Devices, Inc (ASD). This instrument measures infrared energy of short-wavelengths, including the visible and near infrared (VNIR) and short-wave infrared regions (SWIR), in a field setting. The instrument contains three detectors: a VNIR detector, from 350 – 1050 nm, and SWIR 1, from 1000 – 1800nm, and SWIR 2, 1800– 2500nm. The instrument is controlled by an IBM Think Pad PC via wireless network, utilizing ASD's proprietary software package, RS^3. The data from each detector are patched together into a single spectrum. The detectors are connected to the instrument in a single fiber optic cable, which contains 19 fibers for each detector. The cable is inserted into a “pistol grip”, a device that secures and directs the fiber optic cable during analysis. It can be either hand-held or mounted on a tripod, and both configurations were tested in this study (Figure 5.3). Individual readings take one-tenth of a second, and the spectra are created by averaging 25 successive readings. The RS^3 program collects and displays the signal from the detectors, producing a real-time display of the absorption spectra. The displayed spectrum automatically refreshes after each new average and can be saved by hitting the space bar on the computer or pressing the trigger that can be attached to the pistol grip. Each target location typically requires 2-3 screen refreshes for the spectra to stabilize. A reading is considered stable when the shape and intensity of each peak stops visibly changing.

Figure 5.3: Data collection with the FieldSpec® 3. a. Hand-held configuration; b. Tripod mount configuration. Photos by Philip Murgatroyd

Immediately before use, the instrument must be optimized to the current atmospheric and illumination conditions by activating the optimization sequence with the RS^3 software. This procedure helps to prevent the instrument from becoming saturated with reflected IR energy. In the saturated state, more energy has entered the detector than can be evaluated and recorded by the instrument, creating a spectral peak higher than 65000 in intensity. In this case, the RS^3 software displays a flattened graph and the instrument gives an audible warning signal. During optimization, the fiber optic cable is aimed at an optical standard (a Spectralon® panel, see below) that is fully illuminated while the instrument records its reflectance. The sequence subsequently records a dark current reading, which represents the signal within the detector itself. Because of constantly changing atmospheric conditions in the field, optimization was repeated approximately every 15 minutes and whenever the instrument became saturated.

Under field conditions, the instrument records not only the desired absorption/reflection data, but also background noise in the form of ambient illumination, instrument generated signal noise, and atmospheric humidity. Each target reading is preceded by a reading on the

Spectralon® reflectance panel (Target #12137-A*)*, manufactured by Labsphere, Inc. Spectralon® is a thermoplastic resin that is 96-99% reflective in the 250-2500nm wavelength range (http://www.labsphere.com). The near total reflectance of the material means that the spectra generated from the panel only include data from the various sources of noise, rather than from the panel itself. The noise data can later be ratioed out to isolate the target data, resulting in absolute reflectance information for the target alone without interference from the various sources of noise.

The FieldSpec® 3 utilizes solar illumination as the IR source in the field. Optimally, the target should be in full sunlight during analysis. To achieve this, the East facing walls in VI.1.25 were analyzed before noon Central European Summer Time (UTC+2), when they were fully illuminated, and the West facing walls were analyzed after 1:30 pm. The south facing walls were well illuminated for most of the day. Because of the configuration of the structure, the north facing walls were never illuminated well enough for analysis.

Spot-size is the area on the sample that can be "read" by the detector with a given field of view (FOV). The bare fiber optic detector has a 25° FOV, creating a large spot-size. The spot size can be changed by attaching one of four foreoptics (with 18°, 5°, or 1° field of view) and by changing the distance between the detector and the target. The illumination geometry is illustrated in Figure 5.4 by the small and large ellipses, representing perpendicular and oblique targets, respectively.

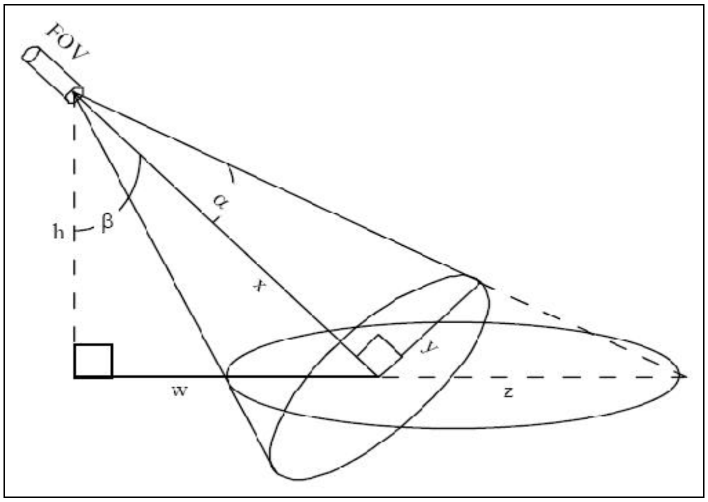

Figure 5.4. Spot size approximation and illumination geometry. Source: ASD (1999).

The illumination geometry is defined by the following equations (ASD 1999):

$$\arctan(y/x) = \alpha = (\text{FOV full angle})/2$$
$$y/x = \tan \alpha$$
$$y = x \tan \alpha$$

where *FOV* is the field of view of the attached foreoptic (or the bare fiber optic cable), *x* is the distance from the target, and *y* is the radius of the desired spot-size. Table 5.1 gives the spot-size calculations for each foreoptic at different distances from a target. The nature of the mortar suggested that a spot size of approximately 1cm would be adequate to analyze a spot of binder, while avoiding large crystals or rock fragments present as aggregate. It is not possible to completely avoid microscopic aggregate fragments. The calculations indicated that a target spot size of approximately 1 cm could be achieved by placing the 5º foreoptic 11 cm from the target.

Table 5.1: Spot-size (diameter in cm) for each foreoptic at a variety of distances

Distance from wall (cm)	1° foreoptic	5° foreoptic	18° foreoptic	(Bare fiber) 25°
100	1.75	8.73	31.68	44.34
75	1.31	6.55	23.76	33.25
50	0.87	4.37	15.84	22.17
60	1.05	5.24	19.01	26.60
40	0.70	3.49	12.67	17.74
30	0.52	2.62	9.50	13.30
20	0.35	1.75	6.34	8.87
15	0.26	1.31	4.75	6.65
14	0.24	1.22	4.43	6.21
12	0.21	1.05	3.80	5.32
11	0.19	0.96	3.48	4.88
10	0.17	0.87	3.17	4.43
5	0.09	0.44	1.58	2.22
3	0.05	0.26	0.95	1.33
2	0.03	0.17	0.63	0.89
1	0.02	0.09	0.32	0.44

On the first day of analysis, the equipment was tested at the spots where samples were collected in July 2007. The test was conducted with the fiber optic cable inserted into the pistol grip, which was mounted to a tripod with the 5° foreoptic attached (Figure 5.3b). The tip of the foreoptic was placed 11cm from the wall, as prescribed for a desired spot size of approximately 1cm (Table 1). The tripod allowed the signal to stabilize quickly and to confidently target the desired sample location. This configuration was problematic because more often than not, the target location was too low for the tripod. When the tripod configuration was unworkable, research assistant Philip Murgatroyd held the pistol grip approximately 11cm from the target location. The hand-held configuration at this distance was difficult, the target location and specific distance from the wall were difficult to maintain. Also, peak shape and the intensity of the signal never stabilized completely, but after 3 screen refreshes, the changes were minimal.

While not ideal, the most feasible configuration was with a single operator using the hand-held configuration with the trigger attached to the pistol grip (Figure 5.3a). The end of the 5° foreoptic was placed 1-3cm from the wall. This distance created a spot size approximately 26mm in diameter. The smaller spot-size allowed for more refined sample selection, and the proximity to the wall allowed for more control over the target location and stability of the pistol grip. Five readings were taken at each sample location, each preceded by the reference panel reading, for a total of 10 files for each sample location. The data were recorded by the RS^3 software as "asd" spectral files, which were later converted to text files with ViewSpec Pro software. Peaks in the spectra represent intensity at each wavelength, and are recorded as digital numbers (DN) (Figure 5.5).

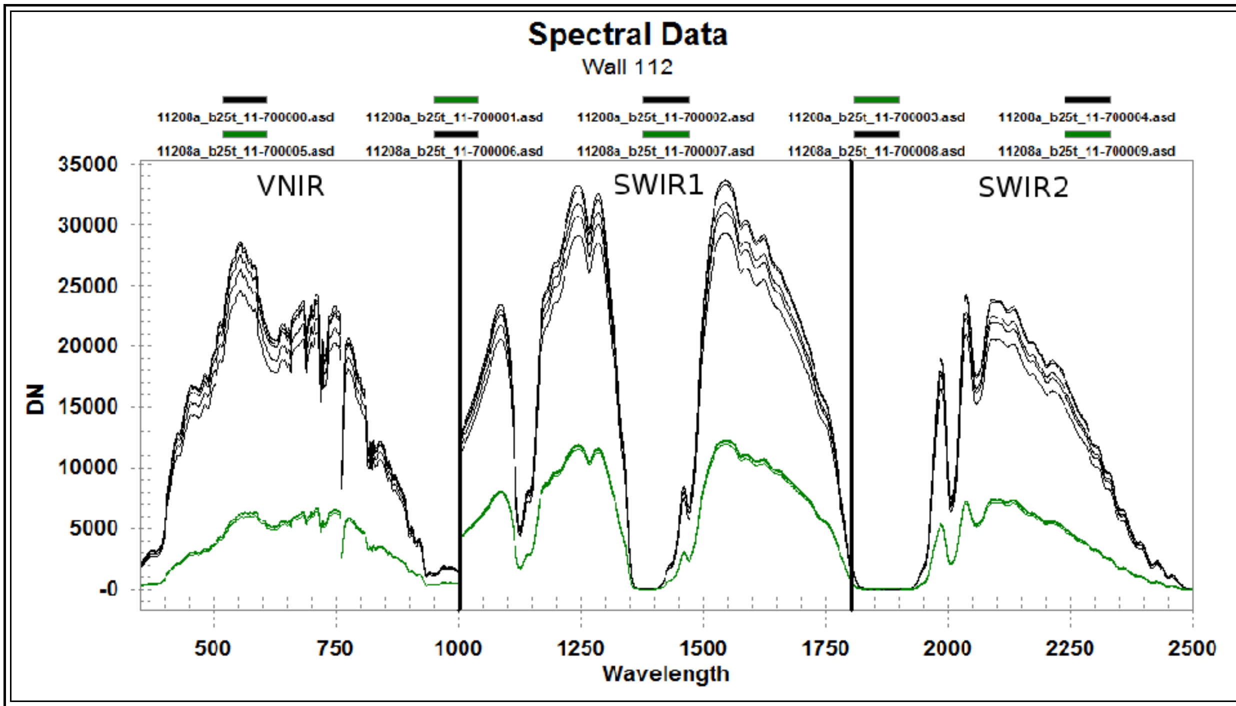

Figure 5.5: Raw FieldSpec®3 data, black=reference panel data, green=target wall reading. Individual detectors marked: VNIR=350-1000nm, SWIR1=1000-1800nm, SWIR2=1800-2500nm.

The field dataset included nine different types of mortar (Table 5.2) from 18 different walls, 16 within property VI.1.25 and two in properties near the Stabian Gate on the southeastern side of the city. Spectra of different mortar types show clear variation, most typically within the 350-750nm and 1950-2500nm regions. Other analyzed materials included plaster, tile, pottery, lime, red scoria fragments used as mortar aggregate, each type of wall stone found in IV.1.25, and natural soil from excavations near the Stabian Gate (Table 5.3).

The reference mortar samples collected in 2007 were also analyzed with the FieldSpec®3 in Athens, Georgia, in August 2008 using solar illumination. The fiber optic cable was equipped with the 5° foreoptic and mounted in the pistol grip in the hand-held configuration. Samples were held 1-3cm from the end of the foreoptic, matching as closely as possible the spot-size used in the field. A collection of reference materials, including rock and mineral samples (Table 5.3), was analyzed with the FieldSpec® 3 in September 2008 using as in infrared light source the ProLamp supplied by Analytical Spectral Devices, Inc.

Table 5.2. Walls analyzed with the FieldSpec® 3

Wall Number	Address	Structure	Mortar Color	Construction Phase	Reference Sample ID
Wall 45	VI.1.25	House of the Vestals	pink	Original	W7-45-16
Wall 45	VI.1.25	House of the Vestals	pink	Original	W7-45-17
Wall 45	VI.1.25	House of the Vestals	white (lime)	Original	W7-45-18
Wall 108	VI.1.25	House of the Vestals	pink	Original	W7-108-13
Wall 108	VI.1.25	House of the Vestals	brown	Bourbon	W7-108-22
Wall 112	VI.1.25	House of the Vestals	pink	Original	W7-112-08
Wall 116	VI.1.25	House of the Vestals	pink	Augustan	W7-116-07
Wall 118	VI.1.25	House of the Vestals	pink	Original	W7-118-09
Wall 118	VI.1.25	House of the Vestals	yellow	Unknown	W7-118-21
Wall 118	VI.1.9	House of the Surgeon	grey	Unknown	W6-118-24
Wall 123	VI.1.25	House of the Vestals	pink	Augustan	W7-123-10
Wall 124	VI.1.25	House of the Vestals	grey	Augustan	not sampled
Wall 125	VI.1.25	House of the Vestals	pink	Original	W7-125-01
Wall 126	VI.1.25	House of the Vestals	pink	Unknown	W7-126-19
Wall 128	VI.1.25	House of the Vestals	pink	Unknown	W7-128-11
Wall 136	VI.1.25	House of the Vestals	pink	Original	W7-136-14
Wall 151	VI.1.25	House of the Vestals	pink	Original	W7-151-02
Wall 152	VI.1.25	House of the Vestals	pink	Augustan	W7-152-06
Wall 152	VI.1.25	House of the Vestals	grey	Modern	W7-152-25
Wall 205	VI.1.25	House of the Vestals	pink	Original	W7-205-12
Wall 701	VI.1.25	House of the Vestals	pink	Original	W7-701-03
Wall 701	VI.1.25	House of the Vestals	pink	Re-used, unknown	W7-701-04
Wall 702	VI.1.25	House of the Vestals	pink	Original	W7-702-05
Wall Segment 38	VIII.7.12	Unnamed structure	yellow	Unknown	not sampled
Wall Segment 68	VIII.7.12	Unnamed structure	yellow	Unknown	not sampled
Wall Segment 222	VII.7.5,6	Unnamed private house	white (lime)	Unknown	not sampled

Table 5.3. Additional materials analyzed with the FieldSpec® 3

Material	Source
Black lava with black particles	VI.1.25, Wall 701
Black lava with white flecks	VI.1.25, Wall 701
Red *Cruma*	VI.1.25, Wall 701
Sarno limestone	VI.1.25, Wall 701
Ceramic Tile	VI.1.25, Wall 701
Terra Sigillata Pottery	AAPP AA324 SU24
Marble	Unknown
Natural Soil 1	PARP:PS AA19000 SU13
Natural Soil 2	PARP:PS AA19000 SU22
Calcite	UGA Teaching collection
Gypsum	UGA Teaching collection
Limestone	UGA Teaching collection
Dolostone	UGA Teaching collection
Dolomitic Marble	UGA Teaching collection
Shale	UGA Teaching collection
Kaolinte	UGA Teaching collection
Chalk	UGA Teaching collection

Absolute reflectance at each wavelength was calculated as a ratio of raw data to reference data using the ASD Raw Reflectance Data Template, Version 2.1 (2008), a spreadsheet created by Chris MacLellan of the NERC Field Spectroscopy Facility. The reflectance value represents the percent of reflectance; i.e. the Spectralon® reference panel with an absolute reflectance of .96-.98 is 96-98% reflective. This information from each IR analysis location was plotted for graphical comparison (Figure 5.6). Water produced large absorption bands in two regions, 1350-1460nm, and 1790-1960nm; because these bands caused such large peaks in the reflectance graph, they were removed from the dataset (Figure 5.7). These bands may have included absorption data from materials in the mortar other than mortar, but these would have been obscured by the dominant water peaks.

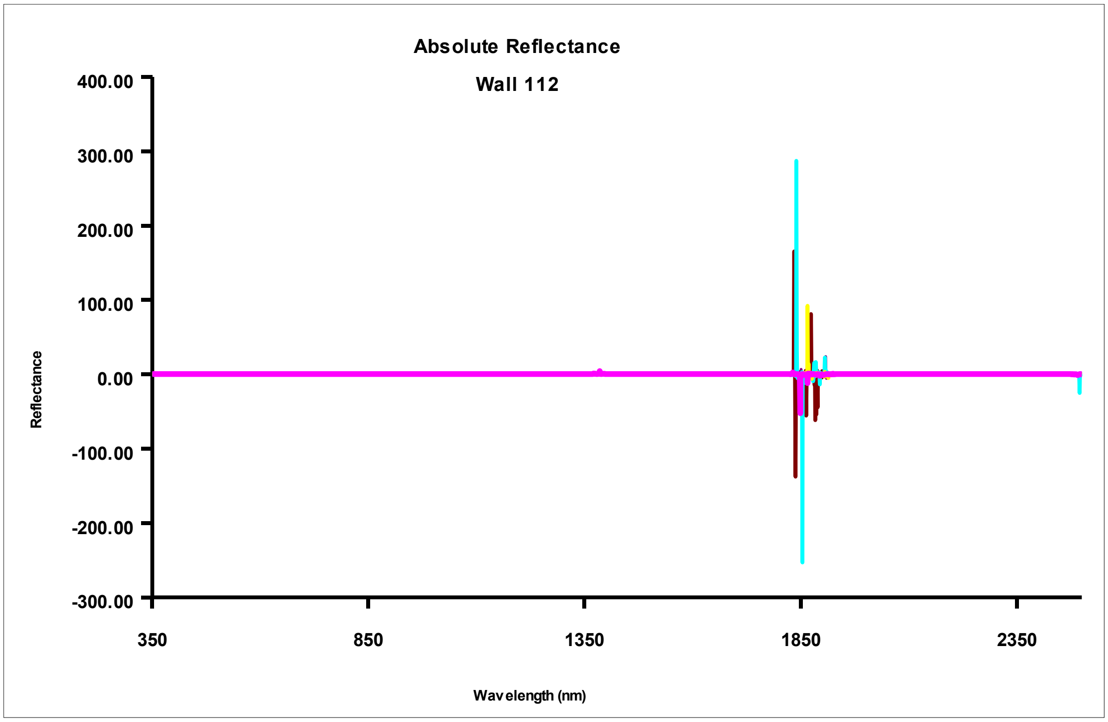

Figure 5.6: Absolute reflectance data of Wall 112, produced by ratio of reference to sample data.

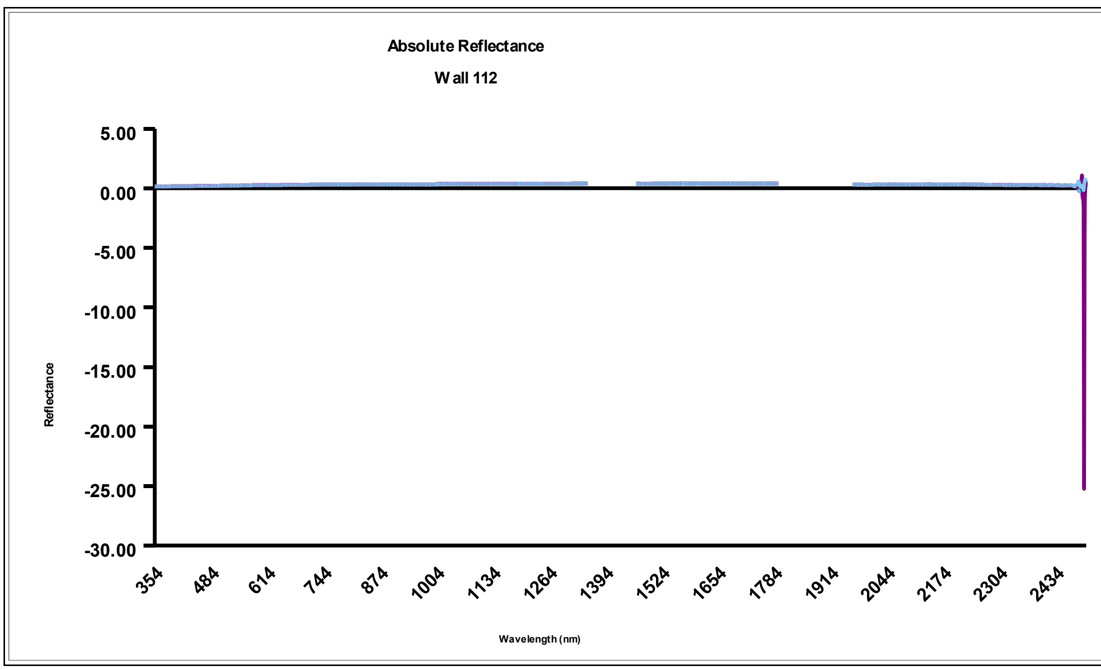

Figure 5.7: Absolute reflectance of Wall l12 with H_2O data removed.

The resulting spectra needed to be further reduced to remove detector inefficiencies that produced large anomalies at the longest wavelengths (2450-2500nm) (Figure 5.7). Data were truncated at 2450nm for display and statistical analysis to eliminate skewing the data with false spectral peaks (Figure 5.8).

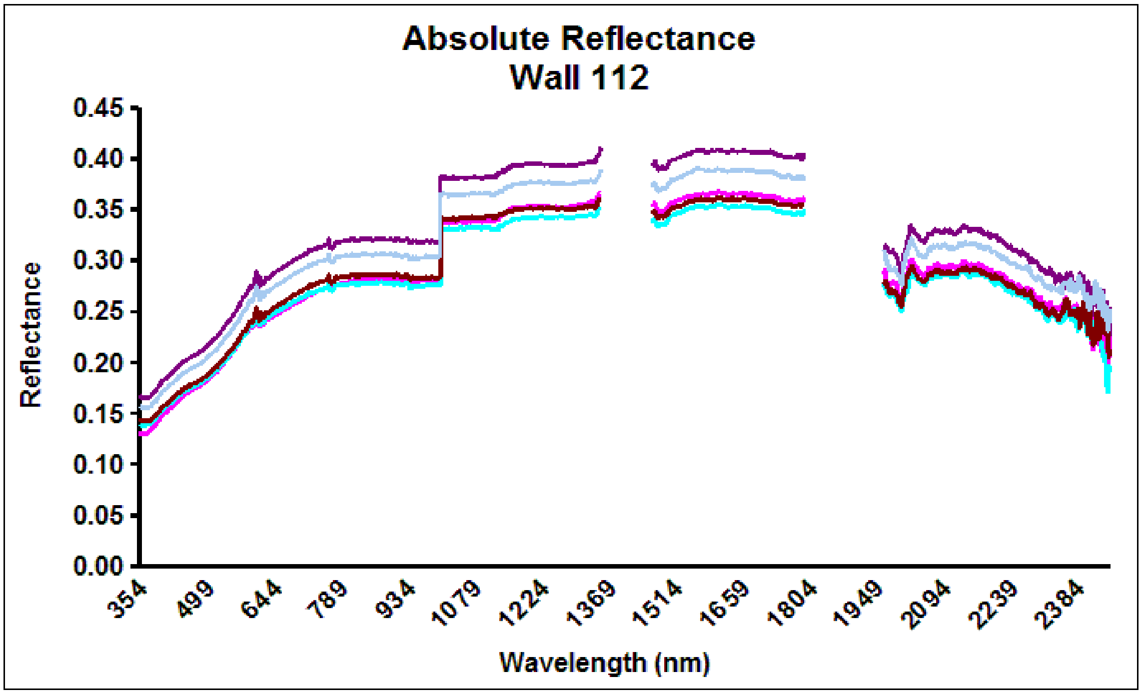

Figure 5.8: Absolute reflectance data with H_2O data and detector edge-effects removed. Figure displays five individual readings at the same location

The absolute reflectance of the five readings were then averaged, resulting in a mean absolute reflectance value and standard deviation for each sample location. Spectra were analysed for major mineral phase identification. Mean absolute reflectance data for each wall were subjected to Principal Components Analysis using The Unscrambler® (Version 9.8, CAMO, Inc.) to identify which bands within the spectra contributed most to the variation between samples.

CHAPTER 6

RESULTS

Simple visual inspection of the walls in the House of the Vestals showed a good number of walls that still contain the distinctive pink mortar used in their original construction. In most cases, the pink mortar is visible along the lowest courses of the wall and often in the original doorway quoining. Initial architectural study of the early phases of the House of the Vestals has shown the pink mortar was used in two properties that were originally separate, but were eventually incorporated into the elite House of the Vestals by its final phase. The addresses of these properties are VI.1.25 to the north and VI.1.24 to the south, labelled House A and House B respectively for the purposes of this project (Figure 6.1). In the interest of controlling the size of the sample set, sample selection was limited to VI.1.25, which allowed for a systematic and representative collection protocol. Pink mortar was utilized during two distinct building phases within the property: the original construction phase dated to the 2nd century BCE and the final phase Augustan-era (31BCE - 14CE) reconstruction (Jones and Robinson 2005). The walls iden-

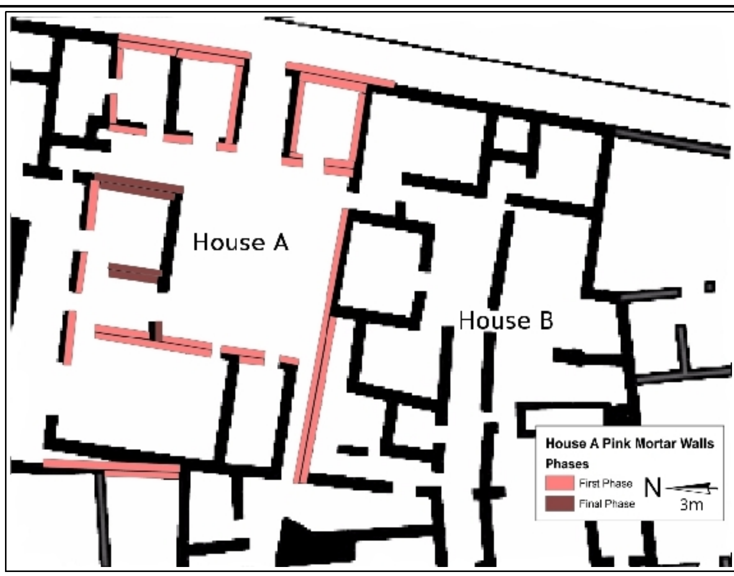

Figure 6.1: House A (Property VI.1.25) with pink mortar walls marked

tified as "pink mortar walls" are illustrated in Figure 6.1, though some additional walls may have been part of the original pink mortar phase but the mortar was obscured by *in situ* wall plaster. The final phase pink mortar walls were connected by a third wall that was constructed with a unique grey mortar.

Sample Collection

The pink mortar under study here was easily identified by its pinkish hue and a unique set of aggregate inclusions in similar proportions: leucite crystals, clinopyroxene crystals, red scoria fragments and lumps of unprocessed lime (Appendix B). Pink mortar was exclusively found in walls of the construction style *opus incertum*, composed of large blocks of travertine in the doorway and grey volcanic stones for the fill of the wall (Figure 6.2). Each of these walls was originally faced with decorative plaster, with some still retaining plaster remnants.

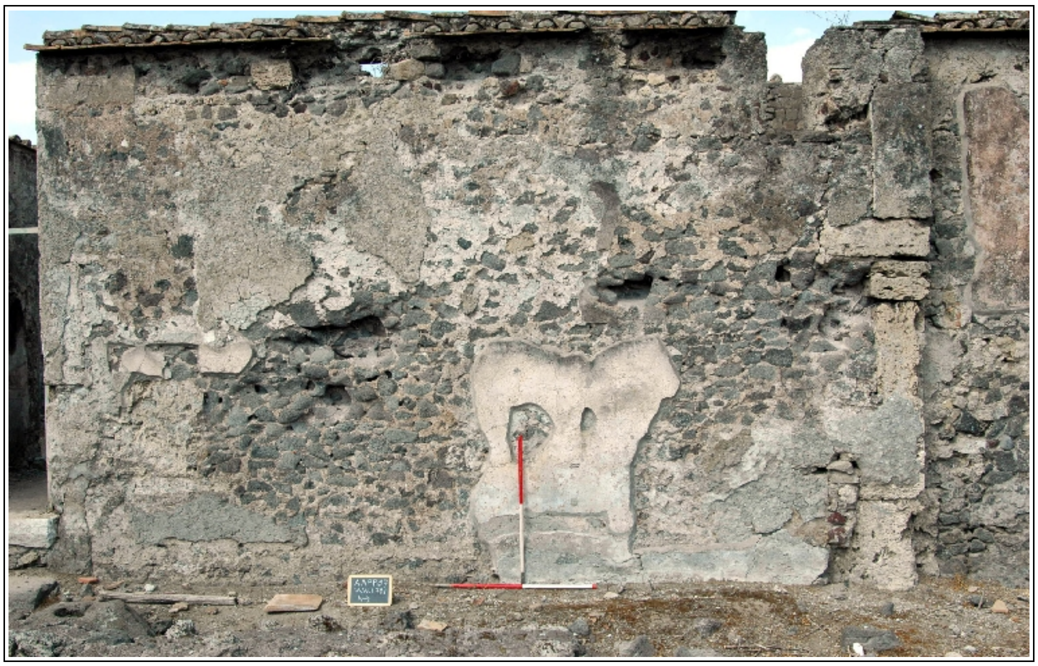

Figure 6.2: Wall 701, illustrating *opus incertum* style with volcanic stone fill, sarno quoins, and remnant plaster facing

Figure 6.3: Repair within Wall 701

Pink mortar typically appeared on the lower courses of volcanic stone and between the large sarno blocks, which indicated it was used in original wall construction (or "first phase"). In cases where pink mortar was seen in association with other rock types, such as red cruma and Nocera tufa, it was found exclusively within obvious wall repairs or reconstructions (Figure 6.3). Here, the pink mortar was not functioning as mortar but as additional wall "rocks" (Figure 6.4). Examples of these re-used mortar fragments were found throughout the House of the Vestals, next door in the House of the Surgeon, and in the southernmost property of the insula, the Bar of Phoebus (see Figure 2.1). A sample of the re-used mortar was collected to determine any chemical alteration that may have occurred from exposure to "new" mortar, as well as to test whether the re-used fragments may be matched to a specific wall.

Figure 6.4: Detail of repair in Wall 701, showing red scoria (Sc), tufa (T), and pink mortar "rocks" (M) set into grey mortar

Portable Microscopy

The ProScope digital microscope was useful for illustrating the size and abundance of the visible aggregate inclusions - clinopyroxene, leucite, lime lumps, and scoria fragments (Figures 6.5-6.8). Figure 6.9 shows lime lumps and binder with visible inclusions.

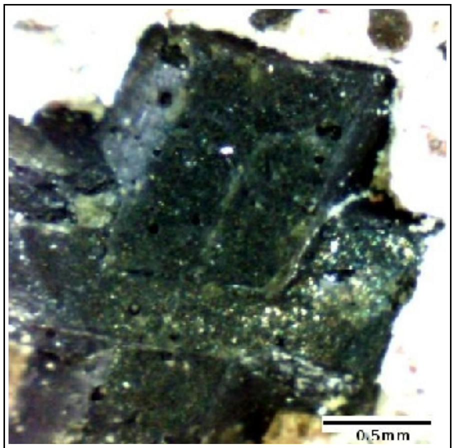

Figure 6.5: Clinopyroxene grain in Wall 139

Figure 6.6: Leucite fragment in Wall 701

Figure 6.7: Lime lump in Wall 701

Figure 6.8: Red scoria fragment in Wall 701

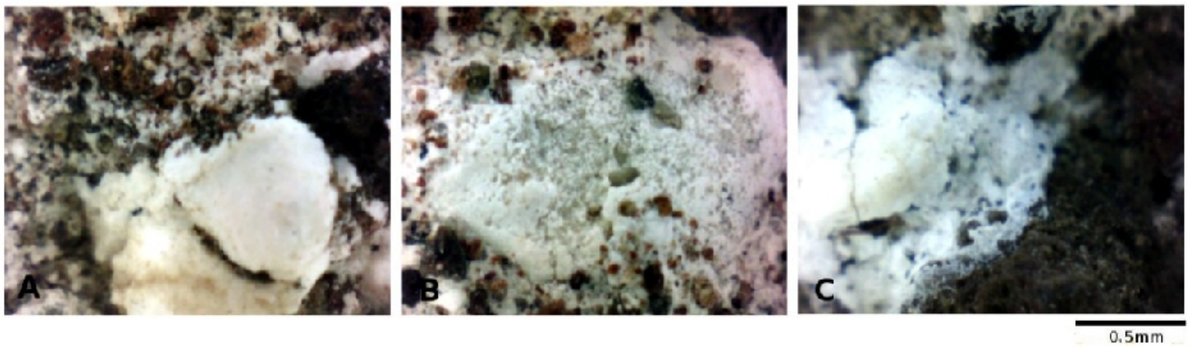

Figure 6.9: A: First phase pink mortar, Wall 125; B: Possible-Augustan phase pink mortar, Wall 152; C: Modern grey mortar, Wall 152

Data Management and GIS

The GIS analysis conducted at this stage was primarily for simple data display, but it demonstrated potential as a data analysis tool. A plot of inclusion densities of aggregate fragments within the ancient pink mortar showed that all of the low density (<30%) pink mortar walls were from the final construction phase (Figure 6.10). The majority of original phase pink mortar samples contained 30-60% aggregate inclusions. Only one wall exhibited a high inclusion density (>60%). The estimated percentage of clinopyroxene, leucite, and lime lumps were also plotted to test whether samples from different parts of single walls or from the same construction phases produced similar results (Figures 6.11-6.12). These images were based on visual estimates and represent a preliminary investigation of variance between samples from the same construction phase.

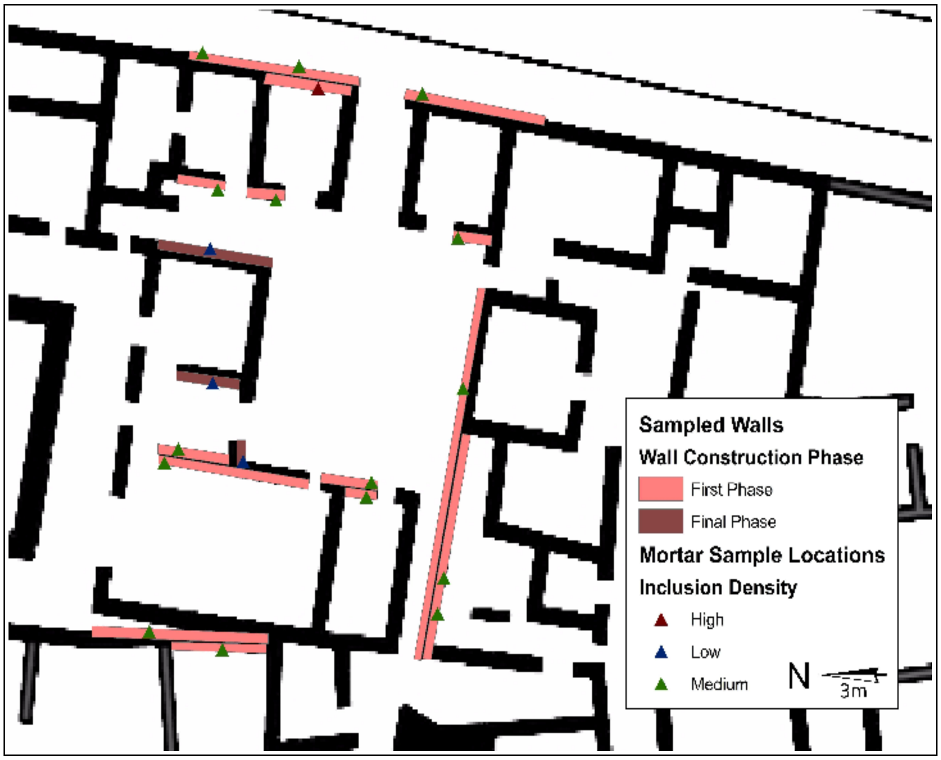

Figure 6.10: Estimated inclusion density of aggregate fragments in ancient pink mortar samples

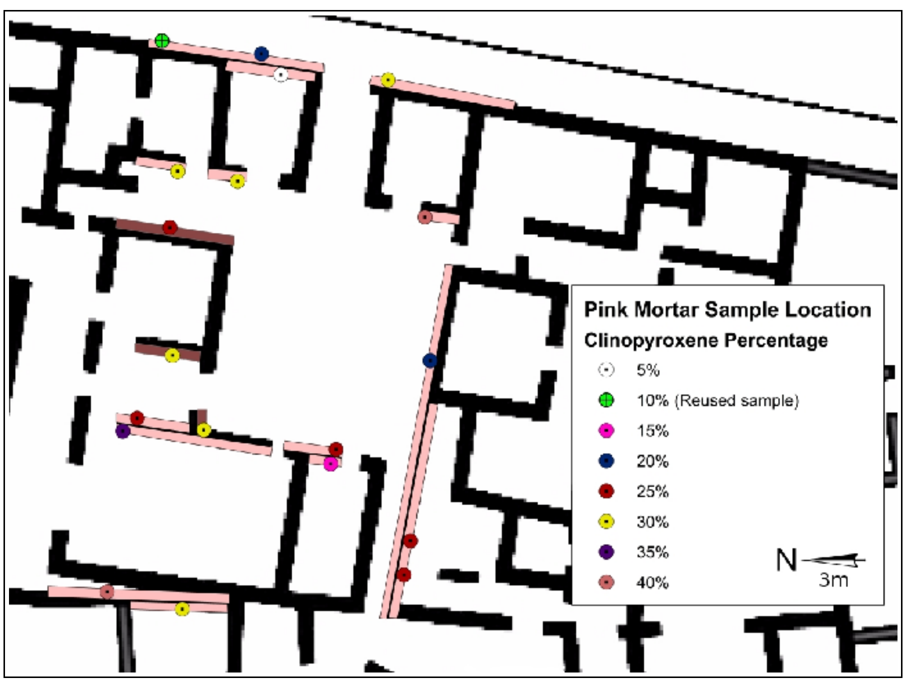

Figure 6.11: Plot of estimated percentages of Cpx in ancient pink mortar samples

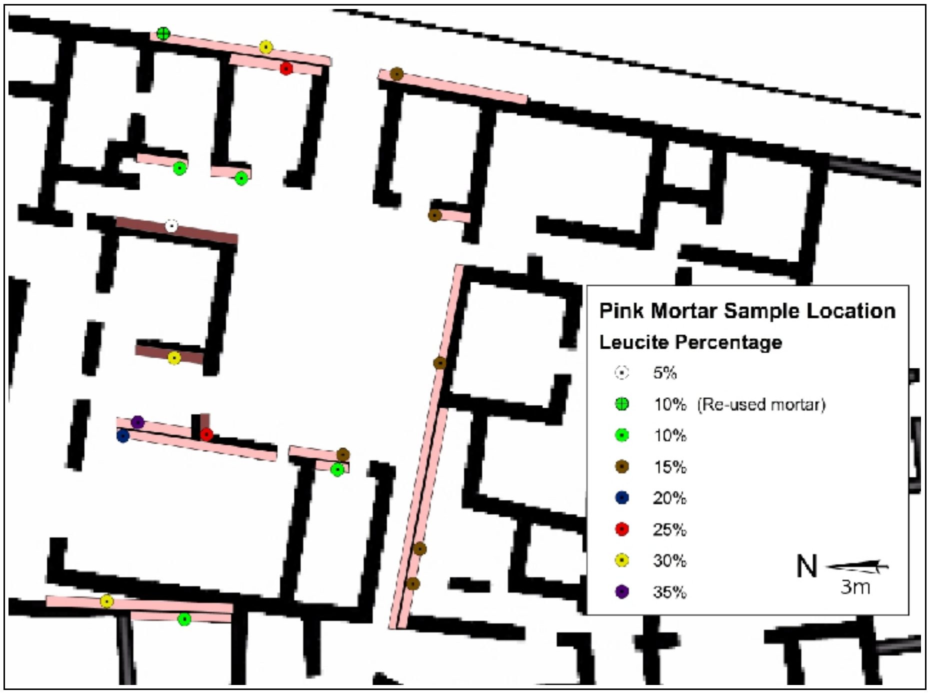

Figure 6.12: Plot of estimated percentages of Leucite in ancient pink mortar samples

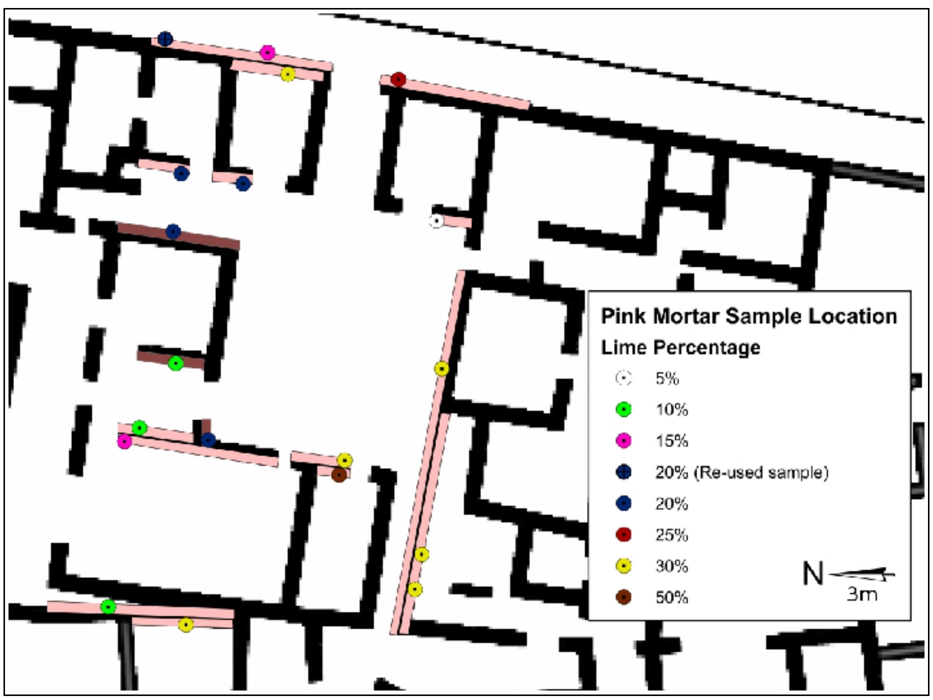

Figure 6.13: Plot of estimated percentages of Lime lumps in ancient pink mortar samples

Thin Section Petrography

The mineral phases identified in thin sections of the ancient pink mortar included leucite, clinopyroxene, olivine, and plagioclase (Figures 6.14-6.16; Appendix D). Red scoria lithic fragments, a few ceramic fragments, and lime lumps were also visible (Figures 6.17-6.18). The binder of the ancient pink mortars ranged from pink to reddish brown, often within the same sample; the lighter pink areas were invariably along the outer edges of the slide, suggesting the variation is caused by the thickness of the thin section (Figure 6.14).

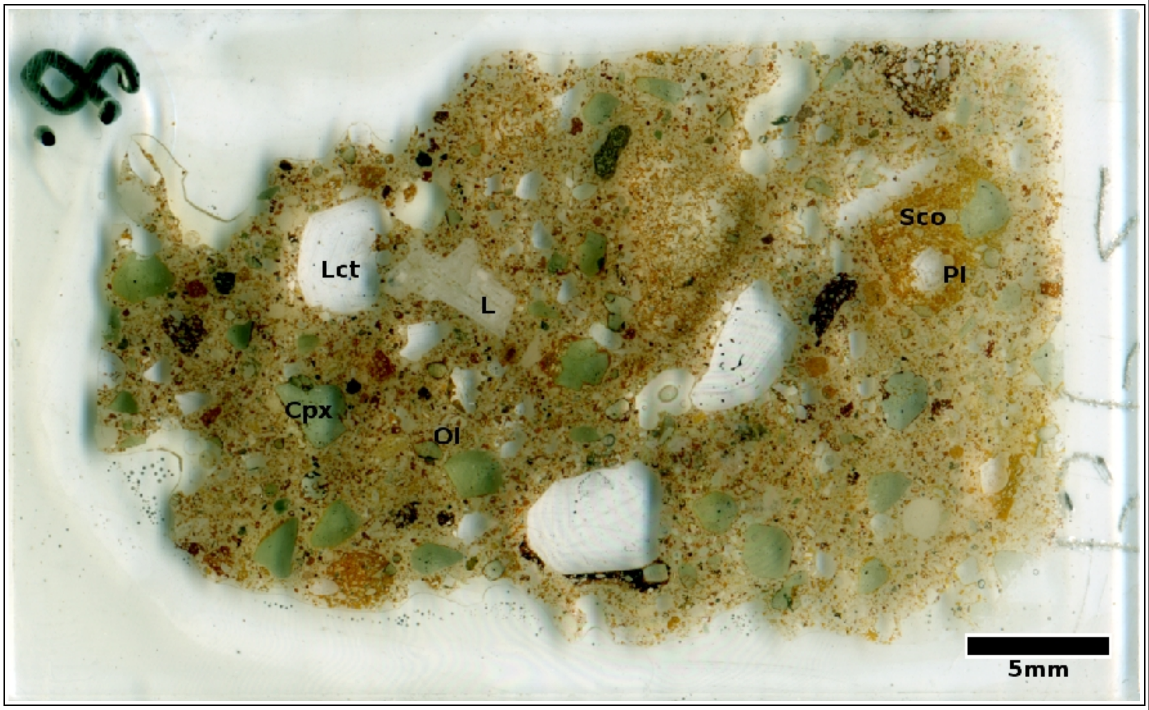

Figure 6.14: Scan of thin section W7-128-08 with inclusions labeled. Lct= leucite; Cpx=clinopyroxene; Pl=plagioclase; Ol=Olivine; Sco=scoria fragment; L=lime lump

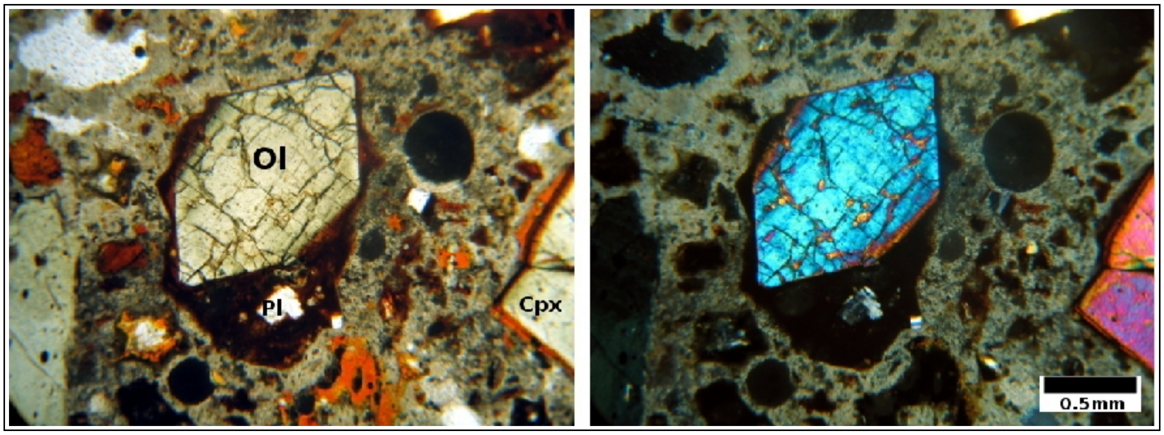

Figure 6.15: Photomicrograph of sample W7-152-06 in PPL (left) and XPL(right) showing clinopyroxene, plagioclase, and olivine grains; Cpx=clinopyroxene; Pl=plagioclase; Ol=Olivine

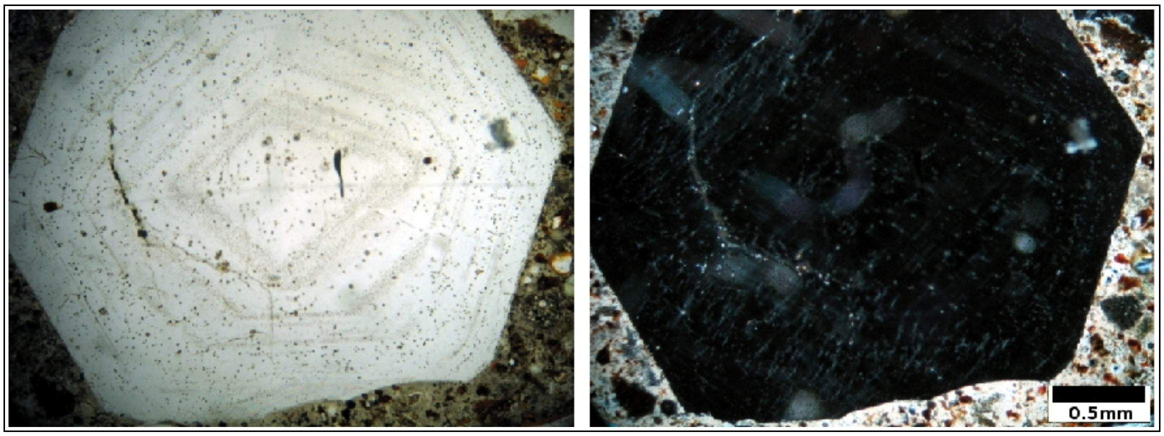

Figure 6.16: Photomicrograph of sample W7-128-11 in PPL (left) and XPL (right)showing leucite grain

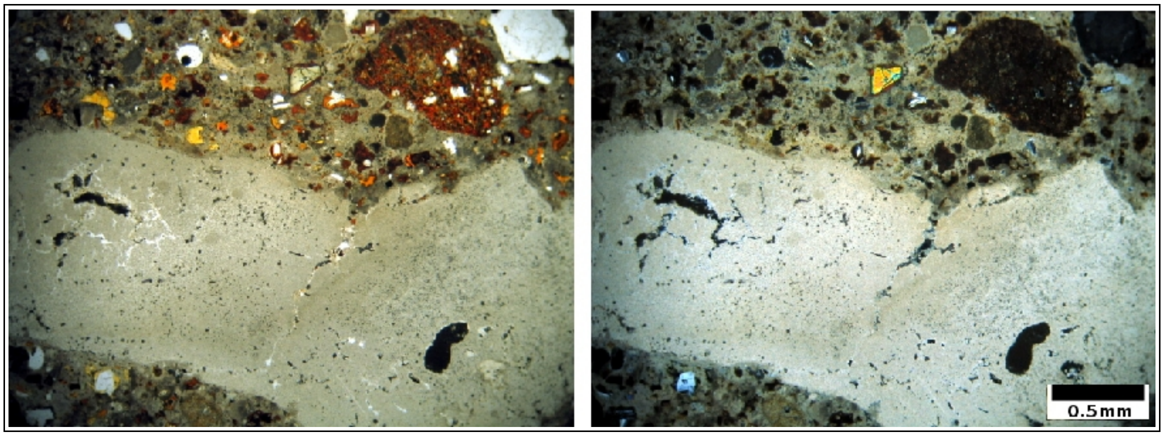

Figure 6.17: Photomicrograph of sample W7-152-06 in PPL (left) and XPL(right) showing lime lump

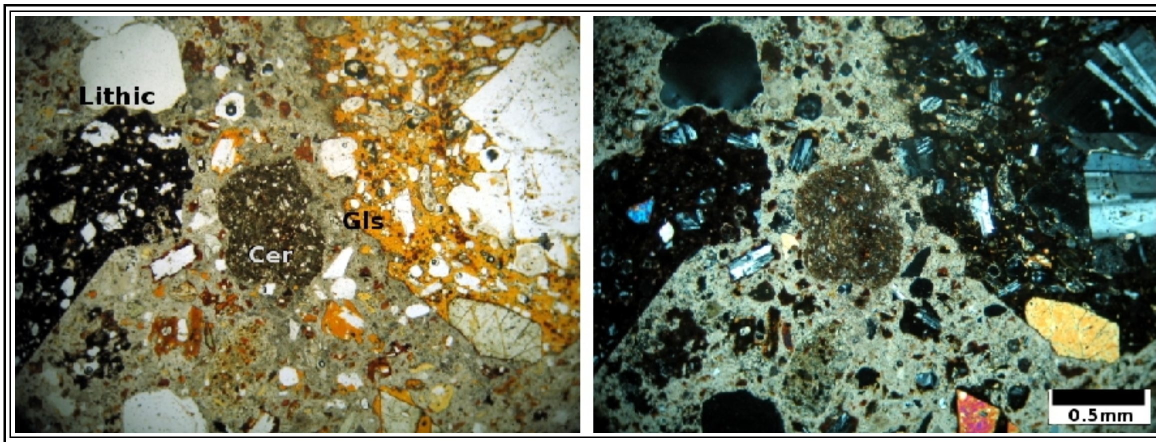

Figure 6.18: Photomicrograph of sample W7-112-08 in PPL (left) and XPL(right) showing lithic fragment, orange volcanic glass, and a small ceramic fragment; Cer=ceramic; Gls=volcanic glass

By comparison, the historic brown mortar, sample W7-108-22, had a much lighter beige colored matrix that was noticeably more porous (Figure 6.19). This sample lacked red scoria fragments but did contain darker grey lithic fragments. The major mineral phases visible were plagioclase and biotite. The brown mortar appeared quite different from the ancient pink mortar samples, including a larger average size of unprocessed lime lumps, multiple types of lithic aggregate fragments, and a lighter binder color. This was as expected because the brown mortar *in situ* looked so different from the original pink mortar (Figure 6.20).

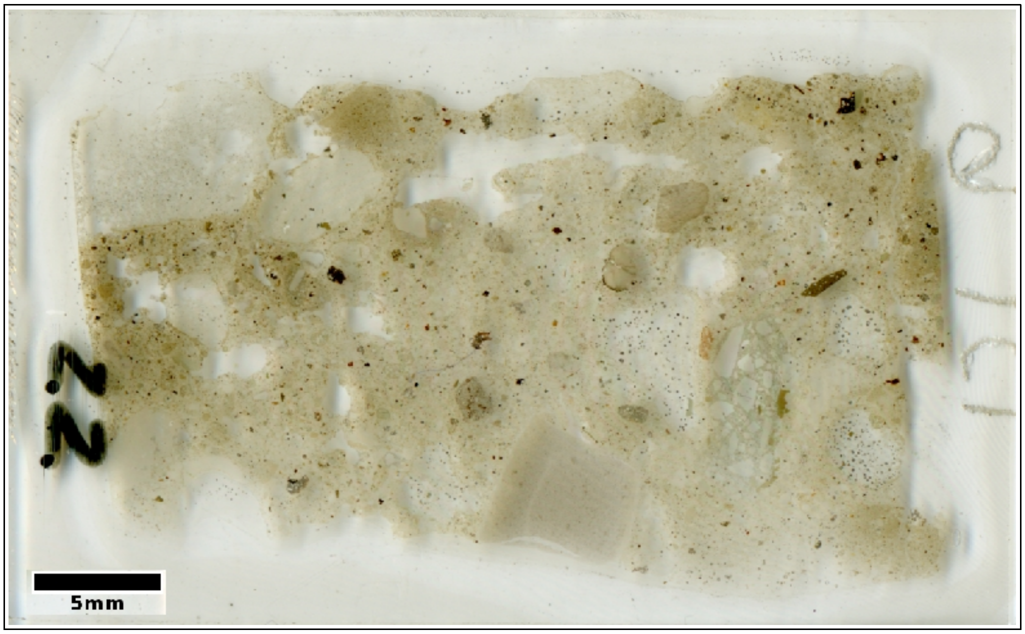

Figure 6.19: Scan of thin section W7-108-22

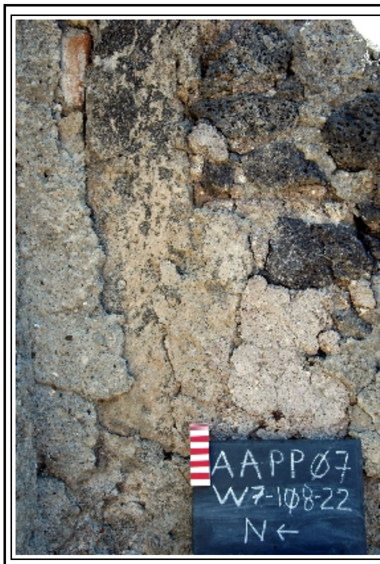

Figure 6.20: Brown repair mortar (left) overlying original pink mortar

X-ray Diffraction

The patterns generated with XRD analysis indicated that all samples contained the same major phases, detailed below (Figure 6.21). The diffractograms showed some peak broadening at 22-34º 2Θ, probably the effect of glassy material from the scoria fragments. The spectrum for the brown historic mortar contained the same major mineral phases and glass material as the ancient pink mortar, with the additional peaks at 8.7º 2Θ (unidentified) and 11.6º 2Θ (possibly gypsum) (Figure 6.21). Unfortunately, additional analysis of this sample was not possible within the parameters of this project.

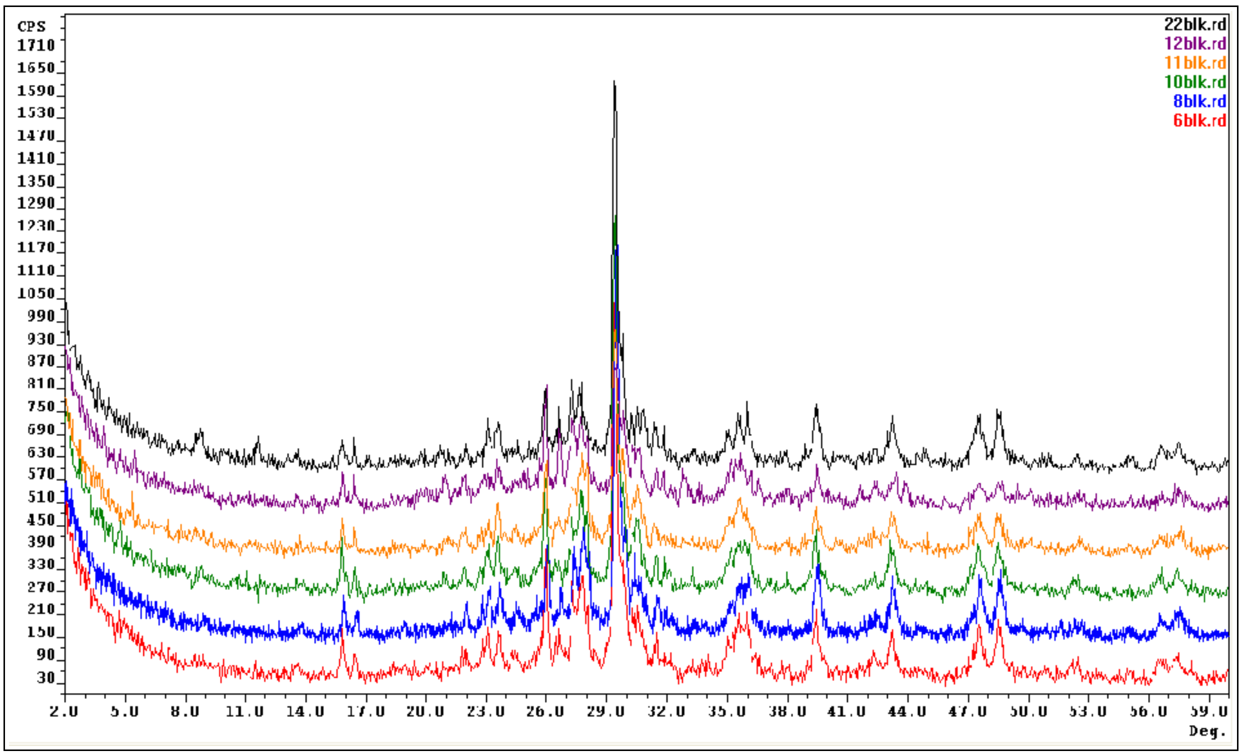

Figure 6.21: X-ray diffractograms of all analysed samples

The major mineral phases identified with XRD analysis were leucite, clinopyroxene, olivine, plagioclase (identified as albite), orthoclase (identified as sanidine), and calcite (Figures 6.22-6.27). Figure 6.28 illustrates that tall major peaks have been identified in the pink mortar.

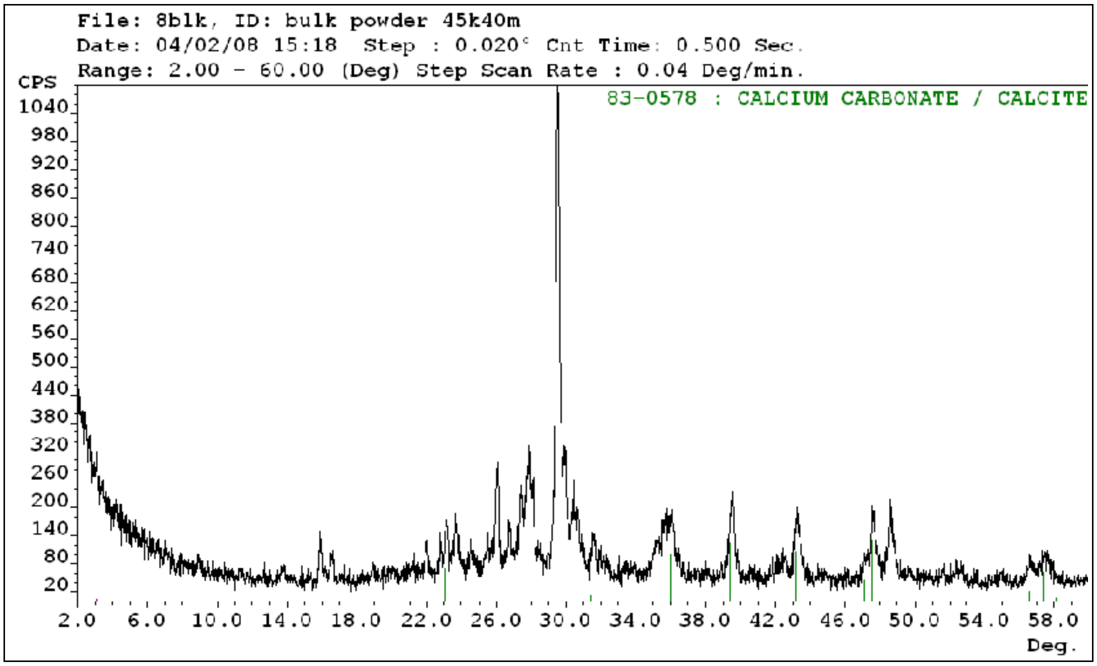

Figure 6.22: Sample W7-112-08 overlain with major peak data for calcite from the Powder Diffraction File

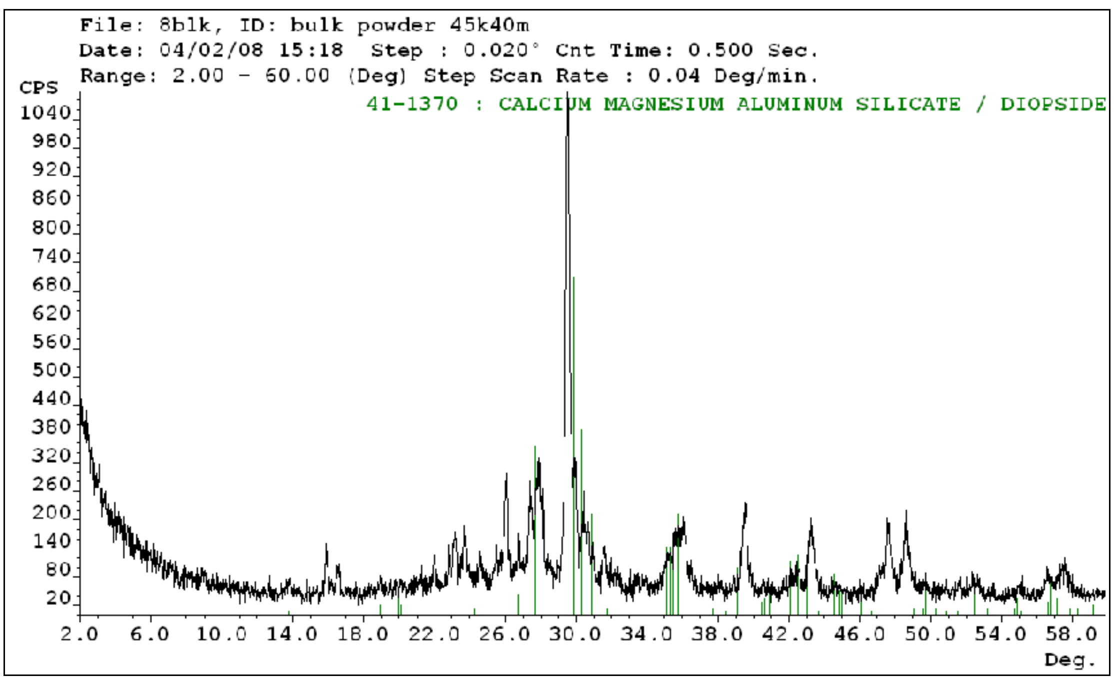

Figure 6.23: Sample W7-112-08 overlain with major peak data for diopside from the Powder Diffraction File

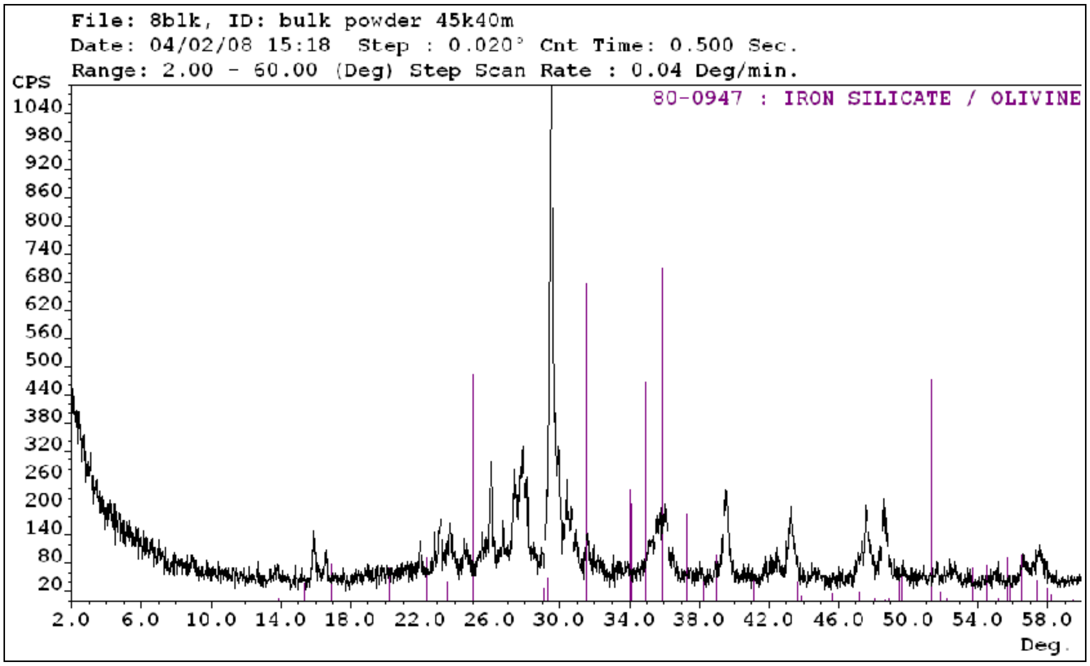

Figure 6.24: Sample W7-112-08 overlain with major peak data for olivine from the Powder Diffraction File

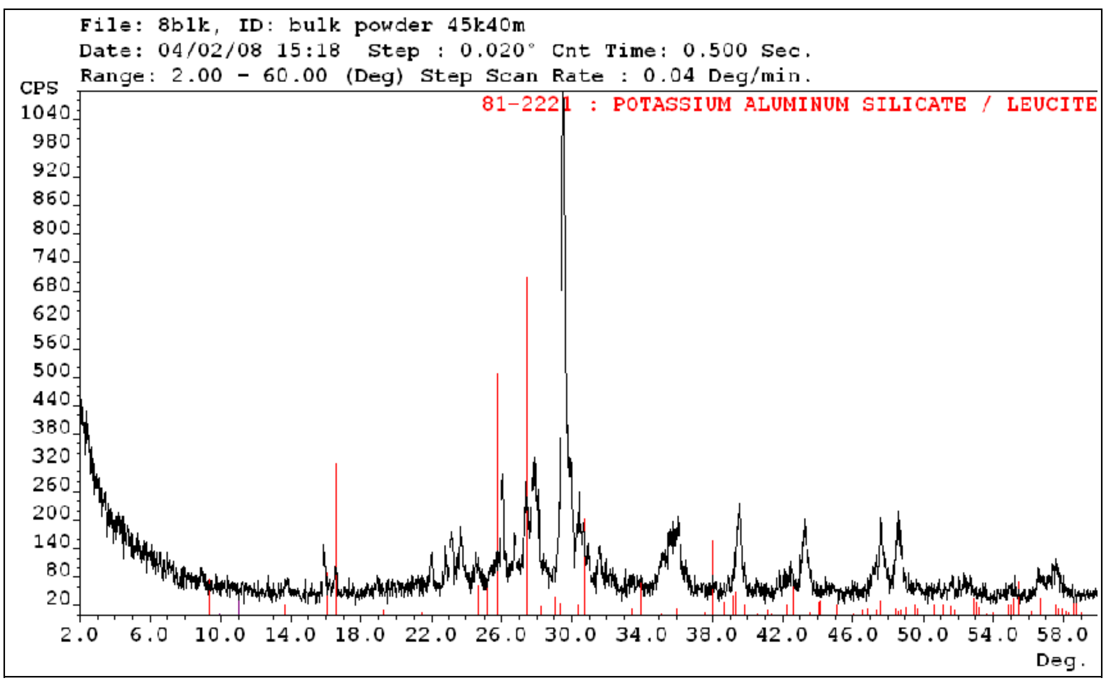

Figure 6.25: Sample W7-112-08 overlain with major peak data leucite from the Powder Diffraction File

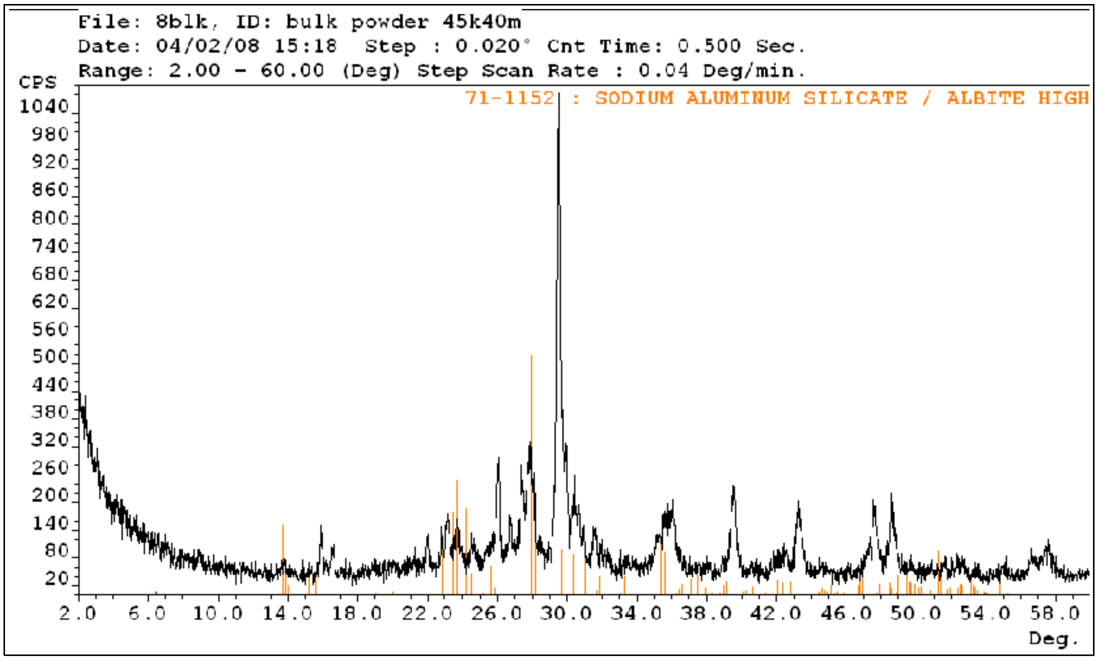

Figure 6.26: Sample W7-112-08 overlain with major peak data for albite from the Powder Diffraction File

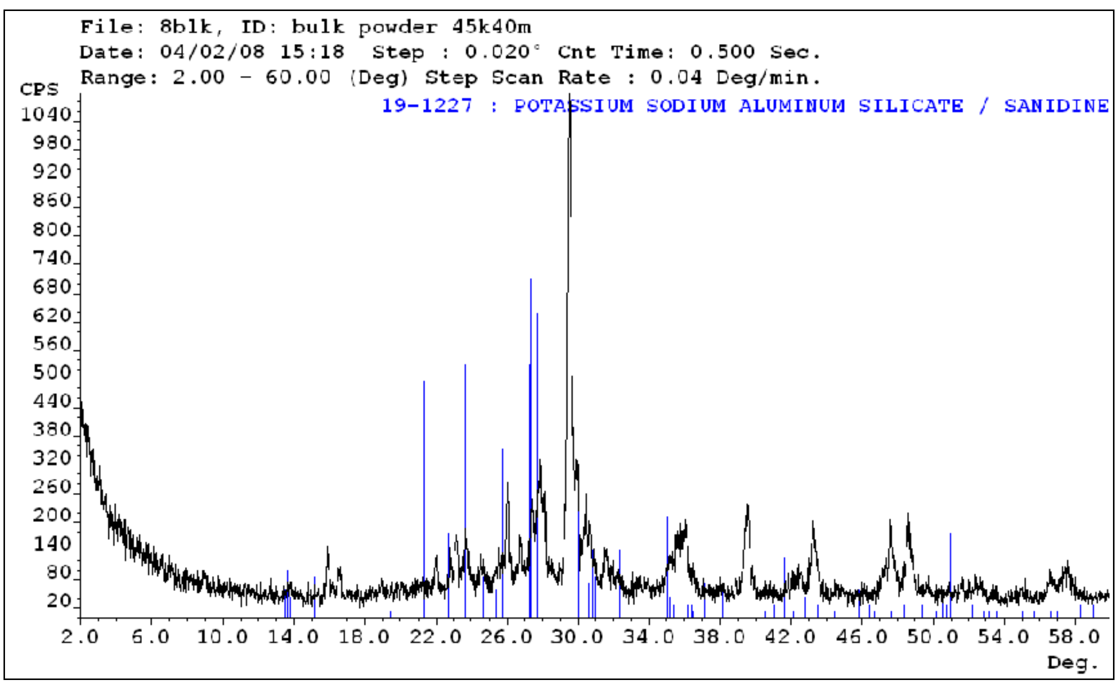

Figure 6.27: Sample W7-112-08 overlain with major peak data for sanidine from the Powder Diffraction File

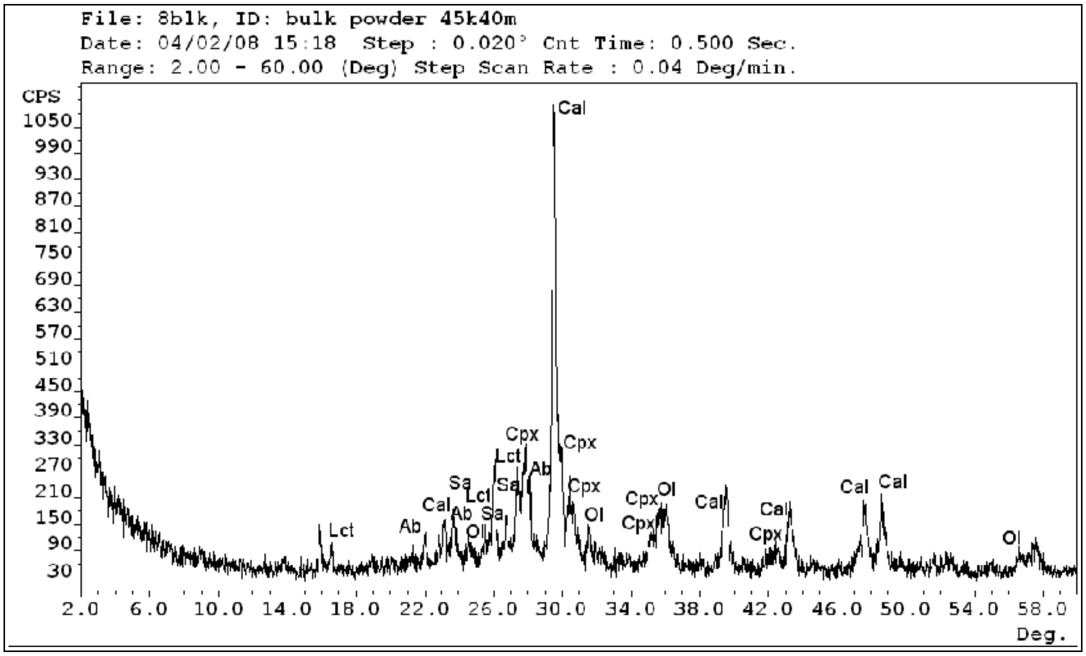

Figure 6.28: X-ray diffractogram of sample W7-112-08, all major mineral phases labeled; Cal=calcite; Cpx=clinopyroxene; Lct=leucite; Ol=olivine; Al=albite; Sa=Sanidine

X-ray Fluorescence

Reported XRF data for each element, including mean and standard deviation, are listed in Table 6.1. Those with the highest standard deviation include SiO_2, CaO, and LOI. The correlation matrix produced by the XLSTAT software showed that CaO, MgO and LOI shared strong positive correlation to each other, but strong negative correlations to all other elements (Table 6.2). These components represent the lime-based binder. Al_2O_3 and SiO_2, representing the silicate aggregate, shared a strong positive correlation to each other, and near equal negative correlation to CaO (-0.938 and -0.939 respectively).

Table 6.1: Normalized XRF data

Sample ID	Mortar Color	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3	LOI
W7-125-1	**Original Pink**	1.94	4.14	13.55	34.59	0.43	2.76	20.30	0.52	0.09	4.80	16.89
W7-151-2	**Original Pink**	1.83	4.01	13.34	32.68	0.37	2.53	21.67	0.49	0.25	4.52	18.31
W7-701-3	**Original Pink**	2.20	4.04	14.95	35.91	0.43	3.26	17.82	0.53	0.86	5.23	14.77
W7-701-4	**Re-Used Pink**	2.49	3.62	14.09	35.36	0.47	3.63	18.37	0.53	0.08	4.61	16.77
W7-702-5	**Original Pink**	1.85	3.72	12.72	30.88	0.50	2.80	20.36	0.46	0.08	4.34	22.31
W7-152-6	**AugustanPink**	1.78	4.39	14.42	34.58	0.41	3.05	19.17	0.52	0.09	4.76	16.82
W7-116-7	**Original Pink**	1.92	3.42	15.02	36.94	0.44	3.32	18.70	0.54	0.09	4.99	14.63
W7-112-8	**Original Pink**	1.89	4.14	13.73	35.54	0.39	2.95	20.54	0.51	0.09	4.86	15.35
W7-118-9	**Original Pink**	2.26	4.01	14.14	33.74	0.41	3.54	19.49	0.48	0.08	4.47	17.37
W7-123-10	**AugustanPink**	2.30	4.23	14.82	35.47	0.38	3.31	19.28	0.51	0.09	4.85	14.77
W7-128-11	**Original Pink**	2.23	3.74	14.83	36.41	0.43	3.44	18.12	0.53	0.08	4.78	15.41
W7-205-12	**Original Pink**	1.98	5.32	16.02	38.46	0.37	3.53	15.11	0.53	0.09	5.00	13.59
W7-108-13	**Original Pink**	2.05	3.78	13.63	34.50	0.37	2.90	20.29	0.50	0.19	4.67	17.13
W7-136-14	**Original Pink**	1.93	3.80	14.01	35.12	0.42	2.83	19.83	0.52	0.09	4.89	16.56
W7-127-15	**Original Pink**	2.03	3.51	13.71	33.87	0.42	2.63	21.47	0.52	0.09	4.73	17.03
W7-45-16	**Original Pink**	1.83	3.96	12.98	33.23	0.46	2.91	21.75	0.48	0.08	4.49	17.84
W7-45-17	**Original Pink**	2.50	3.69	13.27	31.66	0.39	3.28	21.56	0.48	0.17	4.38	18.60
W7-45-18	**Lime Lump**	0.19	10.71	3.22	2.53	0.04	0.23	44.36	0.06	0.02	0.40	38.24
X701-2-20	**Floor Mortar**	1.80	3.01	14.20	36.20	0.39	4.03	13.04	0.56	0.13	4.76	21.88
W7-118-21	**AncientYellow**	2.45	2.23	17.05	42.62	0.27	4.69	11.56	0.54	0.10	4.73	13.76
W7-108-22	**HistoricBrown**	2.00	4.02	13.26	31.92	0.32	3.55	21.52	0.44	0.09	3.72	19.17
W9-16-23	**Original Pink**	1.86	5.87	14.70	37.73	0.42	3.29	16.05	0.54	0.09	5.11	14.34
W6-118-24	**Ancient Grey**	1.98	4.83	15.62	38.87	0.40	3.28	14.76	0.56	0.39	5.14	14.17
W7-152-25	**Modern Grey**	1.25	4.97	14.21	35.55	0.36	1.58	25.78	0.56	0.17	4.86	10.72

Table 6.2: Correlation matrix of XRF data for all mortar samples

Variables	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3	LOI
Na_2O	**1**	**-0.832**	**0.797**	**0.782**	**0.660**	**0.857**	**-0.803**	**0.733**	0.177	**0.735**	**-0.670**
MgO	**-0.832**	**1**	**-0.805**	**-0.825**	**-0.702**	**-0.779**	**0.801**	**-0.814**	-0.106	**-0.781**	**0.667**
Al_2O_3	**0.797**	**-0.805**	**1**	**0.989**	**0.668**	**0.814**	**-0.938**	**0.954**	0.223	**0.940**	**-0.923**
SiO_2	**0.782**	**-0.825**	**0.989**	**1**	**0.703**	**0.797**	**-0.939**	**0.974**	0.189	**0.958**	**-0.925**
P_2O_5	**0.660**	**-0.702**	**0.668**	**0.703**	**1**	**0.498**	**-0.661**	**0.776**	0.154	**0.817**	**-0.638**
K_2O	**0.857**	**-0.779**	**0.814**	**0.797**	**0.498**	**1**	**-0.914**	**0.704**	0.087	**0.667**	**-0.576**
CaO	**-0.803**	**0.801**	**-0.938**	**-0.939**	**-0.661**	**-0.914**	**1**	**-0.894**	-0.193	**-0.875**	**0.755**
TiO_2	**0.733**	**-0.814**	**0.954**	**0.974**	**0.776**	**0.704**	**-0.894**	**1**	0.223	**0.983**	**-0.917**
MnO	0.177	-0.106	0.223	0.189	0.154	0.087	-0.193	0.223	**1**	0.284	-0.233
Fe_2O_3	**0.735**	**-0.781**	**0.940**	**0.958**	**0.817**	**0.667**	**-0.875**	**0.983**	0.284	**1**	**-0.920**
LOI	**-0.670**	**0.667**	**-0.923**	**-0.925**	**-0.638**	**-0.576**	**0.755**	**-0.917**	-0.233	**-0.920**	**1**

Values in bold are significantly different from 0 with a significance level alpha=0.05

Scatter plots were created to examine the relationships between elemental oxides with both strong and negative correlations. Figure 6.29 illustrates the ratio of CaO:MgO for each mortar sample (lime sample 18 has been excluded from this and subsequent plots). The cluster in the center includes all but two of the ancient pink mortar samples; it also includes the brown mortar sample. The outliers include ancient yellow mortar (sample 21), ancient grey mortar (sample 24), ancient pink flooring mortar (sample 20), modern grey mortar (sample 25), and two ancient pink mortar samples from different sides of the same wall (samples 23 and 12, see Figure 5.2 for sample locations). Figure 6.30 illustrates the ratio of CaO:SiO_2 for all mortar samples, though the cluster is not as tight, the groupings and outliers are generally the same.

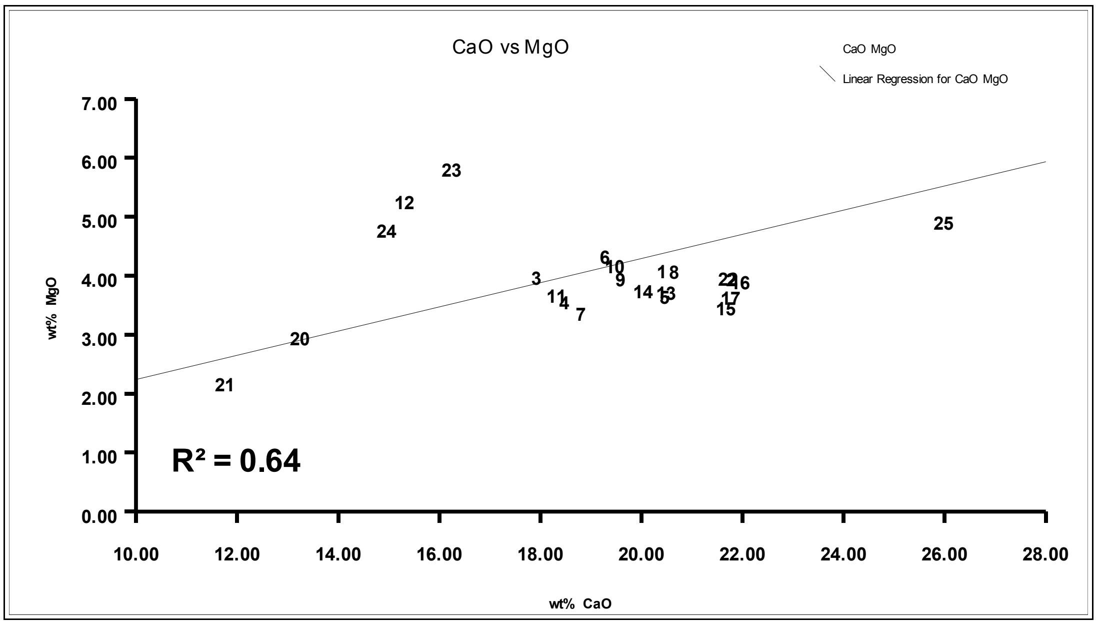

Figure 6.29: Scatter plot of CaO and MgO wt % oxide in mortar samples

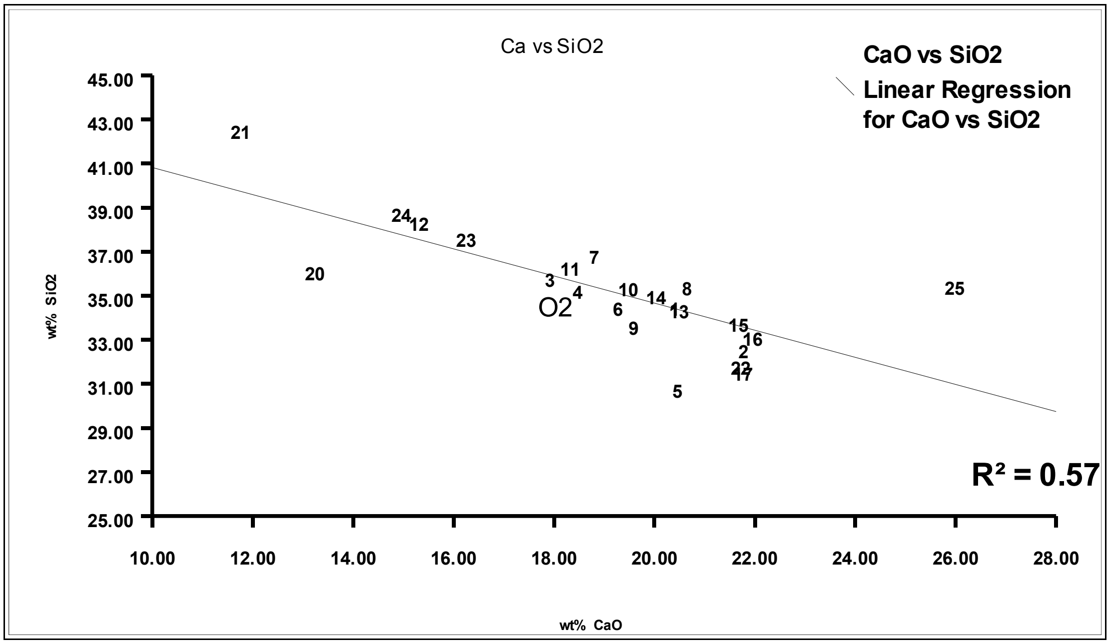

Figure 6.30: Scatter plot of CaO and SiO_2 wt % oxide ratios in mortar samples

PCA showed that CaO, LOI, and MgO strongly contributed toward variance within the sample set (Figures 6.31A). MnO also stood out as a potential key component, though it was present in very low amounts, so its true importance is not clear. It may be connected to the outlier sample 3 (W7-701-3), which had a much higher concentration of MnO than any other sample (Figure 6.31B, Table 6.1). Other clear outliers include sample 18 (large lime sample), sample 24 (ancient grey mortar), and sample 25 (modern grey mortar).

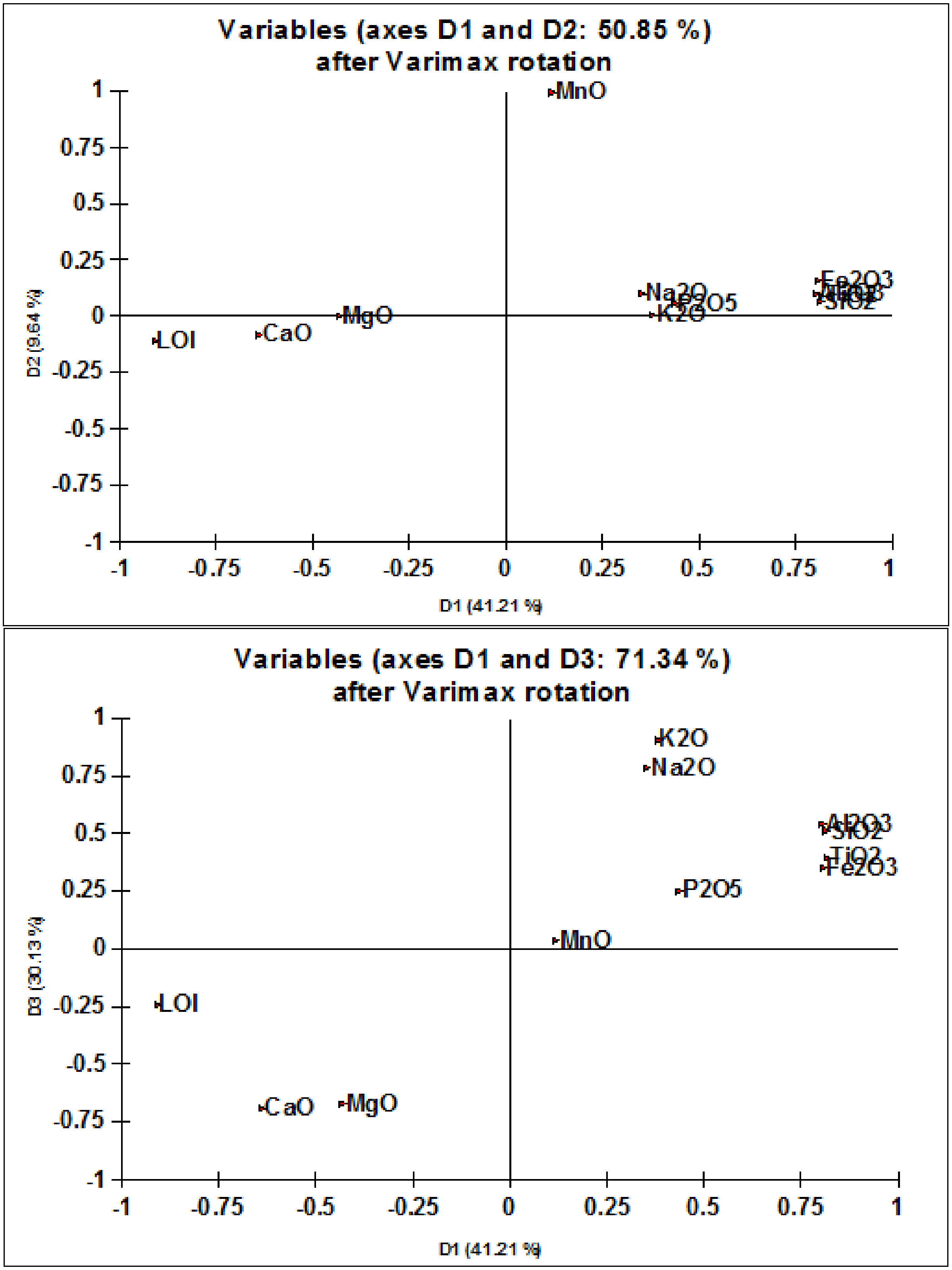

Figure 6.31: PCA results for XRF data - variables

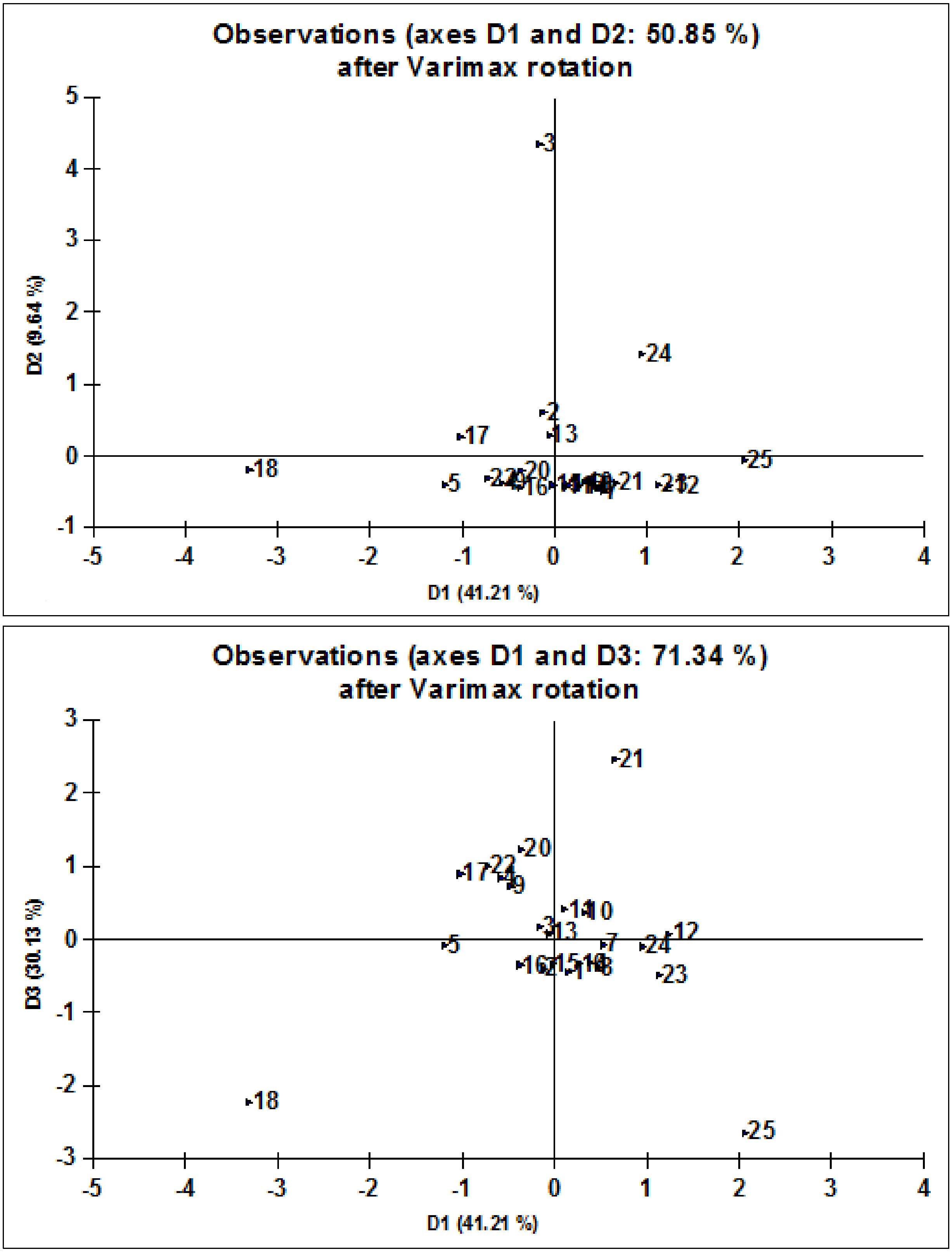

Figure 6.32: PCA results for XRF data - observations

Portable NIR

The averaged pattern for pink mortar produced near-infrared spectra that in key wavelengths resembled concrete spectra published by JPL (Figure 6.32). A conspicuously similar band was the broad peak at 2000-2250nm, present in all three spectra. When compared to each other, the most apparent differences among the *in situ* mortar types were again in the 2000-2250nm band (Figure 6.33). Averaged spectra for all tested walls are included as Appendix F.

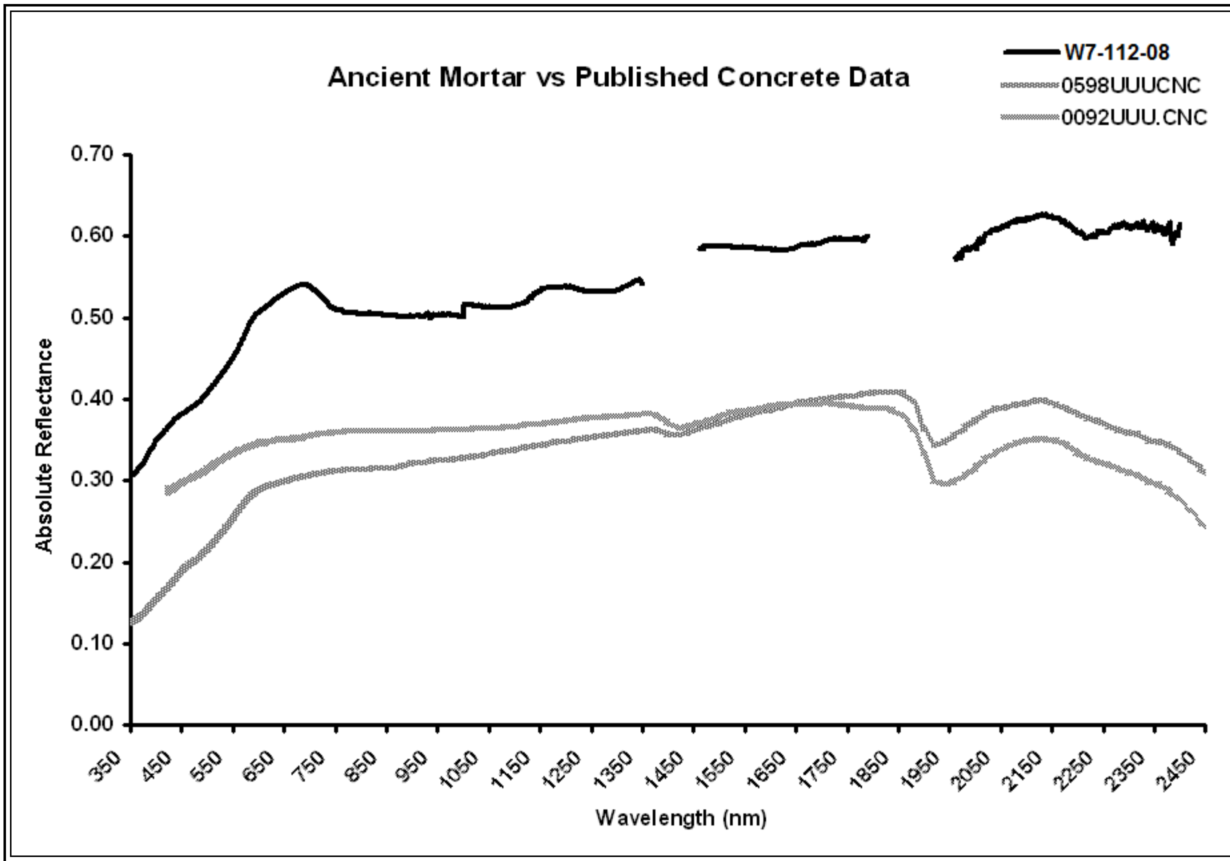

Figure 6.33: Comparison of ancient mortar sample W7-112-8 to modern concrete data published by JPL.

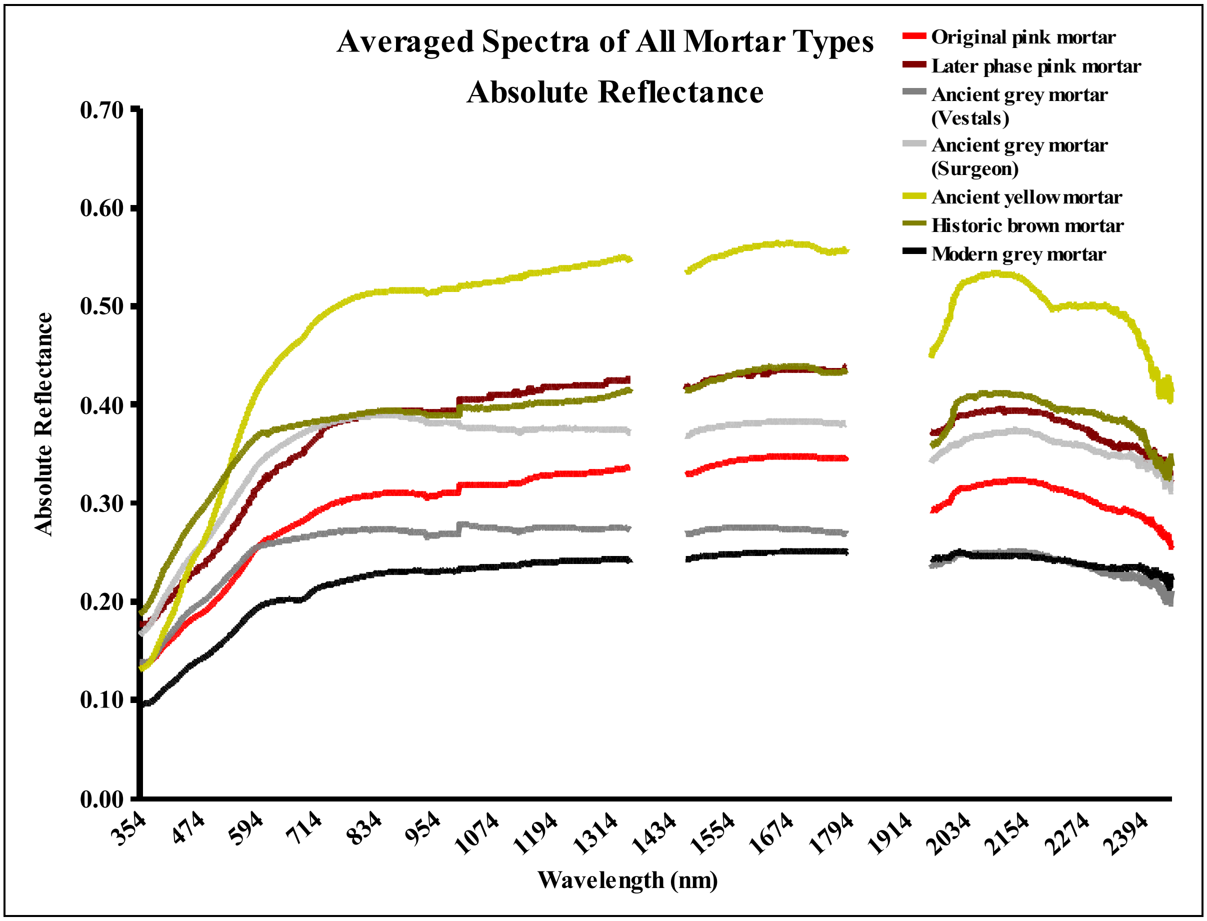

Figure 6.34: Comparison of all anlaysed mortar types.

Spectra from collected bulk samples were compared to field collected spectra to test whether the samples "matched" the spectra from their original location on the walls. Looking again at the peaks in the higher wavelengths, there was not a consistent similarity between the mortar samples and their parent walls. Figure 6.34 illustrates a sample/wall pair showing significant differences in the band at 2200-2250nm. The lower wavelength bands at 500-750nm also showed very different features in this and other samples. Ten of the 18 walls sampled varied dramatically from the collected mortar sample in peak shape, breadth, or placement (Appendix G).

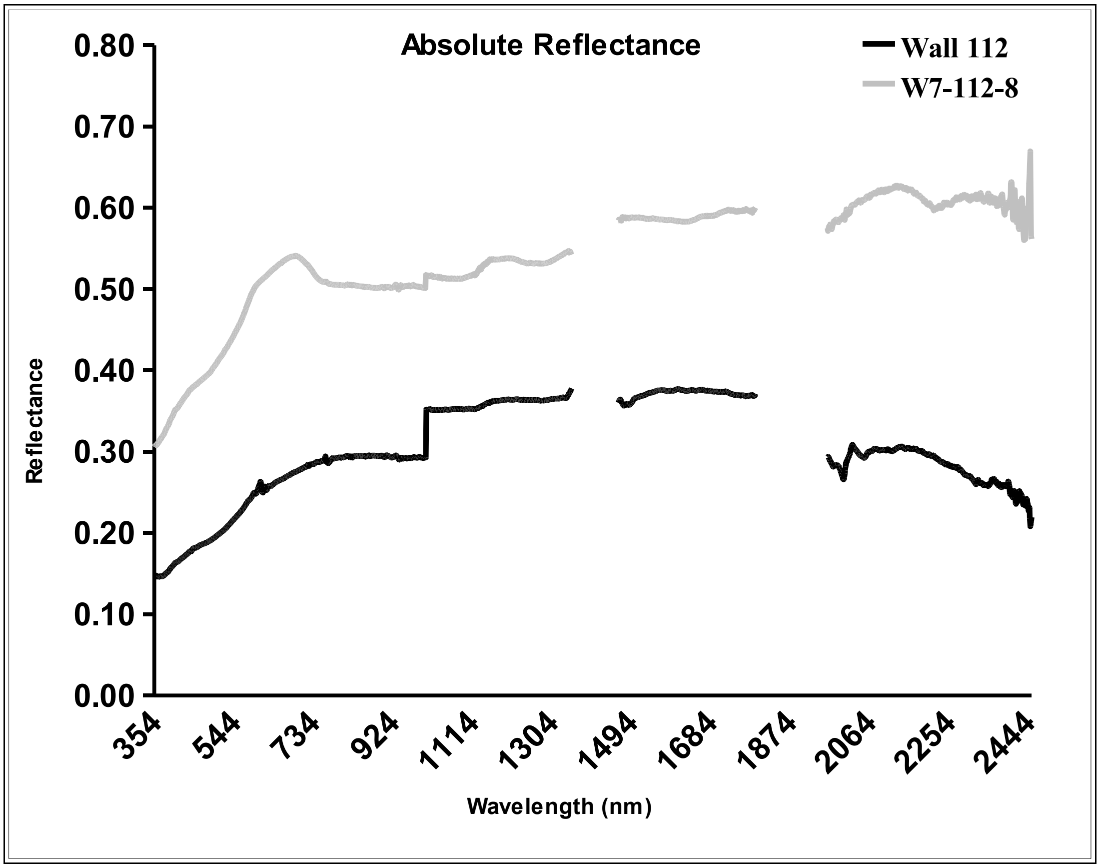

Figure 6.35: Comparison of a mortar sample to its parent wall

Portable NIR analysis of wall mortar and collected samples did not detect the silicate minerals identified with thin section and XRD. Figures 6.35-6.39 illustrate the spectra from a bulk mortar sample compared to published mineral data of clinopyroxene, olivine, albite and sanidine. No published NIR spectral data were found for leucite, as of this writing. The silicate minerals are infrared active in the mid-IR region, wavelengths which are beyond detection with the FieldSpec® 3.

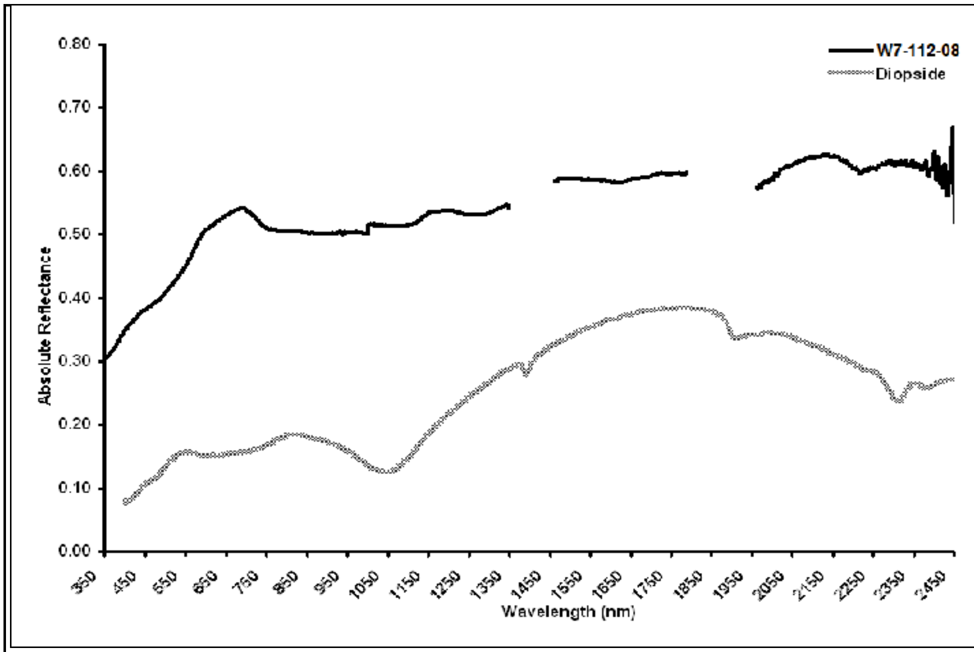

Figure 6.36: Comparison of mortar sample to JPL data for clinopyroxene

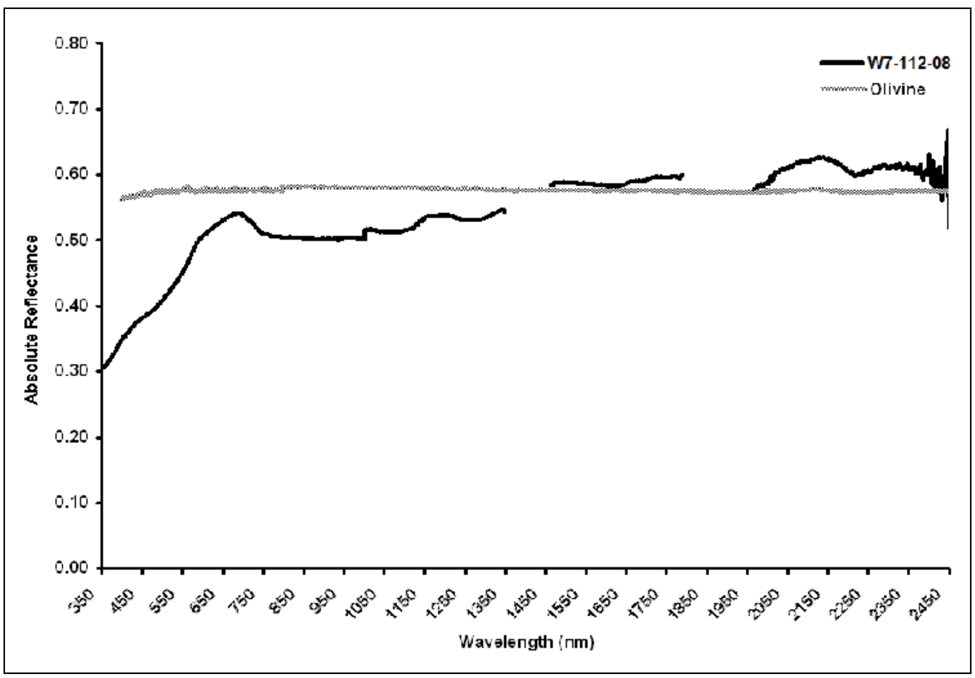

Figure 6.37: Comparison of mortar sample to JPL data for olivine

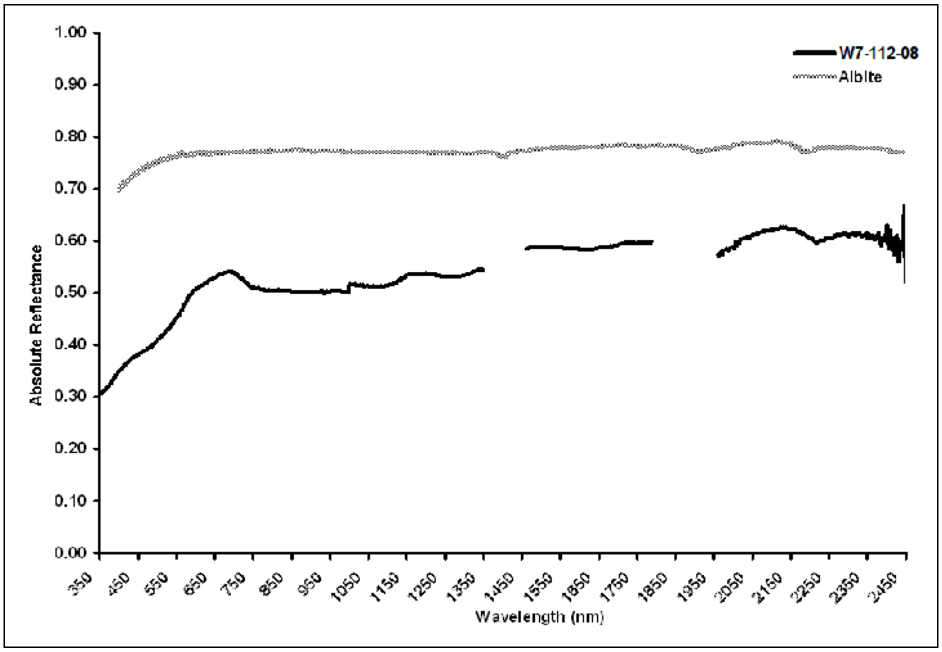

Figure 6.38: Comparison of mortar sample to JPL data for albite

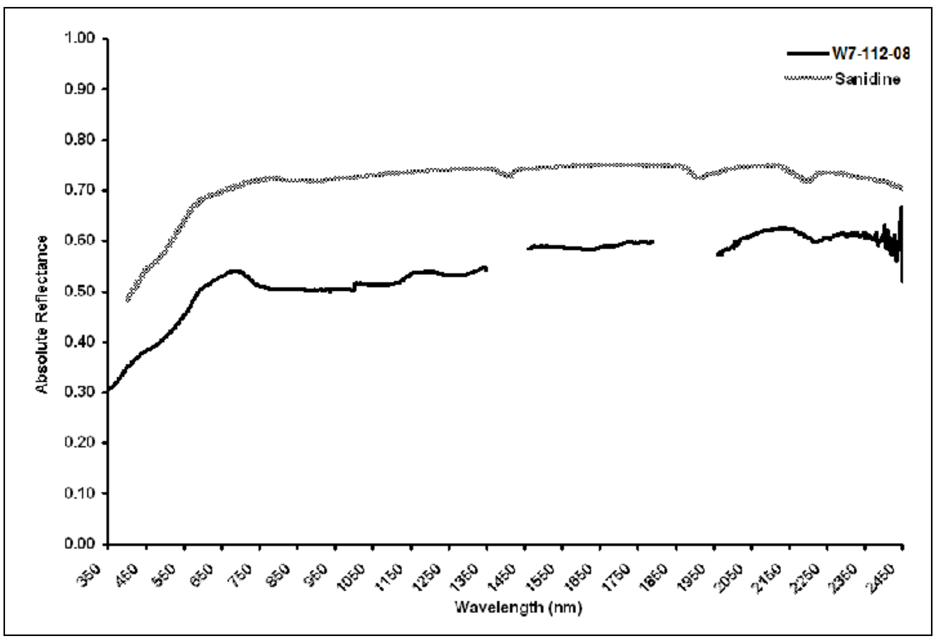

Figure 6.39: Comparison of mortar sample to JPL data for sanidine

Infrared activity in the 2000-2350nm band is typically associated with carbonate minerals, such as the calcite identified with XRD (Gaffey 1986). The reference sample of calcite contained the same basic pattern as published data for calcite, especially peaks in the bands from 2000-2160nm and 2160-2200nm and an absorption trough at 2330nm (also seen in the lime lump sample) (Figure 6.39). Intensity of the lime is closer to that of published calcite data, but the calcite sample tested with the FieldSpec® 3 had a lower intensity than either.

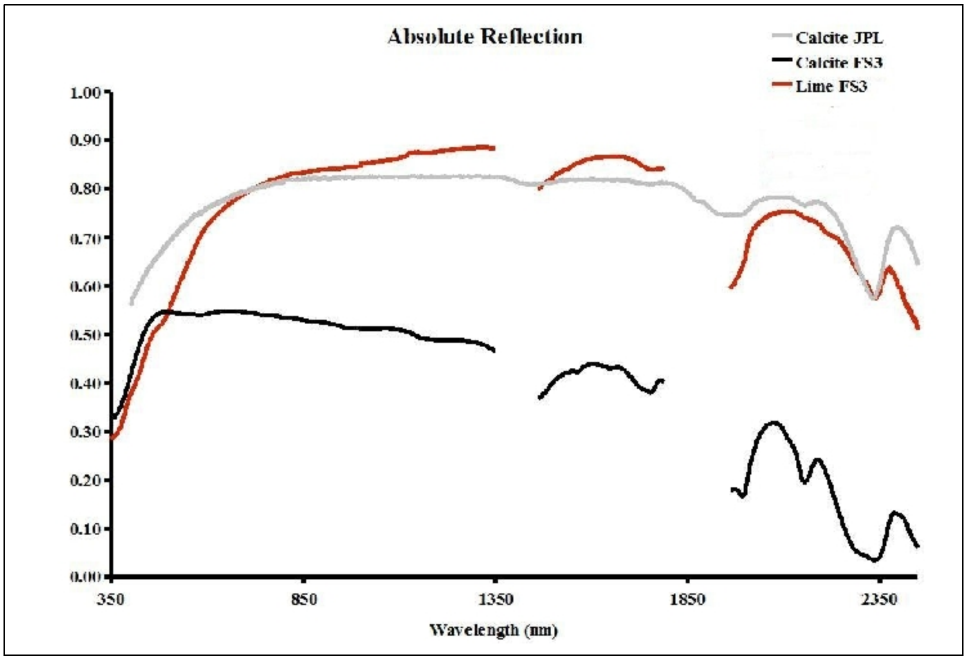

Figure 6.40: Comparison of calcite and lime samples to JPL data for calcite

Statistical analysis of the spectral data identified the bands that quantitatively contribute most to the variance between samples. The Unscrambler software displayed the PCA data as a plot of factor loadings for each wavelength along the x-axis (Figure 6.40). The key bands 500-750nm, 2000-2250nm, and 2250-2400nm appeared as peaks in the graph. A plot of factor loadings for each wall reveals one extreme outlier, Wall 701, one of the original phase pink mortar samples.

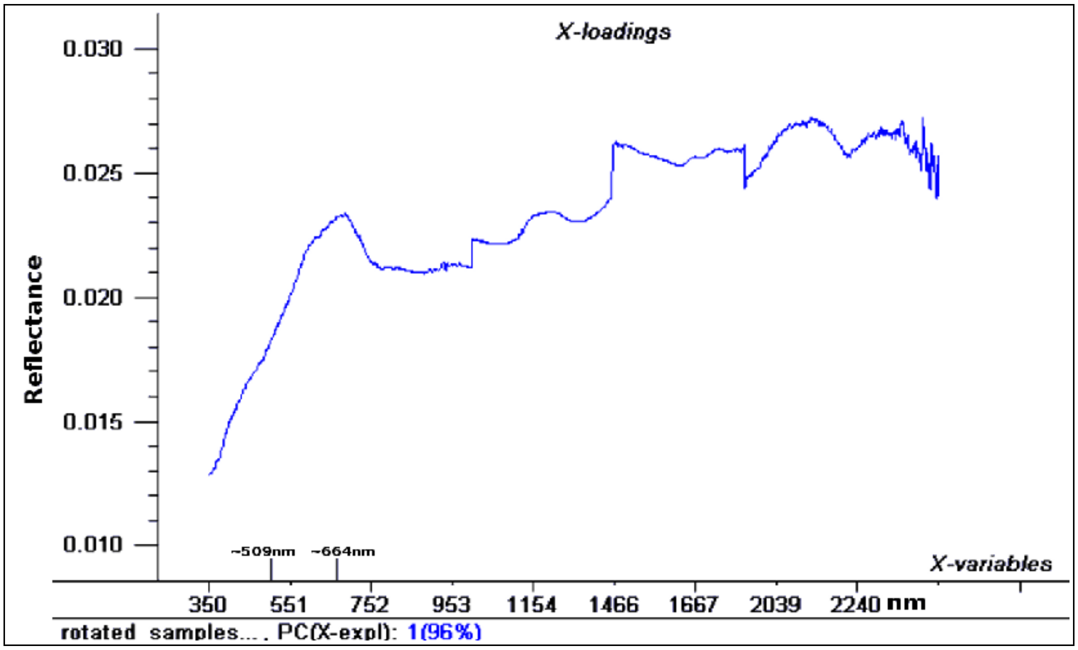

Figure 6.41: Factor loadings of NIR spectral data

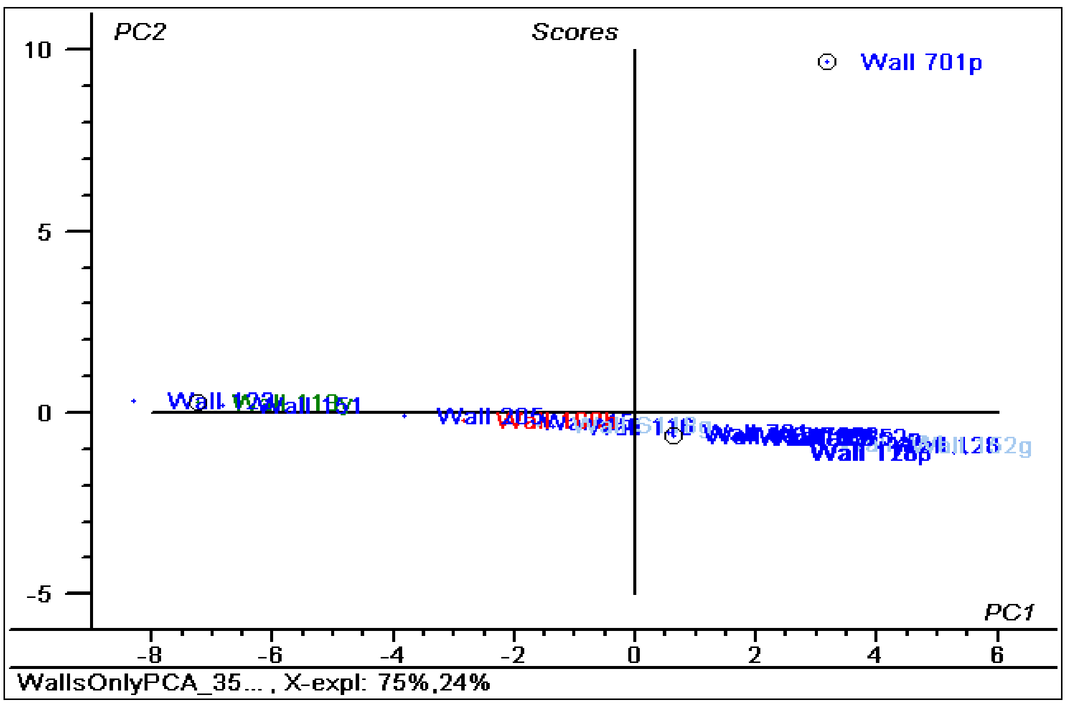

Figure 6.42: PCA of NIR spectral data

CHAPTER 7

DISCUSSION

Sample collection and preliminary analysis raised the following series of research questions that could be addressed with a comprehensive mortar study:

- What is the complete mineral assemblage of the pink mortar?
- Can this assemblage be linked to the geology of the area?
- What causes the distinctive pink color?
- What makes the pink mortar so distinctively strong?
- How compositionally similar or different are mortar samples from within a single construction phase?
- Is there a range of compositional values for each component within a single construction phase?
- Is there a chemical distinction between early and later phase mortars?
- Is there a chemical distinction between in situ pink mortar and re-used pink mortar “rocks”?
- Can re-used pink mortar be linked to specific walls containing in situ pink mortar?
- Can the lime lumps be used to identify distinct mortar batches?
- Can weathering be identified, analysed, or explained with this research model?
- Is there a distinction between the mortar of interior and exterior walls?
- Is there a distinction between mortar from the inner core and the outer face of walls?

This project did not attempt to answer all of the above questions, but rather to test the suitability of portable field methods to address these and other questions. In order to test the reliability and quality of collected data, preliminary composition determinations with traditional laboratory techniques was necessary, if only to outline what successful results and quality data *should* be.

Throughout sample collection, the pink mortar was consistently harder and less friable than that of subsequent building phases. All "non-pink" mortars would typically reduce to a powder with only a fingernail scratch along the surface, while the pink mortar was very hard and difficult to remove. In fact, the Marshalltown trowel blade often bent in resistance before the pink mortar would separate from the wall stones. The apparent superior strength of the pink mortar can be attributed to the use of crushed scoria as aggregate. Hossain (2006) has determined that scoria is naturally pozzolanic and therefore acts as an additional cementing agent. The alkali-silica reaction in the presence of water and lime causes expansion of the cement during the curing process, adding both strength and insulation to the mortar (Hossain 2006).

The re-use of the pink mortar as a wall component underscores the apparent relative strength of this particular mortar compared to other types seen throughout the House of the Vestals. The presence of re-used pink mortar in the southern bar (Bar of Phoebus) suggests a potential relationship between construction events in the north and south of the insula. In a comprehensive insula-wide mortar study, comparison of excavation data, artifact assemblages, and architectural analysis from both properties should be compared for evidence of concurrent construction phases that may indicate insula-wide changes.

The study of the aggregate inclusion density has been conducted in lieu of traditional binder/aggregate ratio tests. These typically require chemical separation of aggregate materials which are beyond the scope of this project (Casadio et al 2005). The crude estimates recorded in Appendix B and plotted in Figures 6.10 may indicate some variation in the mortar found in walls presumed to be have been built in different construction phases. When investigated individually, the estimated percentages of identifiable aggregate inclusions are only slightly more provocative. A pair of samples from two walls that were originally a single wall (Walls 151, 125) consistently showed the same estimated percentage of clinopyroxene, leucite, and lime (Figures 6.11-6.12). Likewise, three samples from the north and south sides of the same wall (Wall 127/45) contained the same percentages of leucite and lime and only a five percent difference in visible clinopyroxene grains. The extent of variation illustrated by inclusion densities may be representative of different mortar batches, but more likely may be related to differential weathering of the relatively soft binder component in the exposed mortar.

The portable microscope provided valuable images of the mortar interior, revealing differences not visible on the surface. Magnification revealed differences in the porosity and texture of lime lumps and possible small inclusions in the lime itself. This suggested some compositional differences in the lime. The more porous lime lumps seemed to be in locations where the pink mortar was directly associated with sarno limestone rather than volcanic stones, suggesting a unique reaction between the lime and wall stones in these locations. The images further suggested the lime lumps may be a good source of information about the distinct properties of different mortar batches.

As seen in the microscope images and in thin section, the ancient pink mortar contained only a single type of rock, indicating a single type of aggregate that was selected specifically for the mortar mix. The clinopyroxene, plagioclase, and olivine grains visible in thin section occurred both within rock fragments and on their own in the mortar matrix. The possible Augustan phase mortars from Room 35 contained the same aggregates as the original phase mortars, suggesting these two walls may not actually have been a later phase room construction, but part of the original structure. This does not rule out an Augustan-era reconstruction within that particular room, especially given that a third wall (Wall 124) connecting two pink mortar walls had a unique grey mortar (see Figure 6.1). Again, a closer investigation of the excavation data could assist the interpretation of construction phases. Coins and pottery from wall construction trenches were used to date construction phases throughout the House of the Vestals, though the locations of such trenches have not been reported (DeSena and Ikaheimo 2003). If the date for Room 35 has been estimated from artifacts associated with Wall 124, this may have skewed the original interpretation.

The mineral phases identified with XRD were typical of those found in igneous rocks from the region (Andronico and Cioni 2002). The identified mineral phases were also typical of those found in mortar samples from the region (Benedetti et al 2004, Silva et al 2005). Local minerals suggest that the source for aggregate material most likely also was local, though provenance for these materials is beyond the scope of this project. The volcanic plain surrounding Mt. Vesuvius was known to ancient builders as a location for high quality mortar additives that strengthen the final product (Vitruvius, *De Architectura, Book II, 6.1*). The original construction of the House of the Vestals pre-dates the Vitruvius manuscript by approximately one century, so the builders were not following the suggested protocols laid out in *De Architectura.* However, the mortar exhibits the same characteristics as the ideal mortar recipe described, including superior strength and a naturally waterproof nature.

The XRD patterns were provocative as much for specific minerals absent from the pattern as for those present. The feldspathoid mineral leucite commonly alters to clay minerals with weathering, but there were no clay minerals found in the pink mortar samples. The aggregate materials used may have been specifically selected for their lack of weathering or cleaned to remove any traces. This also follows the Vitruvian recipe for mortar, which calls for the aggregate fragments to be cleaned until they leave no marks on a white toga (Vitruvius, *De Architectura, Book II, 4.1*). Similarly, gypsum and vaterite have been found in both ancient and modern concrete samples as alteration products during decay (Sabbioni et al 2001, Signorelli et al 1996). The major peaks for vaterite and gypsum were absent from the XRD spectra of the ancient pink mortar samples (Figures 7.1-7.2). Again, the reason why these common alteration products were missing from the samples would be an interesting line of inquiry but is beyond the scope of this project.

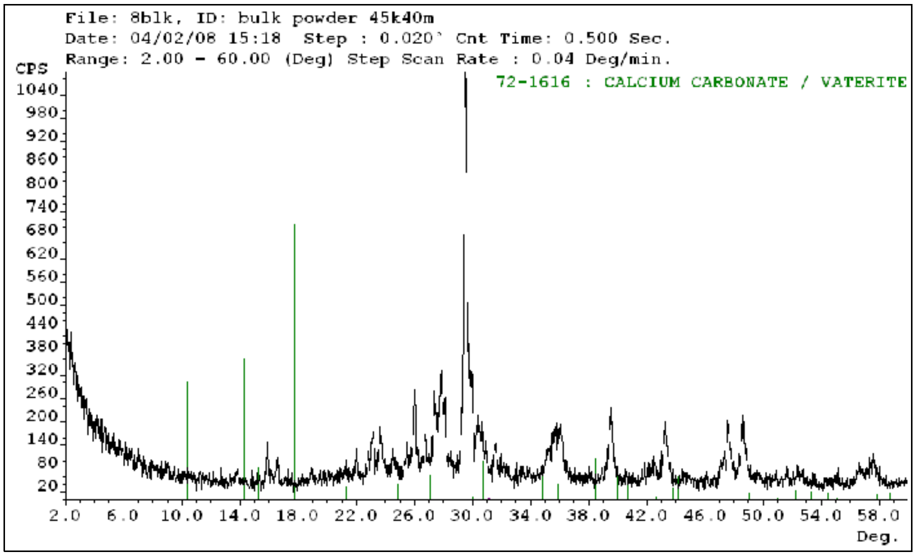

Figure 7.1: X-ray diffractogram of sample W7-112-08 overlain with PDF data for vaterite.

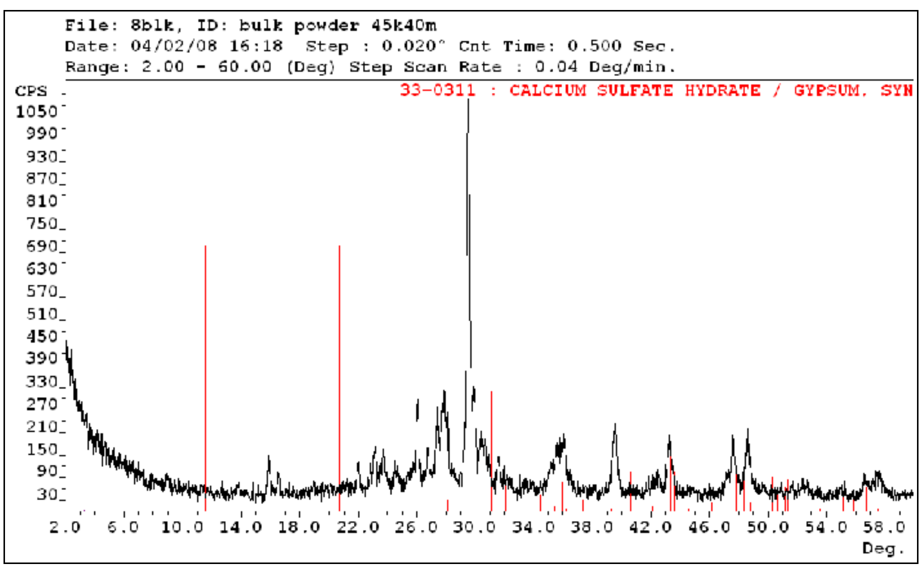

Figure 7.2: X-ray diffractogram of sample W7-112-08 overlain with PDF data for gypsum

Results of XRF analysis supported the hypothesis that the binder was the most useful component for separating mortar samples into compositional groups. The lime sample had a high concentration of MgO, over 40%, which hinted that MgO should be considered a binder component along with CaO and LOI. The scatter plots of CaO:MgO ratios appeared to roughly group the ancient pink mortar samples - both original and presumed Augustan-era construction phases - separately from flooring mortar and the grey and yellow wall mortar samples. Statistical analysis confirmed that the variance between samples could be attributed to CaO, MgO, and LOI. Given these findings, the focus of portable near-infrared analysis was directed toward the binder portion of the *in situ* mortar.

Data collection with the FieldSpec® 3was very fast, required no sample preparation, and the portability of the instrument allowed for completely non-destructive analysis. The equipment performed differently in the tripod and hand-held configurations. The tripod allowed for more consistent results, because the fiber optics were focused on a single target spot without being moved between readings (Figure 7.3). The hand-held configuration required the detector to be moved between the reference panel and the target on the wall during data collection. While all efforts of control were made, it was not possible to sample precisely the same spot every time, which may have actually better represented the extent of variation on and around the target location (Figure 7.4).

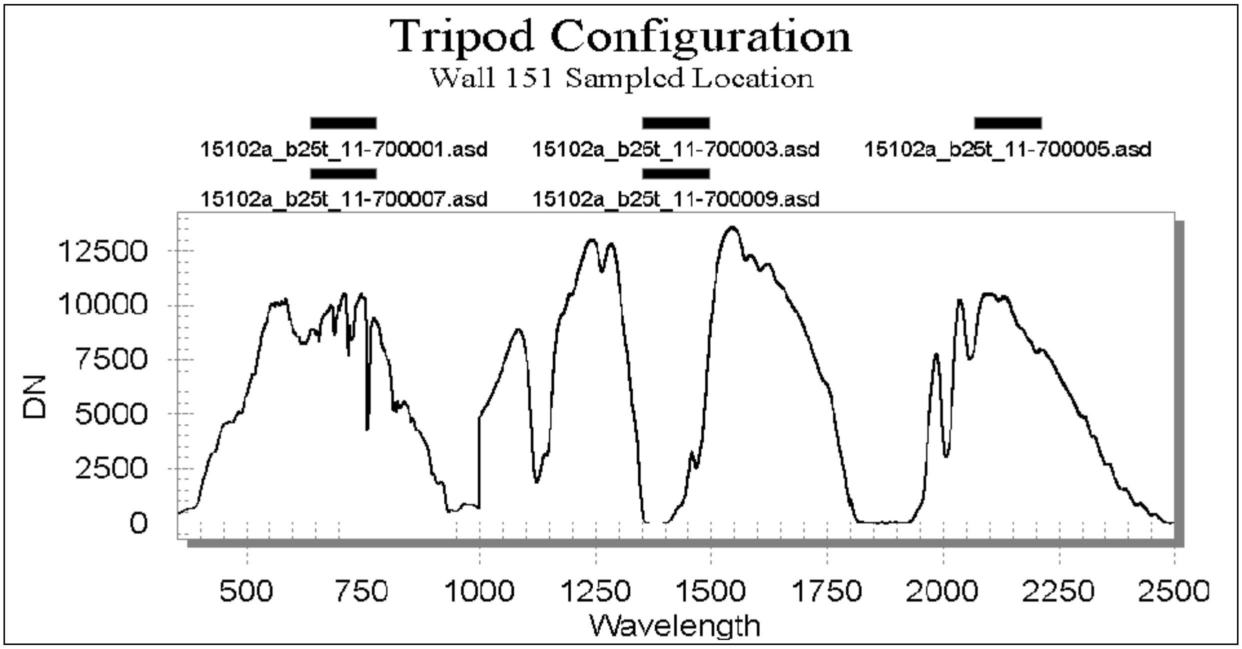

Figure 7.3: Five successive analyses taken at the same location with the tripod configuration.

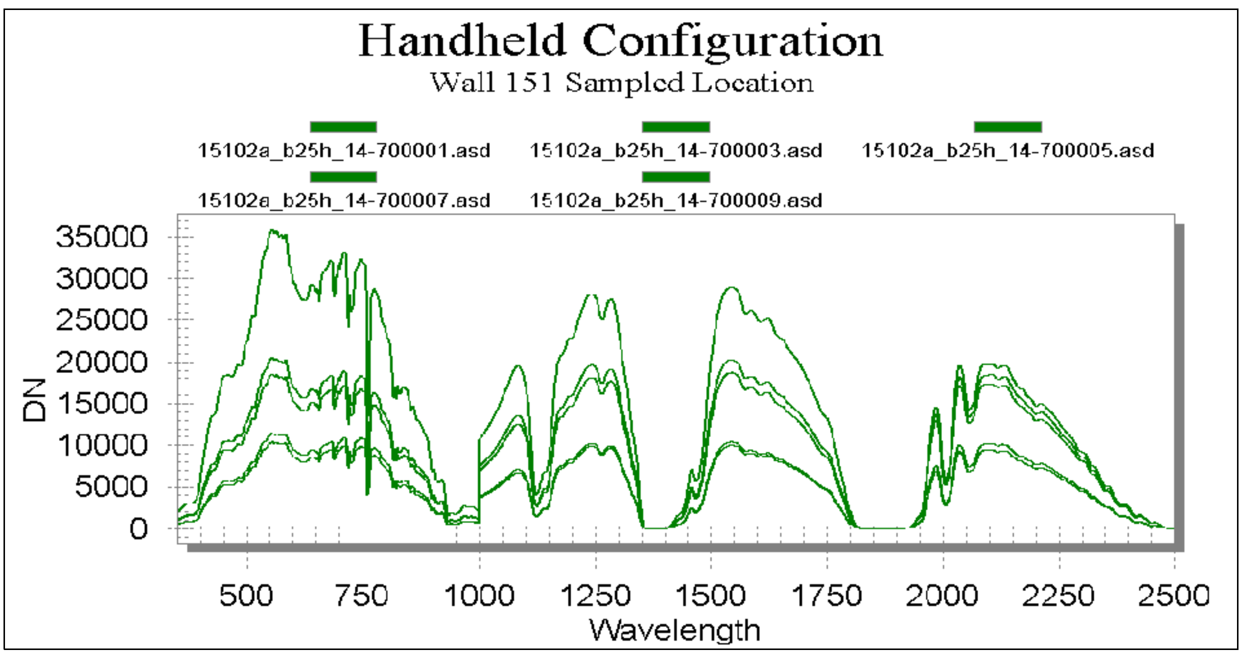

Figure 7.4: Five successive analyses taken at the same location with handheld configuration.

A few difficulties arose during field analysis, most of which involved equipment limitations or logistical struggles, and were easily overcome. Most days were sunny (Table 7.1), but cloud cover and hazy conditions clearly affected both reference and sample readings. As seen in Figure 7.5, intensity was recorded at just over 12500DN under cloud cover, compared to 45000DN in full sun. Similarly, analysis of any individual wall was limited to the time of day when it was in full sun. Even when a wall was fully illuminated, small shadows could form where wall stones slightly overhang the mortar. This problem was solved by only conducting analysis on sunny days under full illumination and choosing sample locations uninhibited by overhang shadows.

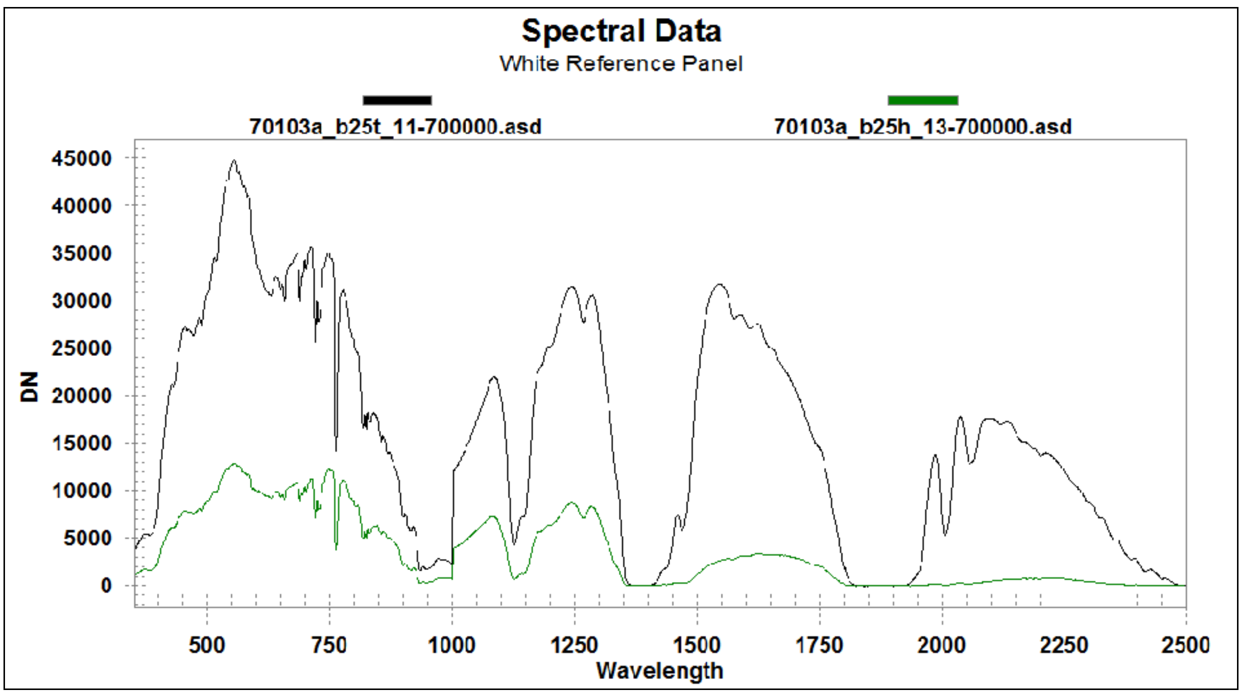

Figure 7.5: Comparison spectral data of white reference panel in full sun (black) and in shade (green).

Table 7.1: Weather data for field analysis days, July 2008.

Date	High Temp. ºC	Temp. Avg ºC	Humidity High %	Humidity Avg %	Humidity Low %	Precipitation (cm)	Cloud Cover
7/7/2008	31	28	85	68	39	0	Partly Cloudy
7/8/2008	28	27	81	71	52	0	Partly Cloudy
7/9/2008	27	25	86	72	64	0	Sunny
7/10/2008	27	22	82	78	50	0	Partly Cloudy
7/11/2008	29	26	70	61	47	0	Sunny
7/12/2008	31	27	67	50	29	0	Sunny
7/13/2008	32	28	81	46	31	0	Sunny
7/14/2008	27	26	91	63	39	0	Partly Cloudy
7/15/2008	29	25	71	49	31	0	Sunny
7/16/2008	30	27	49	40	27	0	Sunny
7/17/2008	27	25	75	63	51	0	Sunny
7/18/2008	27	25	83	69	45	0	Partly Cloudy

When carried in the backpack, the FieldSpec®3 and laptop controller were sometimes cumbersome when attempting to analyze the lower courses of the walls and while taking white reference readings. Generally, operation was easier when the backpack was removed and the instrument carried, rather than worn. The instrument's battery only stored enough power for about 4-5 hours of analysis. When the battery power was low, the spectra took longer to stabilize and rapidly became unreliable. This limited the amount of work that could be done each day, because a full battery recharge took four hours. This problem could have been solved with the addition of a spare battery that could have been changed during the day. The laptop overheated several times and had to be turned off to cool down, again, limiting the amount of work that could be done each day. Overheating the laptop was difficult to avoid, because the sampling required full solar illumination to collect reliable data. A rugged laptop designed for outdoor use may have improved the performance of the instrument controller.

Preliminary analysis of the NIR spectra and comparison to published data illustrated that the FieldSpec® 3 adequately recognized the calcium carbonate in the mortar under study here. This technology could be useful for distinguishing visibly different types of mortar based on the appearance of the peaks at 2000-2400nm. This would be useful for a qualitative study of different mortars throughout a structure. The mortar types in this study were chosen intentionally for their distinct colors, but a study of this kind would be more beneficial in a structure where such distinctions cannot be so easily made. Mineralogical identification of aggregate components FieldSpec® 3 was not successful, as expected; however the chief objective of this study was to compare the binder components of different mortar types. The absence of silicate minerals from the spectral data actually simplified data analysis because the binder components were not obscured like the XRD patterns.

Principal component analysis of NIR spectra confirmed that the significant variance between samples occurred in the two key wavelength bands that appeared most different. One of these bands is from ~600-750nm, which is the visible color region of the infrared spectrum, indicating the portable instrument was able to detect color differences. The other key area is the region from ~1990-2200nm, the signature bands of calcite, further confirming that not only was the binder component ideal for testing variance between mortars, but the FieldSpec® 3 was able to detect the relevant differences. In fact, separate PCA analyses of XRF and spectral data identified essentially the same outliers: XRF sample W7-701-3 and Wall 701 respectively. Refining the subtleties within specific bands would be a necessary aspect of a comprehensive mortar study, but would be beyond the scope of this project. Ultimately, the portable equipment seemed well suited to an investigation of the mortar in the House of the Vestals.

CHAPTER 8

CONCLUSIONS

At this preliminary phase of data analysis, portable NIR spectroscopy with FieldSpec® 3 appears to be a somewhat useful method of studying the type of mortar found in property VI.1.25. Data collection is relatively simple, and unprocessed spectra of raw data appear to vary on a scale that would be expected. Statistical analysis revealed the same outlier in both the XRF and NIR data, indicating that the anomaly is a unique chemical distinction and the FieldSpec® 3 performed well enough to detect it.

Mineralogical analysis alone was not sufficient for distinguishing different types of mortar. First, the mineral phases identified with XRD were consistent among the three mortar types tested. Additionally, the absence of silicate aggregate materials from the NIR spectra left meant that only the binder component could be analysed with this technique; however, PCA confirmed that the binder may be chemically distinct for each mortar type. The pink mortar previously identified as Augustan phase consistently produced results that were similar to the original phase pink mortar. The mineralogical and chemical determinations, with both portable and laboratory methods, indicated that these mortars may well be from the same construction event, which suggests a re-examination of the archaeological record may be in order. While a definitive distinction between these mortars could not be made within the parameters of this project, these results demonstrate the utility of mortar analysis and the potential for informing the archaeological interpretation of structures.

Additional chemical data including trace element signatures would be the next line of investigation in a larger mortar study. The Unscrambler software can create partial least squares regression models for each elemental oxide that would connect the NIR spectra to the XRF data. The software evaluates the spectral data of samples with known weight percent oxide values for each element and thus can predict chemical data of unknown samples from their NIR spectra. This type of analysis could be useful for a project in which limited sample collection and chemical analysis would be permissible or affordable in addition to the non-destructive field analysis. However, this is antithetical to the aim of this study, which seeks to avoid destructive sampling.

A simple solution would be to analyse mortar with a portable XRF unit that could produce major and trace element data. A recently released XRF/XRD combination unit could provide both mineralogical and chemical data. Another technique worth investigating in Pompeii is portable Raman, which has been used with great success to identify alteration products in degrading wall paintings and wall stones (Perez-Alonso et al , 2004, 2006). Information from multiple analytical techniques would permit a broad assessment of ancient structures. Replicable data would support both archaeological interpretations of construction history and visual assessments of the walls' current state of decay.

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APPENDICES

APPENDIX A

MORTAR SAMPLING FORM

Location			
	DATE	**WALL #**	**PHOTO #**
	SAMPLE ID #	**ROOM #**	**DRAWING #**
	BRIEF DESCRIPTION AND LOCATION:		

Wall Construction and Binder

COMPOSITION: (Give rough percentages for materials visible)

Lava with White Flecks		Sarno Stone		White Limestone	
Lava with Black Particles		Opus Signinum		Brick/Tile	
Nocera Tufa		Cruma		Pottery Fragments	
Marble Fragments		Other (describe)			

CONSTRUCTION TECHNIQUES: (check)

Opus quadratum		Opus Incertum		Opus mixtum	
Checker Work		Opus vittatum		Opus spicatum	
Opus Africanum		Opus reticulatum		Opus testaceum	
Opus craticium		Opus quasi-reticulatum			

SCOPE IMAGES:

POWER	#	NOTES
50x		
100x		
200x		

Mortar surface is	very hard		firm		soft		disintegrating	
Mortar interior is	very hard		firm		soft		disintegrating	
Inclusion size is	large		small					
Inclusion density	high		low					
Particles	grain		sand		clay			

Notes:

Additonal Mortar s

color	light	medium	dark
grey			
brown			
yellow			
other			

Aggregate

COMPOSITION: (Give rough percentages for materials visible)

Leucite					
Pumice					
Lime					

Description:

APPENDIX B

SAMPLE CATALOG

Sample ID W7-125-1 **Date Collected** 7/5/2007

Plot Number 7 **Wall Number** 125 **Room Number** 34

AA Number 0 **SU Number** 0

Location Notes Sample taken from South end of wall, approx. 40 cm. from south edge and 65cm down from top, between 2nd and 3rd lava stones from south edge, 4th row up.

Wall Construction and Component Info

Black Lava with Black Particles % 50 **Black Lava with White Flecks %** 50 **Sarno Percentage**

Cruma % **White limestone %** **Nocera Tufa %**

Brick count **Pottery frag count** **Pink mortar _rocks_%**

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black Lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 40 **to** 40 %

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Very Hard **Inclusion Size:** **Most Large** ☐

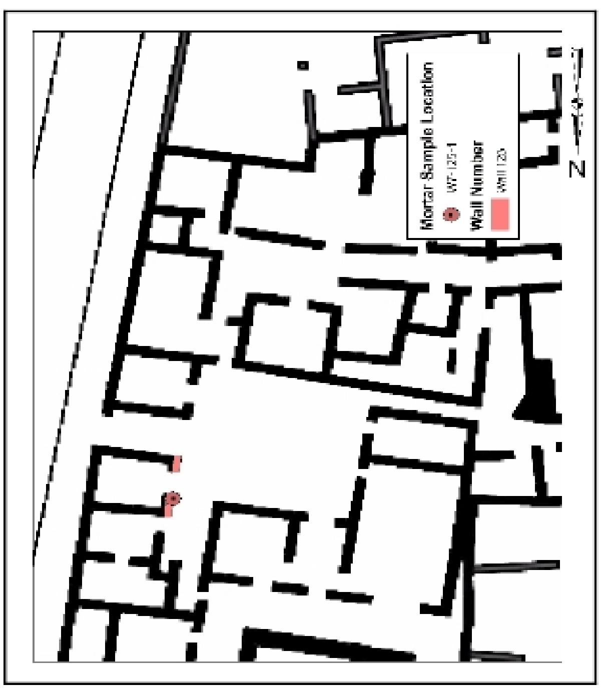
Mortar interior Firm **Most small** ☐

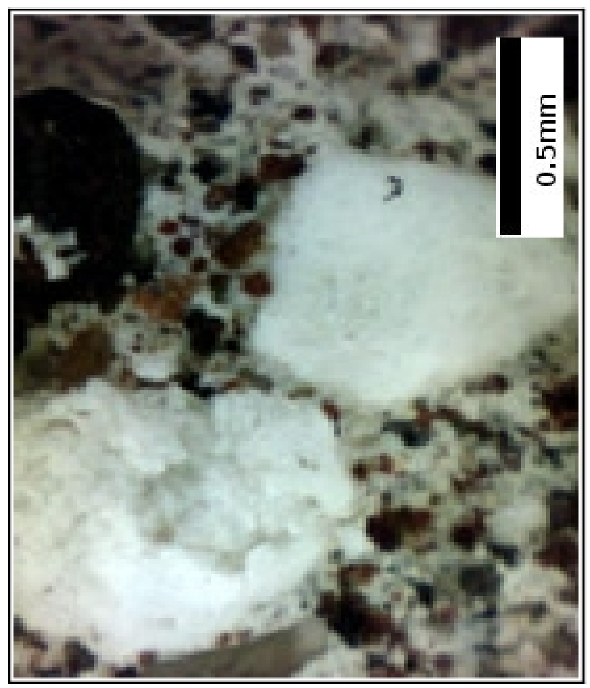
Leucite %	10	small, mostly frags, some whole
Red Pumice %	40	small and large, some have visible crystals
Cpx %	30	small
Lime %	20	small and large lumps

Aggregate Notes weathering is more visible at the top of the wall, changes the color to a darker brownish-pink


AAPP07
WALL 125


AAPP07
W7-125-1


Mortar Sample Location
W7-125-1
Wall Number
Wall 125
N


0.5mm

Sample ID W7-151-2 **Date Collected** 7/5/2007

Plot Number 7 **Wall Number** 15 **Room Number** 34

AA Number 0 **SU Number** 0

Location Notes Sample taken from south end of wall, from just above lower plaster fragments

Wall Construction and Component Info

Black Lava with Black Particles % 50 **Black Lava with White Flecks %** 50 **Sarno Percentage** 0

Cruma % **White limestone %** **Nocera Tufa %**

Brick count **Pottery frag count** **Pink mortar _rocks_%**

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 40 **to** 50 %

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☐

Mortar interior firm **Most small** ☐

Leucite % 10 small, fragments and whole

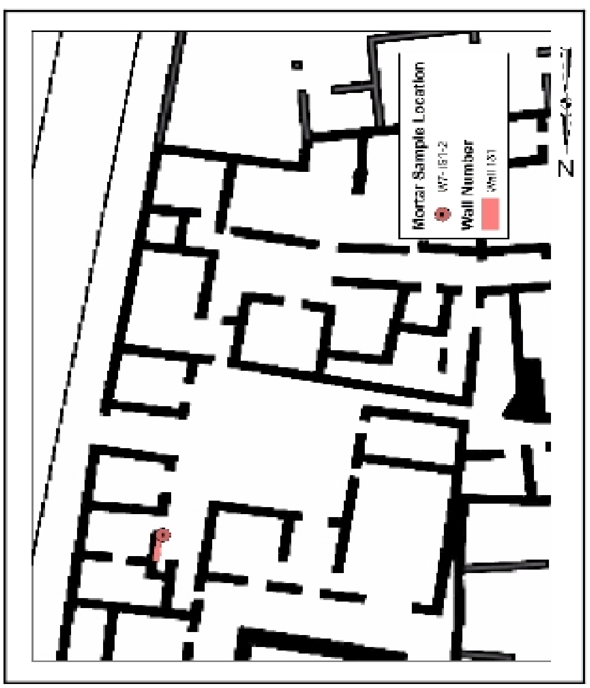
Red Pumice % 40 small and large

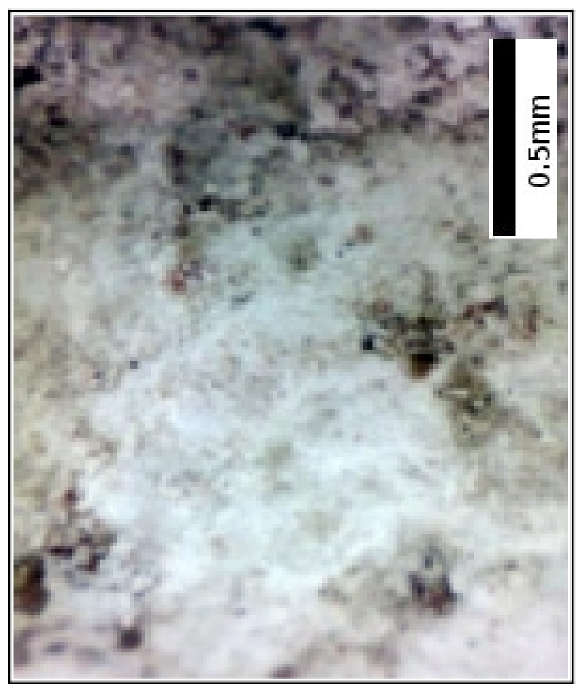
Cpx % 30 small

Lime % 20 small and large lumps

Aggregate Notes


AAPP07
W7-151-2
N


Mortar Sample Location
W7-151-2
Wall Number
Wall 151
N


0.5mm

Sample ID W7-701-3 **Date Collected** 7/5/2007

Plot Number 7 **Wall Number** 701 **Room Number** Narciso

AA Number 0 **SU Number** 0

Location Notes South edge of wall, approx a third of the way up (North) from Sarno quoining, shows considerable weathering

Wall Construction and Component Info

Black Lava with Black Particles % 45 **Black Lava with White Flecks %** 45 **Sarno Percentage** 10

Cruma % **White limestone %** **Nocera Tufa %**

Brick count 1 **Pottery frag count** 5 **Pink mortar _rocks_%**

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 40 **to** 50 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☒

Mortar interior Firm **Most small** ☐

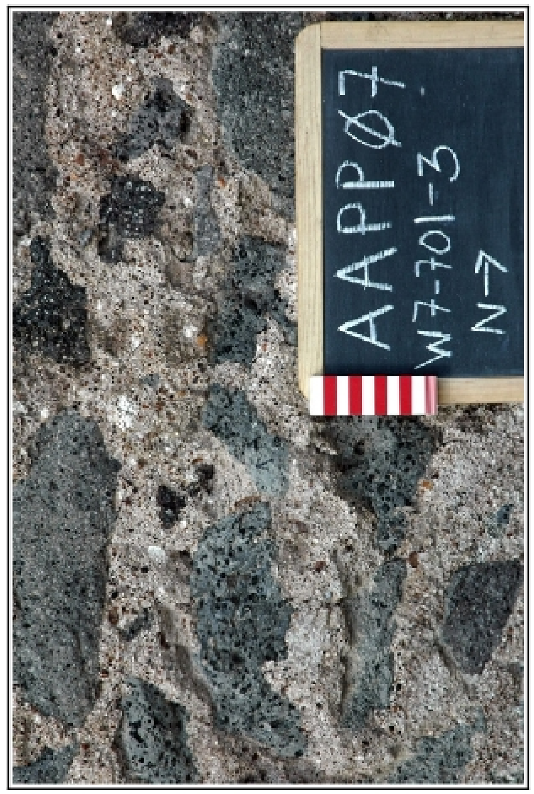
Leucite % 30 most whole, many large, frags and small whole xtals, white, grey, black

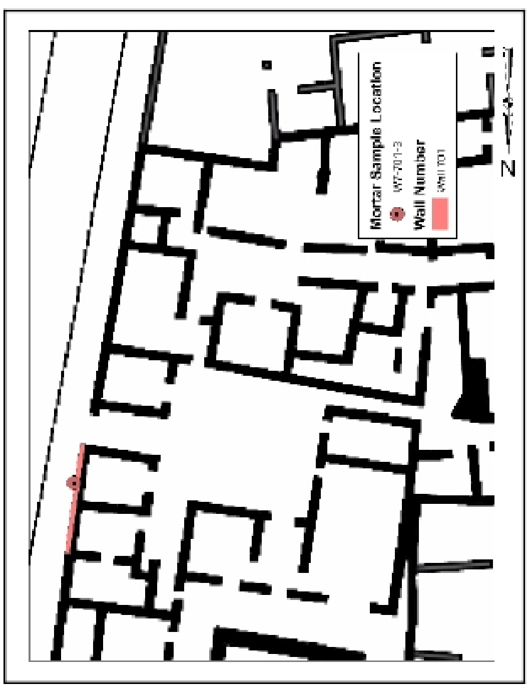
Red Pumice % 30

Cpx % 20

Lime % 15 small and large, some over 5cm

Aggregate Notes much larger inclusions here, high leucite here, definite ceramic fragments as aggregate, but don't seem crushed, crushed black lava gravel (makes up 5%) and some UD yellowish material


AAPP07
W7-701-3
N→


Mortar Sample Location
W7-701-3
Wall Number
Wall 701
N


0.5mm

Sample ID W7-701-4 **Date Collected** 7/5/2007

Plot Number 7 **Wall Number** 701 **Room Number** Narciso

AA Number 0 **SU Number** 0

Location Notes Mortar used as wall rock on the south end of wall, between sarno quoin and incertum, probable repair, sample is one of these pink mortar "rocks"

Wall Construction and Component Info

Black Lava with Black Particles % 0 **Black Lava with White Flecks %** **Sarno Percentage** 0

Cruma % 1 **White limestone %** 0 **Nocera Tufa %** 1

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus incertum **Construction Phase** Late

Mortar Sample Directly Associated with:

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☐ **Inclusion Density:** 30 **to** 40 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☒ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☒

Mortar interior soft **Most small** ☐

Leucite % 10 small, whole and frags, grey

Red Pumice % 60

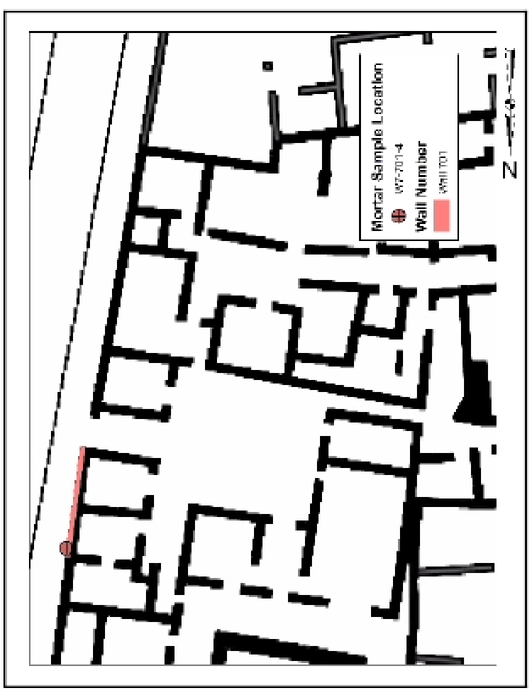
Cpx % 10

Lime % 20 large and small lumps

Aggregate Notes also contains approx 1% black lava gravel

AAPP07
W7-701-4
N→

AAPP07
W7-701-4
N→



Mortar Sample Location
W7-701-4
Wall Number
N

0.5mm

Sample ID W7-702-5 **Date Collected** 7/5/2007

Plot Number 7 **Wall Number** 701 **Room Number** Narciso

AA Number 0 **SU Number** 0

Location Notes from North end of wall, lowest visible course, from between Sarno header and black lava stones

Wall Construction and Component Info

Black Lava with Black Particles % 40 **Black Lava with White Flecks %** 40 **Sarno Percentage** 20

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 1 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Sarno and black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 40 **to** 50 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☐

Mortar interior firm **Most small** ☒

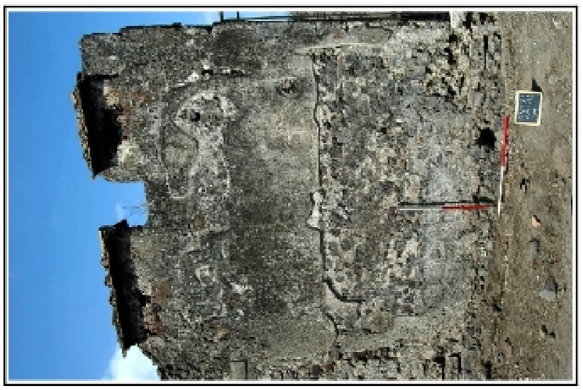
Leucite % 15 most small, some whole

Red Pumice % 30 small and large, most small, some massive

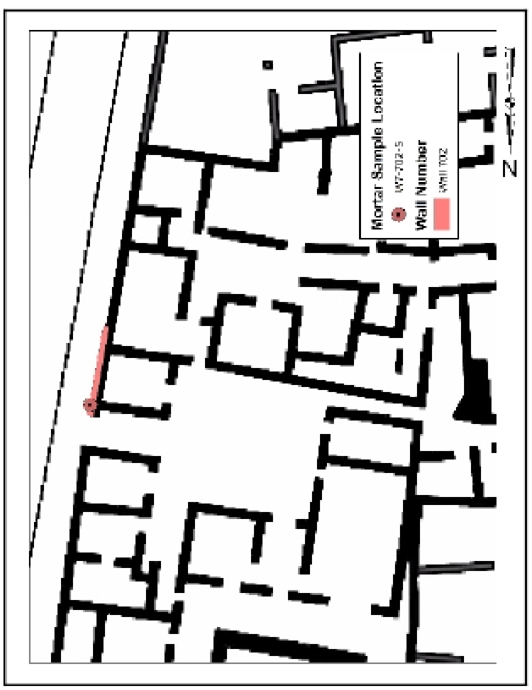
Cpx % 30 tiny frags

Lime % 25 very small lumps, no large lumps visible

Aggregate Notes much smaller inclusions here than Wall 701, also better sorted, some residual pottery frags (not crushed) also 1 large amphora frag used in wall construction




AAPP07
W7-702-5
N→


Mortar Sample Location
W7-702-5
Wall Number
Wall 702
N


0.5mm

Sample ID W7-152-6 **Date Collected** 7/5/2007

Plot Number 7 **Wall Number** 152 **Room Number** 35

AA Number 0 **SU Number** 0

Location Notes This is east face of central room wall, sample from approx center of wall, 1 row of black lava stones up from ground

Wall Construction and Component Info

Black Lava with Black Particles % 35 **Black Lava with White Flecks %** 35 **Sarno Percentage** 30

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** Augustan

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 30 **to** 30 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☐ **Low** ☒

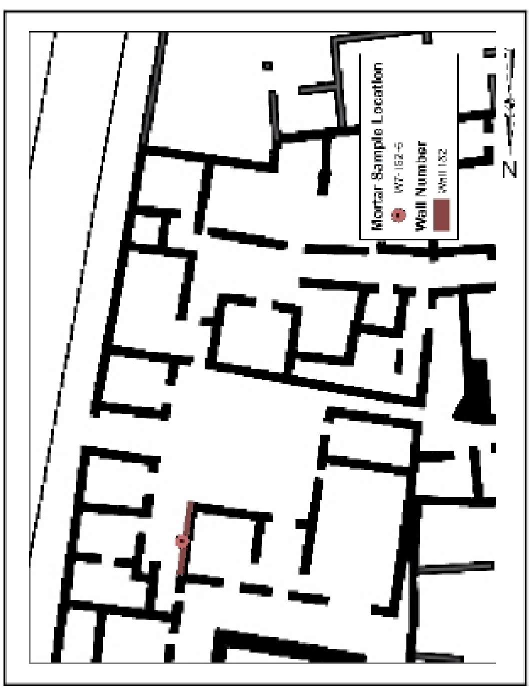
Mortar Color Pink **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☐

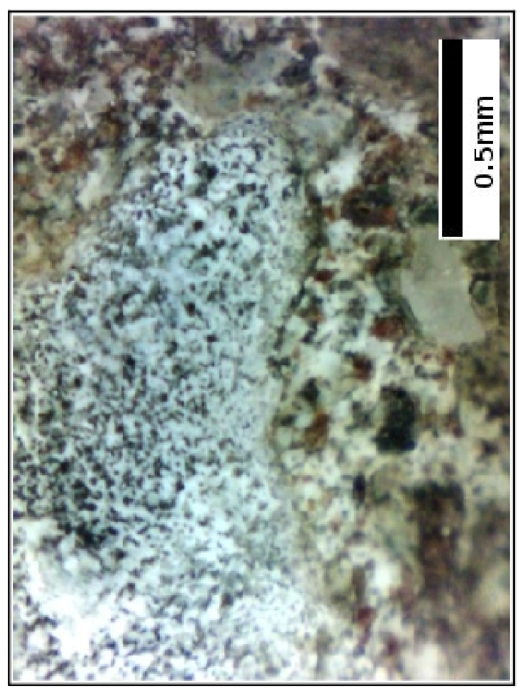
Mortar interior Firm **Most small** ☒

Leucite %	5	tiny frags
Red Pumice %	50	from very small to approx 5mm
Cpx %	25	very small to approx 5mm
Lime %	20	small, more on the interior or sample than exterior

Aggregate Notes


AAPP07
W7-152-6
N→


Mortar Sample Location
Wall Number
N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Sample ID W7-116-7 **Date Collected** 7/5/2007

Plot Number 7 **Wall Number** 116 **Room Number** 36

AA Number 0 **SU Number** 0

Location Notes Southern quarter of wall, between 2 sarno stones, approx half-way up wall, well below repair mortar

Wall Construction and Component Info

Black Lava with Black Particles % 0 **Black Lava with White Flecks %** 5 **Sarno Percentage** 95

Cruma % 0 **White limestone %** 1 **Nocera Tufa %** 0

Brick count 2 **Pottery frag count** 3 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** Augustan

Mortar Sample Directly Associated with: Sarno

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 20 **to** 25 %

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☐ **Low** ☒

Mortar Color Pink **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☐

Mortar interior firm **Most small** ☐

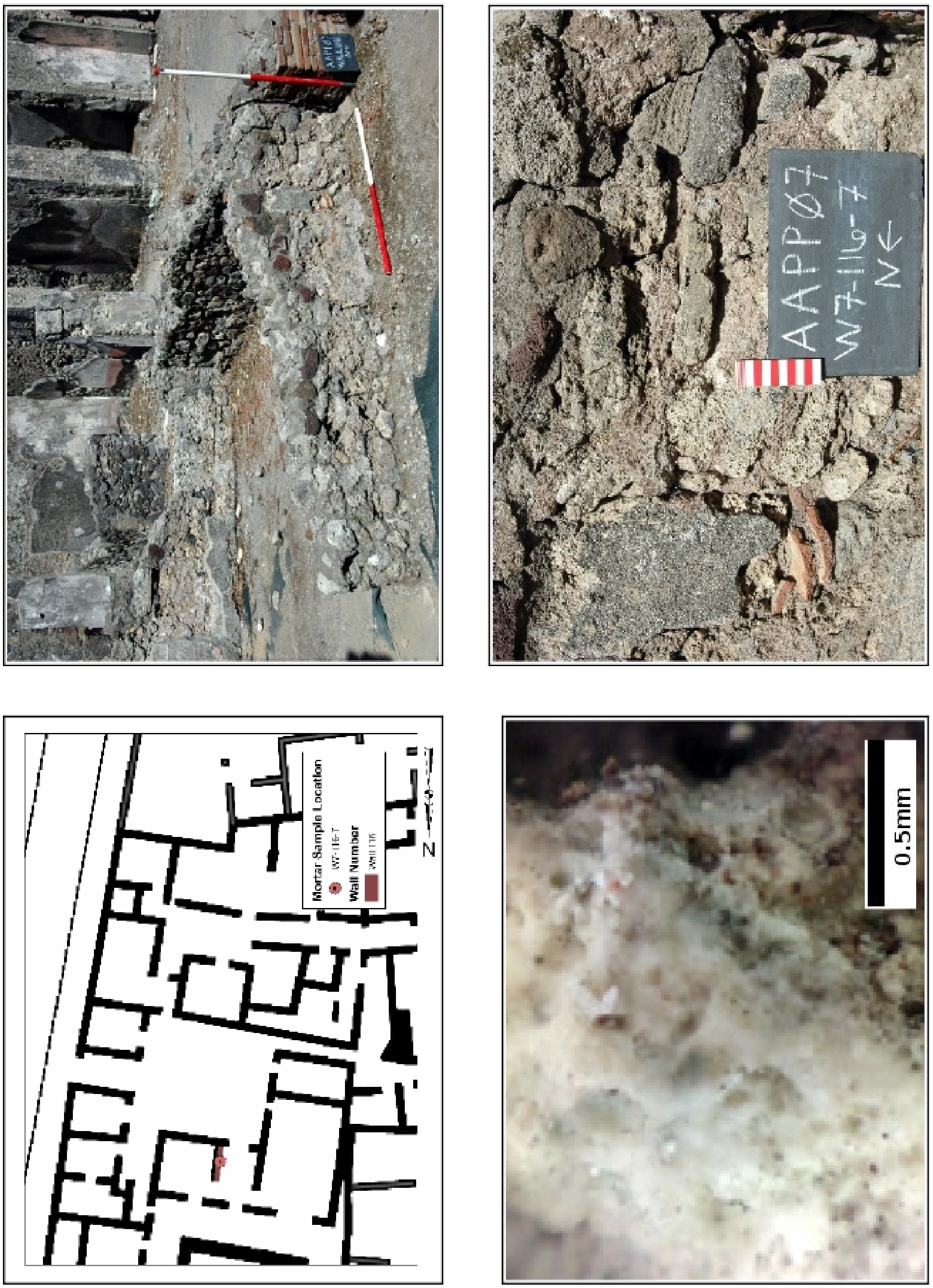
Leucite % 30 light blue and dark grey, sm and med size, whole and frags

Red Pumice % 30 most tiny, more on exterior of sample than interior

Cpx % 30 also some visible in pumice frags

Lime % 10 very little present, small where visible

Aggregate Notes pink mortar visible between pottery frags


AAPP07
W7-116-7
N←
Mortar Sample Location
Wall Number
N
0.5mm

Sample ID W7-112-8 **Date Collected** 7/6/2007

Plot Number 7 **Wall Number** 112 **Room Number** 37

AA Number 0 **SU Number** 0

Location Notes North end of wall, approx half way up from ground level, just south of Northern quoining repair, 1 stone above thick modern plaster layer

Wall Construction and Component Info

Black Lava with Black Particles % 40 **Black Lava with White Flecks %** 40 **Sarno Percentage** 20

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☒ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 40 **to** 40 %

Exterior Wall ☐ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** very hard **Inclusion Size:** **Most Large** ☒

Mortar interior Firm **Most small** ☐

Leucite % 20 white, grey, black, frags and whole, most small

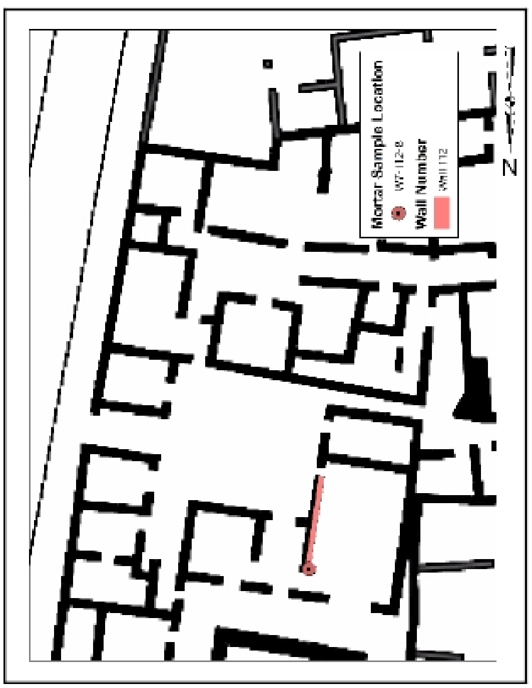
Red Pumice % 30 most very small, some approx 5mm

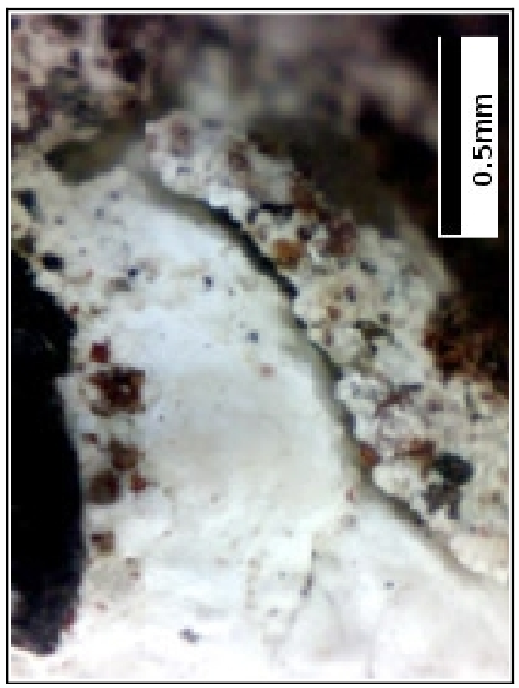
Cpx % 35 small, abundant

Lime % 15 small up to approx 5mm

Aggregate Notes Sample was very difficult to remove, the mortar is harder here than most other samples, not at all friable on exterior


AAPP07
W7-112-8
N


Mortar Sample Location
W7-112-8
Wall Number
Wall 112
N


0.5mm

Sample ID W7-118-9 **Date Collected** 7/6/2007

Plot Number 7 **Wall Number** 118 **Room Number** 36

AA Number 0 **SU Number** 0

Location Notes From lower course of wall, approx 3 rows of stone up from ground level, from area not covered with plaster remnants

---

Wall Construction and Component Info

Black Lava with Black Particles % 50 **Black Lava with White Flecks %** 50 **Sarno Percentage** 0

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 50 **to** 60 %

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☐

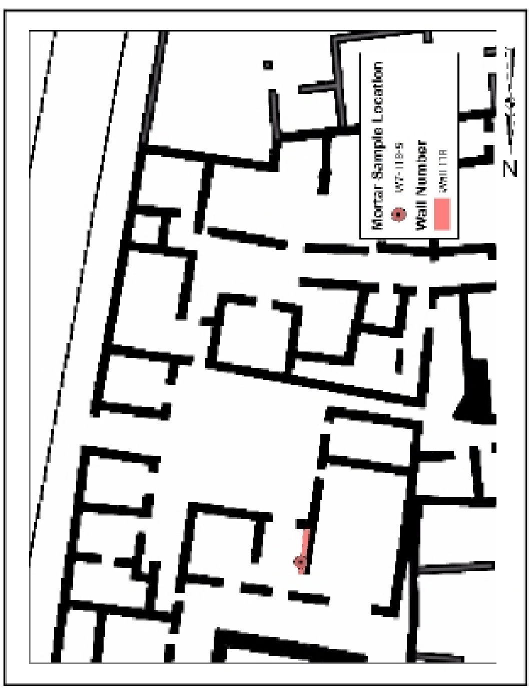
Mortar interior Firm **Most small** ☒

Leucite %	35	grey, large and small whole xtals, some frags
Red Pumice %	30	most very small, a few up to 5mm
Cpx %	25	largest inclusions present
Lime %	10	few present, all small

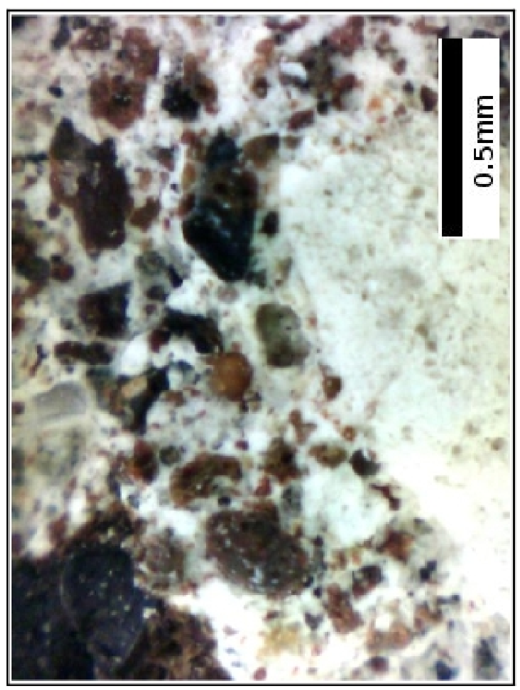
Aggregate Notes this mortar seems not to adhere as well to stones as from other face of this wall (Wall 112), more visible shrinkage

AAPP07

AAPP07
W7-118-9
N→



Mortar Sample Location
Wall Number
N



0.5mm

Sample ID W7-123-10 **Date Collected** 7/6/2007

Plot Number 7 **Wall Number** 123 **Room Number** 37

AA Number 0 **SU Number** 0

Location Notes From western edge of wall "stump" where it meets Wall 128, just above consolidated plaster in corner

---

Wall Construction and Component Info

Black Lava with Black Particles % 100 **Black Lava with White Flecks %** 0 **Sarno Percentage** 0

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** Augustan

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☐ **Inclusion Density:** 20 **to** 30 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☒ **High** ☐ **Med** ☐ **Low** ☒

Mortar Color Pink **Mortar surface** Firm **Inclusion Size:** **Most Large** ☐

Mortar interior Firm **Most small** ☒

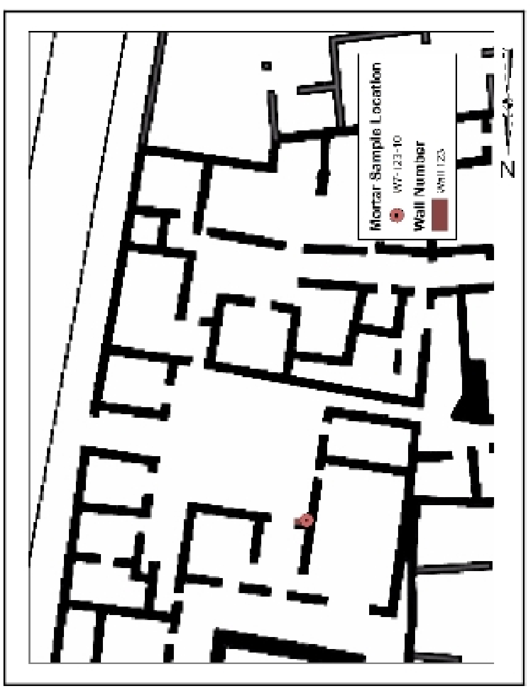
Leucite % 25 grey, small to med size whole crystals

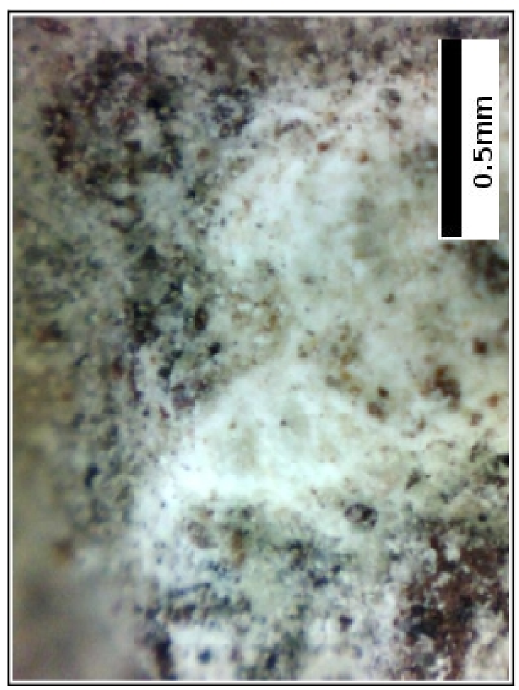
Red Pumice % 25 small

Cpx % 30

Lime % 20 large lumps, up to 1 cm

Aggregate Notes This is a re-used bit of pink mortar, not much present and harder than expected, is surrounded with very soft medium-grey mortar in the wall. This may actually be plaster backing mortar, not construction mortar.


Mortar Sample Location
W7-123-10
Wall Number
Wall 123
N


0.5mm

Sample ID W7-128-11 **Date Collected** 7/6/2007

Plot Number 7 **Wall Number** 128 **Room Number** 27

AA Number 0 **SU Number** 0

Location Notes Southern end of wall, where black lava meets Sarno

Wall Construction and Component Info

Black Lava with Black Particles % 33 **Black Lava with White Flecks %** 33 **Sarno Percentage** 33

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus mixtum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava and Sarno

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 35 **to** 40 %

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

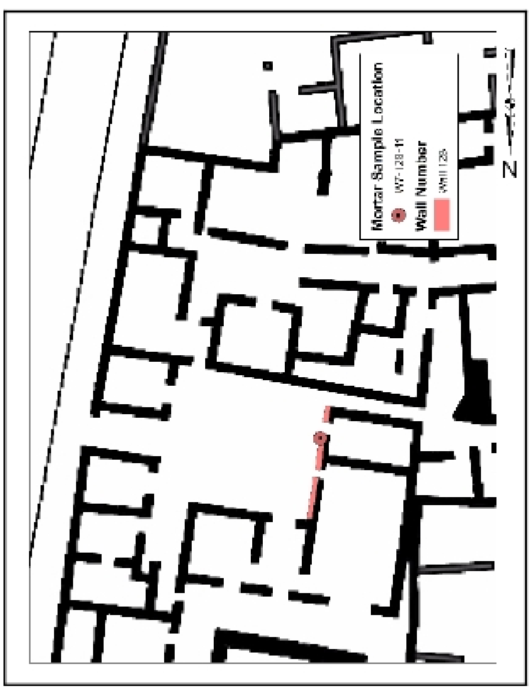
Mortar Color Pink **Mortar surface** Very hard **Inclusion Size: Most Large** ☒

Mortar interior Firm **Most small** ☐

Leucite %	15	whole xtals, large and med size
Red Pumice %	30	most large, some small
Cpx %	25	
Lime %	30	large lumps, relatively abundant

Aggregate Notes


AAPP07
WALL 12.8
W7-12.8-11


Mortar Sample Location
Wall Number
N


0.5mm

Sample ID **W7-205-12** **Date Collected** 7/9/2007

Plot Number 7 **Wall Number** 205 **Room Number** 37-A

AA Number 0 **SU Number** 0

Location Notes Approx. center of accessible wall, about 5 rows of stones up from backfill, 1 stone below tufa repair

---

Wall Construction and Component Info

Black Lava with Black Particles % 50 **Black Lava with White Flecks %** 50 **Sarno Percentage** 0

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☒ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 45 **to** 50 **%**

Exterior Wall ☐ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Firm **Inclusion Size:** **Most Large** ☒

Mortar interior Firm **Most small** ☐

Leucite % 30 whole and frags, most whole, brown, grey, black

Red Pumice % 20 some large but most tiny

Cpx % 40

Lime % 10 most very small, relatively rare

Aggregate Notes Grey repointing mortar overlies pink mortar in places,

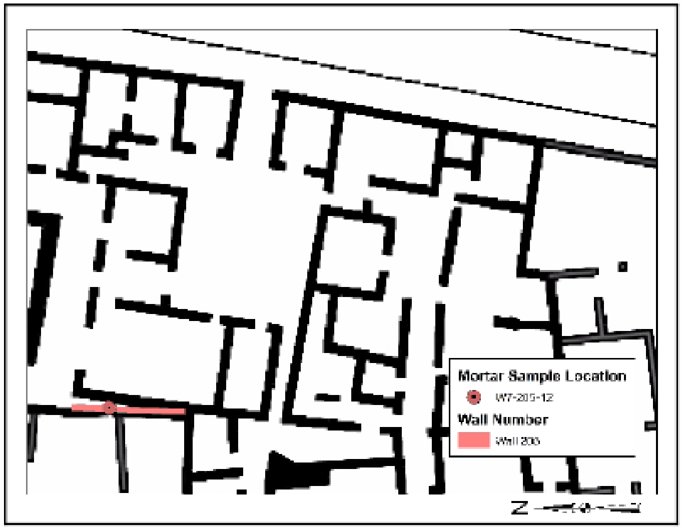


Image not available

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Image not available

Sample ID W7-108-13 **Date Collected** 7/9/2007

Plot Number 7 **Wall Number** 108 **Room Number** 38

AA Number 0 **SU Number** 0

Location Notes Sample is from the bond between a black lava stone and small sarno frag approx center between north and sound ends of wall, about 2/3 up from ground level.

Wall Construction and Component Info

Black Lava with Black Particles % 15 **Black Lava with White Flecks %** 15 **Sarno Percentage** 70

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus incertum **Construction Phase** First

Mortar Sample Directly Associated with: Sarno and black lava

Mortar Sample Info

Interior Wall ☒ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 35 **to** 40 %

Exterior Wall ☐ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Firm **Inclusion Size:** **Most Large** ☒

Mortar interior Soft **Most small** ☐

Leucite % 10 whole and frags, grey

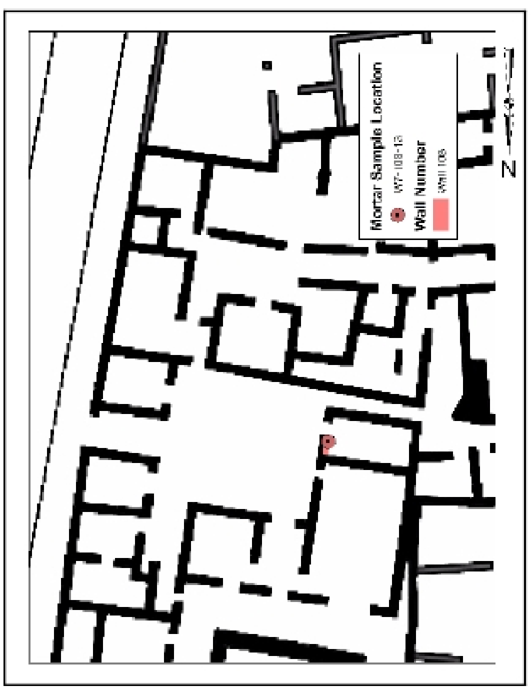
Red Pumice % 25

Cpx % 15

Lime % 50 most are large lumps

Aggregate Notes There is more lime here than in all other samples. The mortar is quite friable here and breaks off easily. Weathering is also more evident here.


AAPPØ7
W7-1Ø8-13
N


Mortar Sample Location
W7-108-13
Wall Number
Wall 108
N


0.5mm

Sample ID W7-136-14 **Date Collected** 7/9/2007

Plot Number 7 **Wall Number** 136 **Room Number** 34

AA Number 0 **SU Number** 0

Location Notes From lowest course of center of wall, just below consolidated plaster.

Wall Construction and Component Info

Black Lava with Black Particles % 60 **Black Lava with White Flecks %** 40 **Sarno Percentage** 0

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☒ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 60 **to** 65 %

Exterior Wall ☐ **Outer face sample** ☒ **Re_use** ☐ **High** ☒ **Med** ☐ **Low** ☐

Mortar Color Pink **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☐

Mortar interior Firm **Most small** ☐

Leucite % 25 Whole and frags, most light colored, some grey

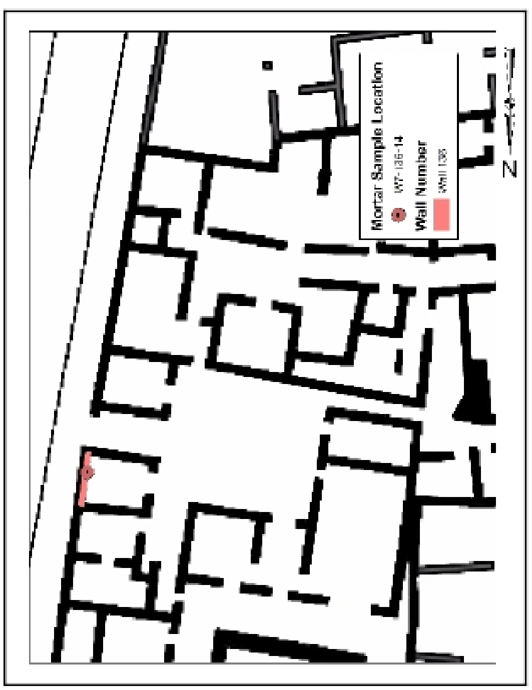
Red Pumice % 40 varying size but most small, largest inclusions overall are red pumice

Cpx % 5 tiny, barely visible

Lime % 30 small lumps but numerous

Aggregate Notes Here, the wall has a lot of mortar between widely spaced stones. Interior of sample is lime-rich. It crumbled a bit when removed.


AAPP07
W7-136-14
N


Mortar Sample Location
W7-136-14
Wall Number
Wall 136
N


0.5mm

Sample ID W7-127-15 **Date Collected** 7/9/2007

Plot Number 7 **Wall Number** 127 **Room Number** 27

AA Number 0 **SU Number** 0

Location Notes In the eastern-most wall scar, just to the west of large bit of consolidated plaster, just east of blocked doorway, approx half way up wall

Wall Construction and Component Info

Black Lava with Black Particles % 50 **Black Lava with White Flecks %** 50 **Sarno Percentage** 0

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 50 **to** 60 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Firm **Inclusion Size:** **Most Large** ☒

Mortar interior Soft **Most small** ☐

Leucite % 15 grey and black, frags and whole

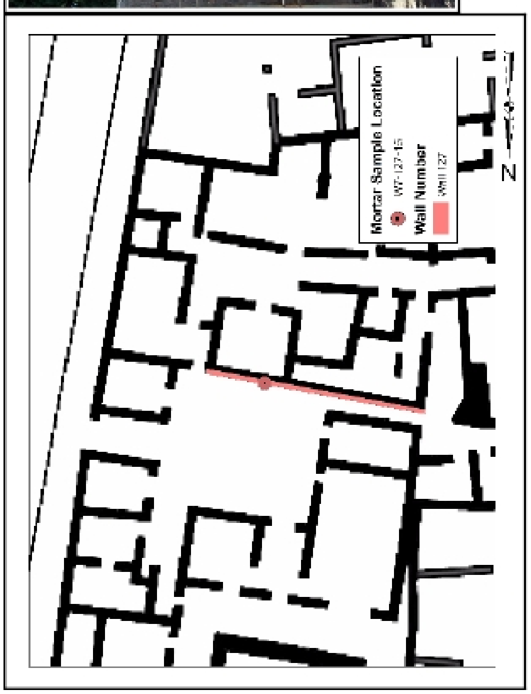
Red Pumice % 35 most large

Cpx % 20 most small or tiny, but some large

Lime % 30 massive lumps, but also some small, all rather soft

Aggregate Notes Very friable, lime-rich including very lumps up to 4 cm. Lighter color overall than most samples, darker areas are harder than the lighter areas.


AAPPØ7
W7-127-15
N↓


Mortar Sample Location
W7-127-15
Wall Number
Wall 127
N


0.5mm

Sample ID W7-45-16 **Date Collected** 7/9/2007

Plot Number 7 **Wall Number** 45 **Room Number** 22

AA Number 0 **SU Number** 0

Location Notes West half of wall below filled window, just west of consolidated plaster.

Wall Construction and Component Info

Black Lava with Black Particles % 40 **Black Lava with White Flecks %** 60 **Sarno Percentage** 0

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 40 **to** 40 %

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

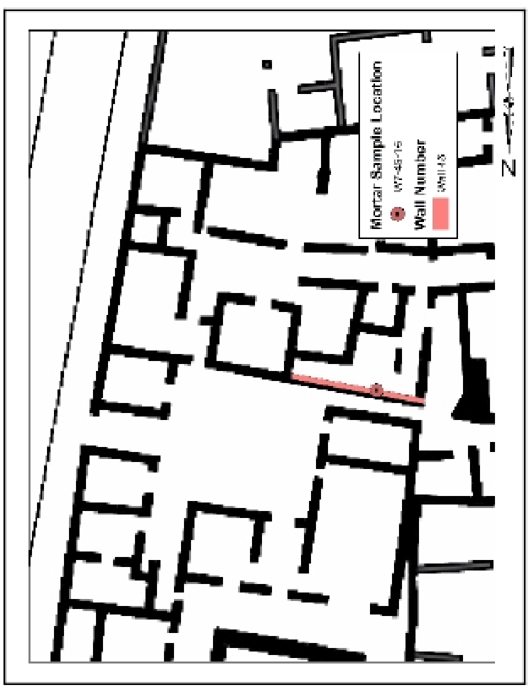
Mortar Color Pink **Mortar surface** Firm **Inclusion Size:** **Most Large** ☐

Mortar interior Soft **Most small** ☒

Leucite %	15	frags, some almost whole, small and large, grey
Red Pumice %	30	large and small, most red pumice is larger than 5mm
Cpx %	25	
Lime %	30	some massive lumps, most small, abundant and soft

Aggregate Notes Breaks easily, crumbles to sand-sized particles quite easily. This wall is very degraded and mortar is fragile.


AAPP07
W7-45-16
N


Mortar Sample Location
Wall Number
N


0.5mm

Sample ID **W7-45-17** **Date Collected** 7/9/2007

Plot Number 7 **Wall Number** 45 **Room Number** 22

AA Number 0 **SU Number** 0

Location Notes Sample taken from within a hole in Wall 45, to west of sample W7-45-16

Wall Construction and Component Info

Black Lava with Black Particles % 40 **Black Lava with White Flecks %** 60 **Sarno Percentage** 0

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☒ **In situ** ☒ **Inclusion Density:** 40 **to** 40 **%**

Exterior Wall ☒ **Outer face sample** ☐ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Firm **Inclusion Size:** **Most Large** ☐

Mortar interior Soft **Most small** ☒

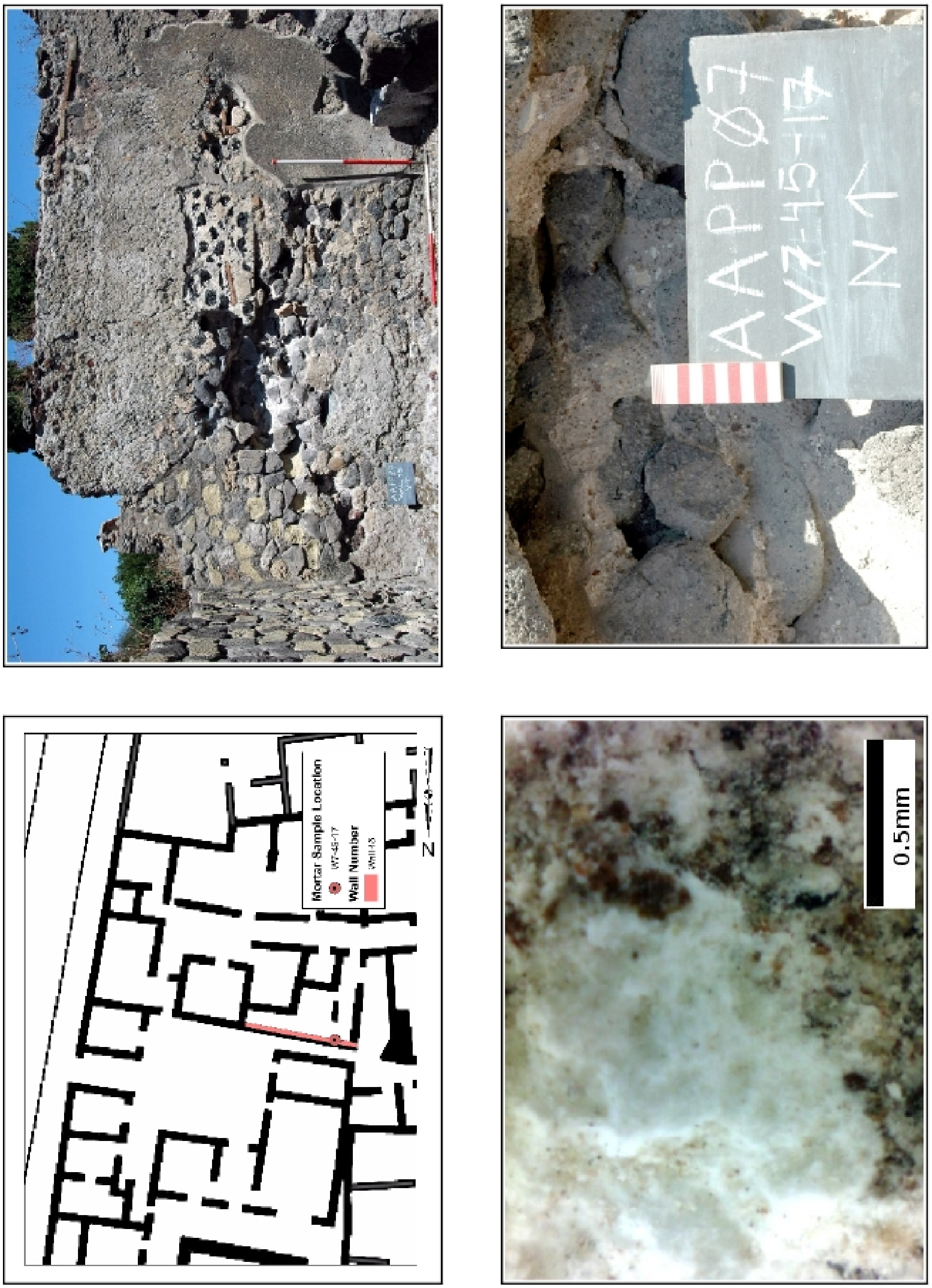
Leucite % 15 frags, some almost whole, small and large, grey

Red Pumice % 30 large and small, most pumice is large

Cpx % 25

Lime % 30 some massive lumps, quite abundant

Aggregate Notes Fragile part of wall, quite degraded, including some of the lava stones which are soft and/or powdery


Mortar Sample Location
Wall Number
N
0.5mm

Sample ID W7-45-18 **Date Collected** 7/9/2007

Plot Number 7 **Wall Number** 45 **Room Number** 22

AA Number 0 **SU Number** 0

Location Notes From hole in Wall 45, sitting loose at base of hole

Wall Construction and Component Info

Black Lava with Black Particles % 40 **Black Lava with White Flecks %** 60 **Sarno Percentage** 0

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☒ **In situ** ☒ **Inclusion Density:** 0 **to** 0 %

Exterior Wall ☒ **Outer face sample** ☐ **Re_use** ☐ **High** ☐ **Med** ☐ **Low** ☐

Mortar Color White (lime) **Mortar surface** N/A **Inclusion Size:** **Most Large** ☐

Mortar interior N/A **Most small** ☐

Leucite % 0

Red Pumice % 0

Cpx % 0

Lime % 100 massive lime lump

Aggregate Notes This is one of 2 lime lumps from within the hole in Wall 45, the other is still in situ.

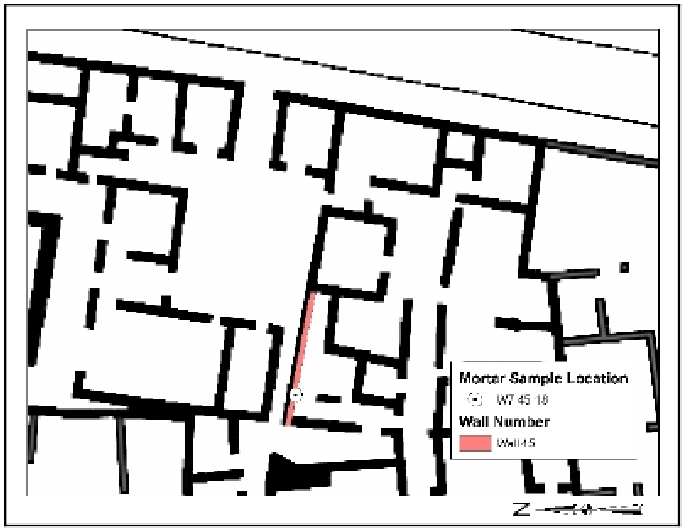


Image not available

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Sample ID W7-126-19 **Date Collected** 7/9/2007

Plot Number 7 **Wall Number** 126 **Room Number** 27

AA Number 0 **SU Number** 0

Location Notes From norther edge of the southern sarno quoin of this doorway frame, between the 2 lowest sarno blocks.

Wall Construction and Component Info

Black Lava with Black Particles % 0 **Black Lava with White Flecks %** 0 **Sarno Percentage** 100

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Sarno

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 40 **to** 40 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☐

Mortar interior Soft **Most small** ☒

Leucite % 15 whole and frags, most frags, small and large frags (most large)

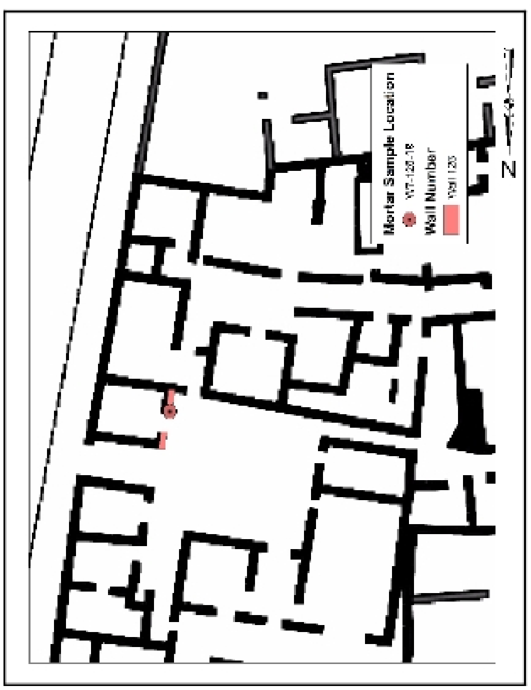
Red Pumice % 40 most pumice frags are large

Cpx % 40 size varying from tiny to large

Lime % 5 small lumps

Aggregate Notes Surface was quite hard, sample was difficult to remove, but interior was quite soft.


AAPPØ7
W7-126-19
N←


Mortar Sample Location
Wall Number
N


0.5mm

Sample ID **X701-2-20** **Date Collected** 7/12/200

Plot Number 6 **Wall Number** 0 **Room Number** 10

AA Number 701 **SU Number** 2

Location Notes Pink sub-flooring mortar from House of the Surgeon - detail and microscope images not available

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Wall Construction and Component Info

Black Lava with Black Particles % 0 **Black Lava with White Flecks %** 0 **Sarno Percentage** 0

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique **Construction Phase** Final phase floor

Mortar Sample Directly Associated with:

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** to %

Exterior Wall ☐ **Outer face sample** ☐ **Re_use** ☐ **High** ☐ **Med** ☐ **Low** ☐

Mortar Color Pink **Mortar surface** Firm **Inclusion Size:** **Most Large** ☐

Mortar interior Firm **Most small** ☐

Leucite % 0

Red Pumice % 0

Cpx % 0

Lime % 0

Aggregate Notes Sample not inspected as wall sample

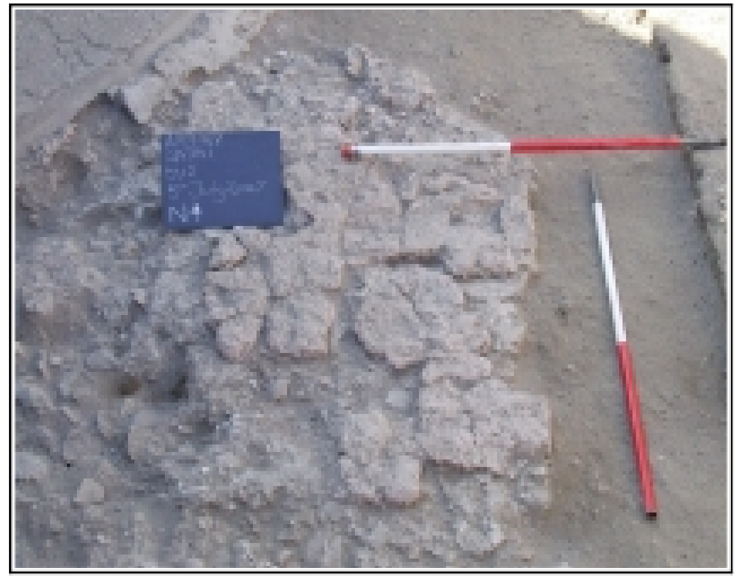


Image not available

Image not available

Sample ID W7-118-21 **Date Collected** 7/12/200

Plot Number 7 **Wall Number** 118 **Room Number** 36

AA Number 0 **SU Number** 0

Location Notes Yellow mortar used in fill of blocked doorway on South end of Wall 118

Wall Construction and Component Info

Black Lava with Black Particles % 0 **Black Lava with White Flecks %** 40 **Sarno Percentage** 30

Cruma % 5 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 5 **Pottery frag count** 0 **Pink mortar _rocks_%** 15

Construction Technique Opus Incertum **Construction Phase** Intermediary

Mortar Sample Directly Associated with:

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 15 **to** 20 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☐ **Low** ☒

Mortar Color Yellow **Mortar surface** Soft **Inclusion Size:** **Most Large** ☒

Mortar interior Soft **Most small** ☐

Leucite % 0

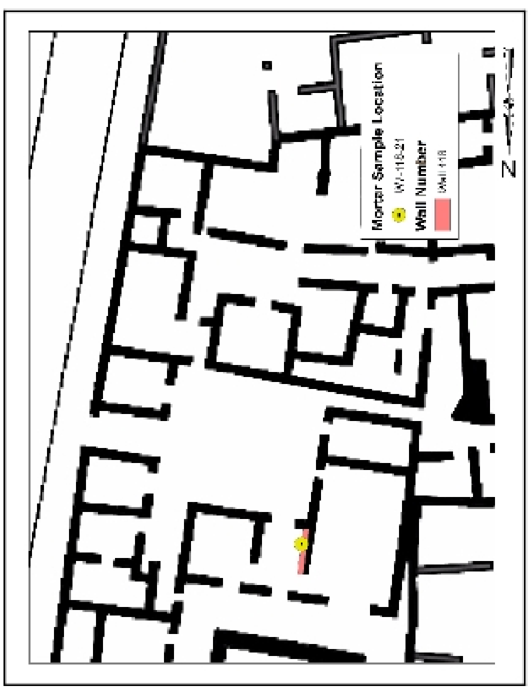
Red Pumice % 0

Cpx % 33 abundant, large crystals

Lime % 33 large and small lumps

Aggregate Notes also contains black pumice gravel, 33% - very soft and degrading, lime-rich


AAPPØ7
W7-118-21
N


Mortar Sample Location
W7-118-21
Wall Number
Wall 118
N


0.5mm

Sample ID W7-108-22 **Date Collected** 7/12/200

Plot Number 7 **Wall Number** 108 **Room Number** 38

AA Number 0 **SU Number** 0

Location Notes Possible Bourbon-era re-pointing mortar from northern section of wall, covering sarno stone

Wall Construction and Component Info

Black Lava with Black Particles % 0 **Black Lava with White Flecks %** 0 **Sarno Percentage** 95

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 5 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** Final

Mortar Sample Directly Associated with: Sarno

Mortar Sample Info

Interior Wall ☒ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 40 **to** 50 **%**

Exterior Wall ☐ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Brown **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☒

Mortar interior Firm **Most small** ☐

Leucite % 0

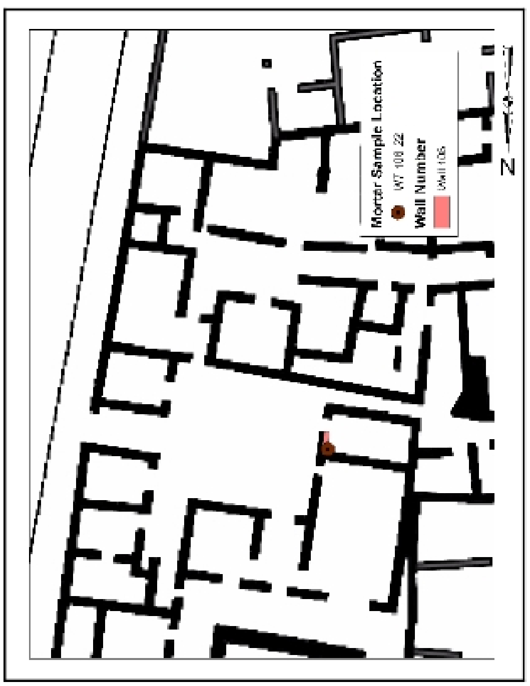
Red Pumice % 0 some very small frags

Cpx % 0

Lime % 0 none visible

Aggregate Notes Contains possible limestone, tufa, and black pumice gravel, possible olivine crystal - it's a brownish-grey mortar with varied and poorly sorted inlcusions overal, though this sample contains mostly small inclusions


AAPP07
W7-108-22
N←


Mortar Sample Location
W7 108 22
Wall Number
Wall 108
N


0.5mm

Sample ID W9-16-23 **Date Collected** 7/12/200

Plot Number 9 **Wall Number** 16 **Room Number**

AA Number 0 **SU Number** 0

Location Notes From third row of stones up from ground level, southern quarter of wall, below white limestone block

Wall Construction and Component Info

Black Lava with Black Particles % 50 **Black Lava with White Flecks %** 40 **Sarno Percentage** 10

Cruma % 0 **White limestone %** 1 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 0

Construction Technique Opus Incertum **Construction Phase** First

Mortar Sample Directly Associated with: Black lava

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 50 **to** 60 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Pink **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☒

Mortar interior Firm **Most small** ☐

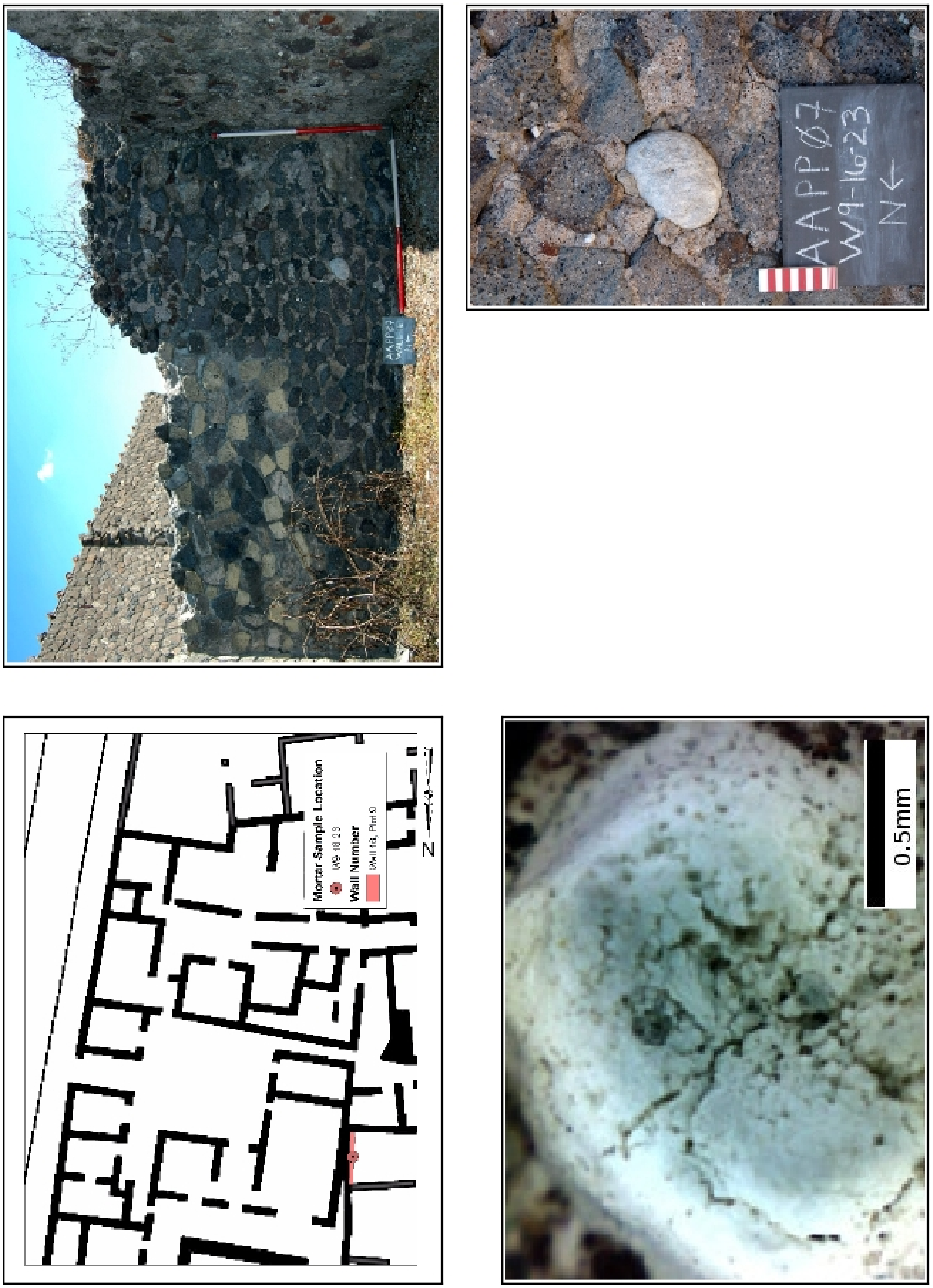
Leucite % 10 whole and frags, most med sized

Red Pumice % 30 small and very large, some with whole leucite crystals

Cpx % 30 some very large, most approx 5mm

Lime % 30 small to massive lumps

Aggregate Notes Sample broke away easily as a large clump but did not break - stayed a single piece which was already loose within the wall


AAPP07
W9-16-23
N←
Mortar Sample Location
W9-16-23
Wall Number
N
0.5mm

Sample ID W6-118-24 **Date Collected** 7/13/200

Plot Number 6 **Wall Number** 118 **Room Number** Narciso

AA Number 0 **SU Number** 0

Location Notes Greyish mortar from approx 1 meter from north edge of wall, where it meets House of Vestals, approx 1.5 meters up from ground level

Wall Construction and Component Info

Black Lava with Black Particles % 0 **Black Lava with White Flecks %** 45 **Sarno Percentage** 40

Cruma % 0 **White limestone %** 0 **Nocera Tufa %** 5

Brick count 0 **Pottery frag count** 5 **Pink mortar _rocks_%** 10

Construction Technique Opus Incertum **Construction Phase** Intermediary

Mortar Sample Directly Associated with: Nocera Tufa

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 40 **to** 50 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☐ **Med** ☒ **Low** ☐

Mortar Color Grey **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☐

Mortar interior Soft **Most small** ☒

Leucite % 20 small and large frags, most small, no visible whole crystals, grey and black

Red Pumice % 35 small and large fragsk, most small

Cpx % 30 most tiny frags, some large

Lime % 15 most tiny, 1 massive lump

Aggregate Notes Grey "look-alike" mortar, not pink but has similar aggregate, associated with different types of stones, contains gravel-size tufa frags, was difficult to remove but crumbly and friable once removed from wall


AAPP07
W6-118-24
N→
Mortar Sample Location
0.5mm

Sample ID W7-152-25 **Date Collected** 7/13/200

Plot Number 7 **Wall Number** 152 **Room Number** 35

AA Number 0 **SU Number** 0

Location Notes Modern mortar consolidation from top of wall 120/152

Wall Construction and Component Info

Black Lava with Black Particles % 10 **Black Lava with White Flecks %** 10 **Sarno Percentage** 50

Cruma % 20 **White limestone %** 0 **Nocera Tufa %** 0

Brick count 0 **Pottery frag count** 0 **Pink mortar _rocks_%** 10

Construction Technique Opus Incertum **Construction Phase** Modern

Mortar Sample Directly Associated with:

Mortar Sample Info

Interior Wall ☐ **Inner core sample** ☐ **In situ** ☒ **Inclusion Density:** 70 **to** 70 **%**

Exterior Wall ☒ **Outer face sample** ☒ **Re_use** ☐ **High** ☒ **Med** ☐ **Low** ☐

Mortar Color Grey **Mortar surface** Very hard **Inclusion Size:** **Most Large** ☒

Mortar interior Very hard **Most small** ☐

Leucite % 0

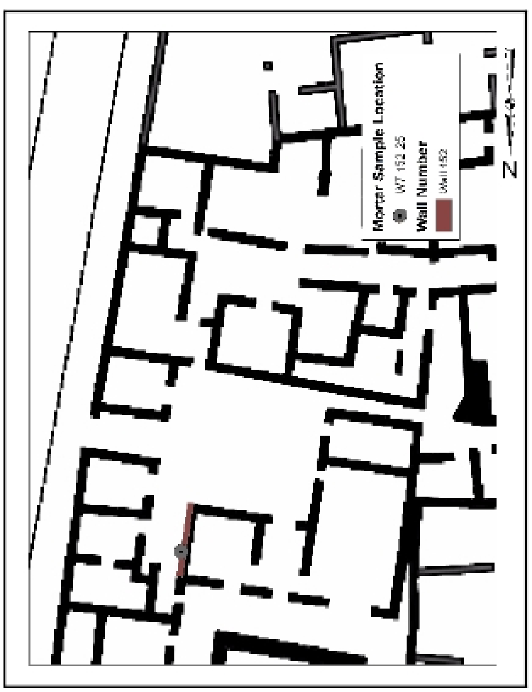
Red Pumice % 0

Cpx % 0

Lime % 0

Aggregate Notes Very coarse, gravelly modern repair/consolidation along top of wall. Common modern material


AAPP07
W7-152-23
N↑


Mortar Sample Location
W7 152 25
Wall Number
Wall 152


0.5mm

APPENDIX C

THIN SECTION FORMS

Sample W7-152-6 Pg 1 of 5 Date 10/29/08

Binder

Notes:
- this slide seems to be about 70% binder, and 25% aggregate inclusions, including glass
- the binder is medium to dark brown color (lighter along slide edges) (PPL)
- in XPL, binder appears micritic
- minimal porosity; a few holes, but the majority are in or near lime lumps
- cracking within lime lumps
- there are 2 large cracks running E-W, one on each side of the slide - 1 is directly related to a lime lump

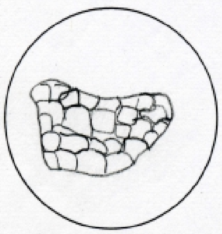
Aggregate:

Notes:
- contains X-tals both in rock fragments and free floating
- majority of the "free crystals" are ringed with glass, indicating they came from glassy rocks (ie, red scoria)
- glass color varies: including very light yellow, dark yellow, bright orange, dark orange, and brown
- also contains a few possible ceramic fragments (pot sherd?) and UID lithic frags (lapilli?)
- biotite? I only see 1 possible grain

Sample w7-152-6 Pg 2 of 5 Date 10/29/08

Aggregate Inclusions:

Type/ID	unknown calcite? limestone frag? rock frag
Relief	low, positive
Color	colorless
Birefringence	up to 4th order green – 0.034 – 0.036
Size Range	(120 marks at 50x)
Count/%	1 grain
Additional Notes Cont'd on back ____	-individual grains in a conglomerate?



Mag 50x PPL
Diam of View ______

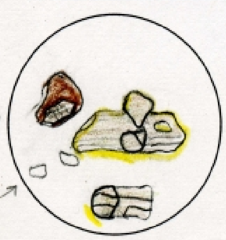
Mag ______
Diam of View ______

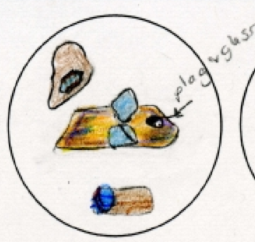
Mag ______
Diam of View ______

Mag ______
Diam of View ______

Type/ID	clinopyroxene
Relief	about equal to cement, some look slightly negative
Color	cloudy, pale green or very pale brown
Birefringence	most 1st order orange/purple, some up to blue
Size Range	
Count/%	
Additional Notes Cont'd on back ____	most X-tals are ringed in orange or yellow glass, several look whole, euhedral

what is this?





Mag 2.5x PPL
Diam of View ______

Mag 2.5x XPL
Diam of View ______

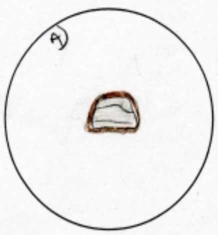
Mag ______
Diam of View ______

Mag ______
Diam of View ______

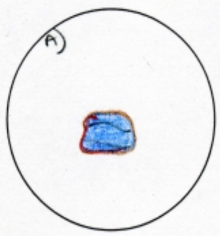
Sample W7-152-6 Pg 3 of 5 Date 10/30/08

Aggregate Inclusions:

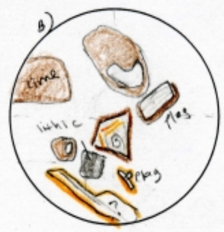
Type/ID	Olivine?
Relief	moderate, positive
Color	colorless
Birefringence	A) 2nd order blue .014 B) 2nd order blue
Size Range	A) ~15 marks at 2.5x B) ~15-20 marks at 2.5x
Count/%	
Additional Notes Cont'd on back ____	A) this grain shows parallel extinction, is ringed with dark brown glass B) parallel extinction, ringed in glass



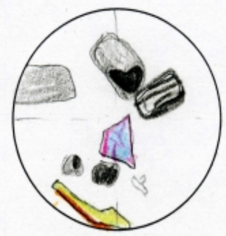
Mag 2.5x PPL
Diam of View______



Mag 2.5 XPL
Diam of View______

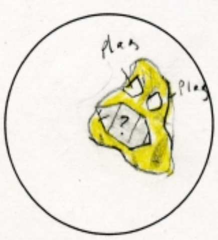


Mag 2.5 PPL
Diam of View______

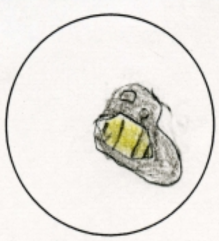


Mag 2.5 XPL
Diam of View______

Type/ID	? Olivine
Relief	difficult to tell here
Color	colorless
Birefringence	low - 1st order yellow, the other 2 go up to 2nd order blue
Size Range	~50 marks at 10x, another is 70 marks at 10x
Count/%	3 of these,
Additional Notes Cont'd on back ____	'football' shaped xtal in glassy rock fragment? - parallel ext. -glass in light yellow, one of several - all colors of glass are visible here



Mag 10x PPL
Diam of View______



Mag 10x XPL
Diam of View______

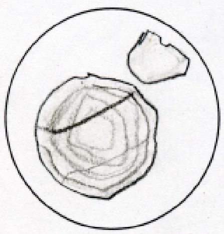
Mag______
Diam of View______

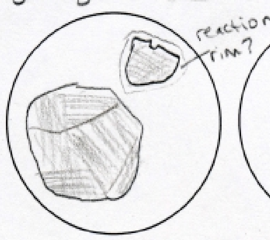
Mag______
Diam of View______

Sample W7-152-6 Pg 4 of 5 Date______________

Aggregate Inclusions:

Type/ID	Leucite
Relief	slightly positive
Color	colorless
Birefringence	isotropic
Size Range	whole - ~90 at 2.5x ; frags 3-50 at 2.5
Count/%	~20% of inclusions are leucite
Additional Notes Cont'd on back _____	some are nearly whole x-tals, many small angular frags, most show evidence of hydration and some glassy inclusions(?), twinning evident in XPL





Mag 2.5x PPL
Diam of View______

Mag 2.5x XPL
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Type/ID	Plagioclase
Relief	low positive
Color	colorless
Birefringence	1st order grey/yellow, variable extinction
Size Range	~1-20 mark at 1.25x
Count/%	approx 40-50% of inclusions are plag. grains, very abundant
Additional Notes Cont'd on back _____	albite twinned, "radiating" clusters of grains, in rock frags, ceramic frags, + free floating, many ringed or encased in glass

(near the cpx [illegible]

XPL

Mag 10x ~80 at 10x
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

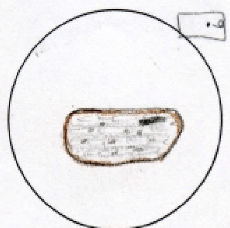
Sample W7-152-6 Pg 5 of 5 Date______________

Aggregate Inclusions:

Type/ID	Lithic frags (poss. scoria, poss. lapilli)
Relief	very low, negative
Color	dark brown (scoria?); dark grey with much plag +
Birefringence	isotropic
Size Range	~120 marks at 2.5x, ~20 at 2.5x, ~15 at 2.5x (scoriae) -
Count/%	
Additional Notes Cont'd on back _____	most look like the red scoria slide - glassy, porous with phenocrysts of plag + olivine?

it looks like mortar is sitting on the frag here?

Mag 2.5x PPL
Diam of View______



lapilli?

Mag 10x PPL
Diam of View______
~120 marks at 10x

goes isotropic apart from a few small grains

Mag 10x XPL
Diam of View______

Mag______
Diam of View______

Type/ID	ceramic frags?
Relief	very low, ,
Color	dark reddish brown
Birefringence	nearly isotropic
Size Range	
Count/%	~3 frags
Additional Notes Cont'd on back _____	same color as some of the glass frags but no glassy texture, contains small laths of plag

Mag 1.25x
Diam of View______

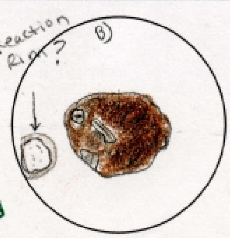
A)

acicular plag = quenched = volcanic frag

PPL

Mag 10x ~120 at 10x
Diam of View______

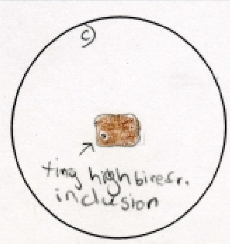
Reaction Rim? B)



PPL

Mag 10x ~90 at 10x
Diam of View______

C)



Mag 10x ~40 at 10x
Diam of View______

Sample W7-112-8 Pg 1 of 3 Date 10/30/08

Binder

Notes:

- binder is quite dark brown, lime lumps are very dark
- contains large holes - generally not round and some are & some not x-tal shaped - could it be degradation? sample prep?
- micritic in XPL
- lime lumps are large - possibly 2 kinds? (dark brown and very dark brown)
- generally more porous than sample 6

lime lump size, rounding, porosity more important

Aggregate:

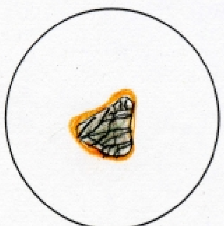
Notes:

- Contains rather large x-tals that are nicely colored (where appl.)
- lots of small glass frags visible, seem to be sitting on x-tals
- yellow pumice?
- med-brown ceramic frags
- glass is yellow, orange, brown
- scoria frags

Sample W7-112-8 Pg 2 of 3 Date 11/3/08

Aggregate Inclusions:

Type/ID	? ~~Olivine~~? cpx
Relief	med - positive
Color	greenish-brownish-pale
Birefringence	low - 1st order yellow?
Size Range	~20 marks at 2.5x ~50 at 10x
Count/%	1 here
Additional Notes Cont'd on back ____	I've seen of these in sample 6 is it just a very ~~cracked~~ grain? lots o visible cleavage?



Mag 10x PPL
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Type/ID	biotite? not any more → very heated + "oxidized biotite"
Relief	
Color	
Birefringence	
Size Range	
Count/%	
Additional Notes Cont'd on back ____	(near the above grain)

Mag______
Diam of View______

Mag______
Diam of View______

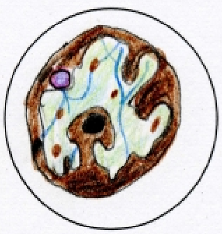
Mag______
Diam of View______

Mag______
Diam of View______

Sample W7-112-8 Pg 3 of 3 Date 11/3/08

Aggregate Inclusions:

Type/ID	? - sk. div.
Relief	positive
Color	colorless
Birefringence	~ .021 – .024
Size Range	~ 100 mults at 10x
Count/%	
Additional Notes Cont'd on back ____	What are the blue veins?



Mag 10x XPL
Diam of View____

Mag____
Diam of View____

Mag____
Diam of View____

Mag____
Diam of View____

Type/ID	
Relief	
Color	
Birefringence	
Size Range	
Count/%	
Additional Notes Cont'd on back ____	

Mag____
Diam of View____

Mag____
Diam of View____

Mag____
Diam of View____

Mag____
Diam of View____

Sample W7-128-11 Pg 1 of 1 Date 11/03/08

Binder

Notes:
- light to med brown color
- micritic in XPL
- moderately porous, minimal cracking, - lumps are cracked/porous
- some lumps are dark brown, some light brown, some greyish,

Aggregate:

Notes;
- possible biotite
- ceramic
- dark (pumice) lithic frags
- yellow, orange, brown glass
- strange brown glass frag near the whole leucite Xtal in center
- lime lumps may have "reaction rims"

Sample W7-205-12 Pg 1 of 2 Date 11/03/08

Binder

Notes:
- light, medium, & dark brown
- micritic in XPL, lumps even more dramatic
- a few large holes, several small ones
- lumps are dark grey, light brown, med brown
- most lumps are small
- some small cracks along slide edge

Aggregate:

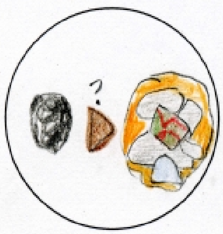
Notes:
- yellow pumice?
- yellow, orange, brown glass
- large Scoria frags, and small dark lithics
- biotite?
- CPX with herringbone pattern? xtl } next door to eachother

is olivine - straight lines are places where xtal didn't completely crystallize

Sample W7-205-12 Pg 2 of 2 Date 11/03/08

Aggregate Inclusions:

Type/ID	? ~~ceramic frag~~? lithic
Relief	
Color	
Birefringence	
Size Range	
Count/%	
Additional Notes Cont'd on back ____	contains micas



Mag 2.5x
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Type/ID	
Relief	
Color	
Birefringence	
Size Range	
Count/%	
Additional Notes Cont'd on back ____	

Mag______
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Sample W7-108-22 Pg 1 of 2 Date 11/3/08

Binder

Notes:
- is a light to medium brown color
- porous (large holes up to 150 marks at 1.25x)
- one large lime lump actually contains visible calcite, including at least one well-formed rhomb.
- binder is micritic

prolly means poorly fired

Aggregate:

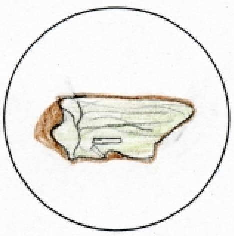
Notes:
- aggregate inclusions are generally large, are mostly lithic fragments and lime lumps
- lithics are grey/black
- small shards of yellow and orange volcanic glass are present (visible only with 10x lens)
- contains biotite
- some of the lime lumps seem to contain xtals (how can you tell an "inclusion" from a "stack"

slide is really thin

Sample W7-108-22 Pg 2 of 2 Date 11/03/04

Aggregate Inclusions:

Type/ID	lime lump with mineral grain
Relief	low positive
Color	pale greenish brown
Birefringence	1st order yellow → purpley-pink - .010 - .011
Size Range	~130 at 10x
Count/%	
Additional Notes Cont'd on back _____	could this be an inclusion in a lime lump or a X-tal sitting on top - ? - is in a volc. rock matrix - really fine grained



PPL

Mag 10x
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Type/ID	biotite
Relief	difficult to tell
Color	yellow-brown
Birefringence	
Size Range	
Count/%	
Additional Notes Cont'd on back _____	

Mag______
Diam of View______

Mag______
Diam of View______

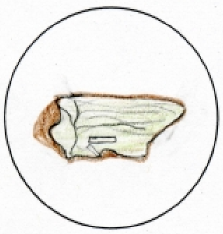
Mag______
Diam of View______

Mag______
Diam of View______

Sample W7-108-22 Pg 2 of 2 Date 11/03/04

Aggregate Inclusions:

Type/ID	lime lump with mineral grain
Relief	low positive
Color	pale greenish brown
Birefringence	1st order yellow → purpley-pink - .010 - .011
Size Range	~130 at 10x
Count/%	
Additional Notes Cont'd on back _____	could this be an inclusion in a lime lump or a x-tal sitting on top - ? — is in a volc. rock matrix — really fine grained



PPL

Mag 10x
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Mag______
Diam of View______

Type/ID	biotite
Relief	difficult to tell
Color	yellow-brown
Birefringence	
Size Range	
Count/%	
Additional Notes Cont'd on back _____	

Mag______
Diam of View______

Mag______
Diam of View______

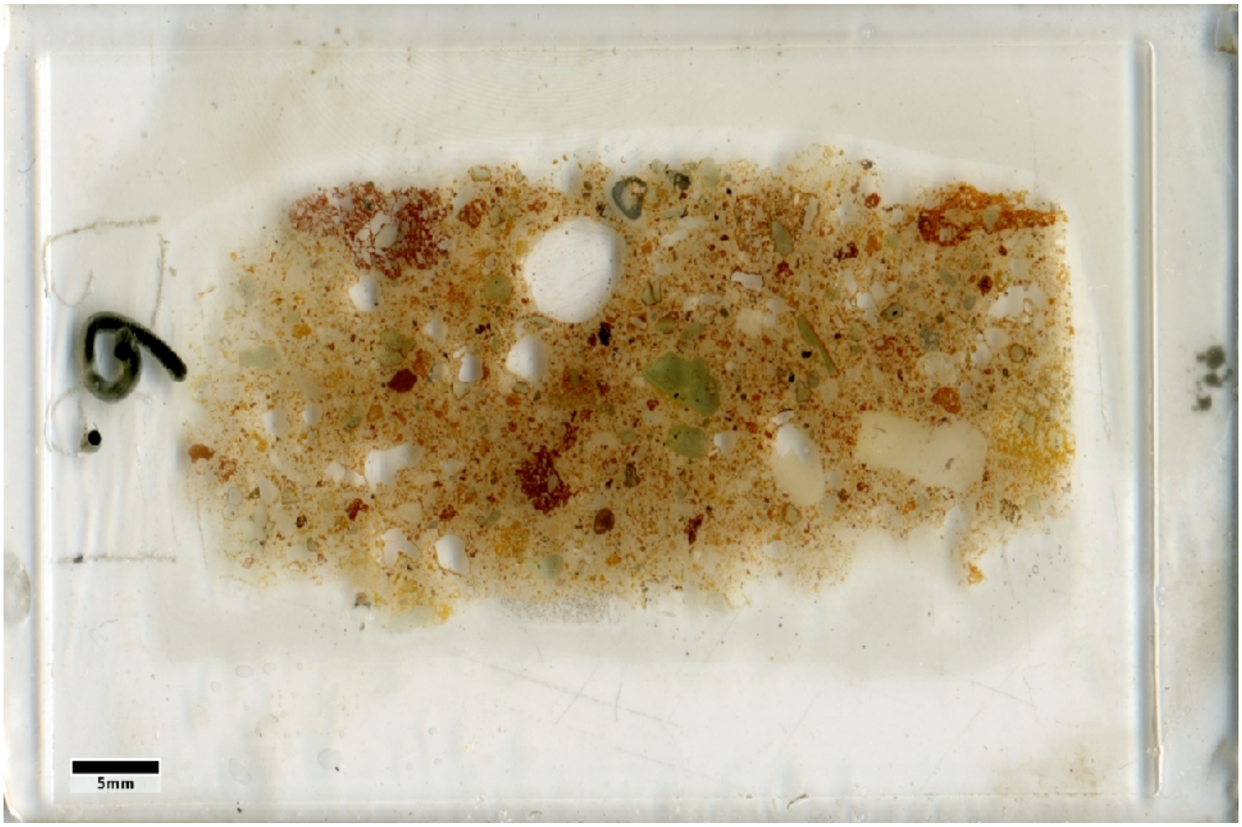
Mag______
Diam of View______

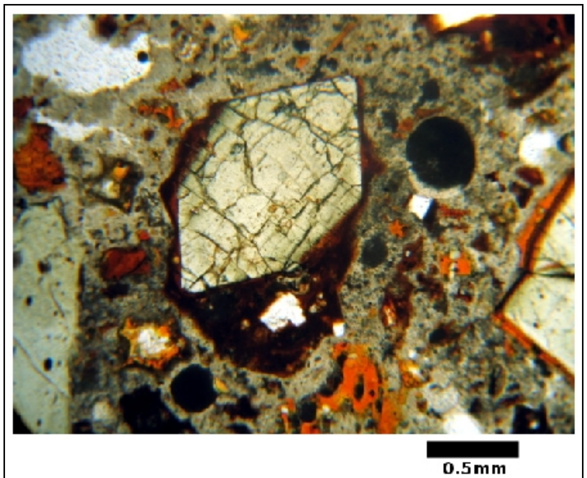
Mag______
Diam of View______

APPENDIX D

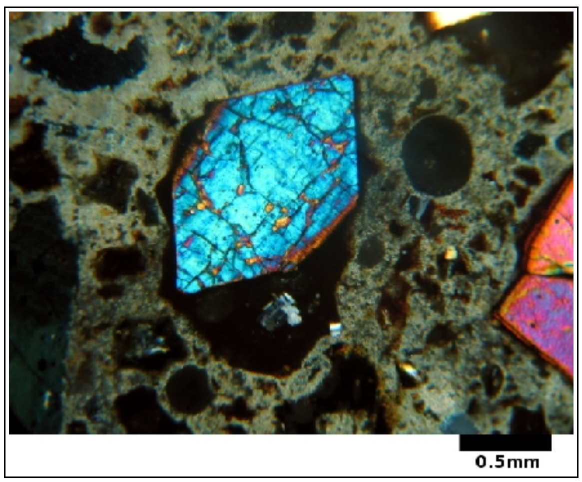
THIN SECTION SCANS AND PHOTOMICROGRAPHS

SAMPLE W7-152-06

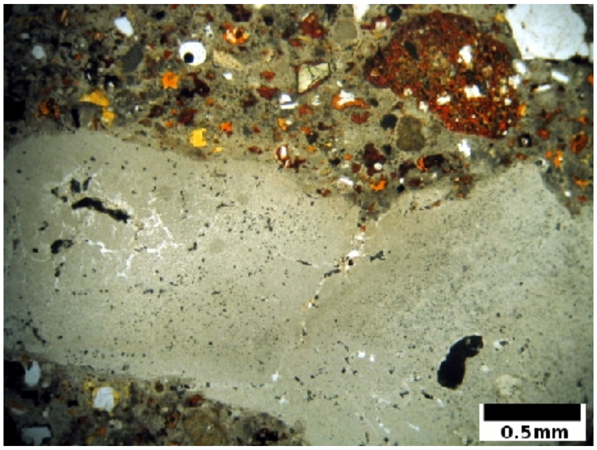




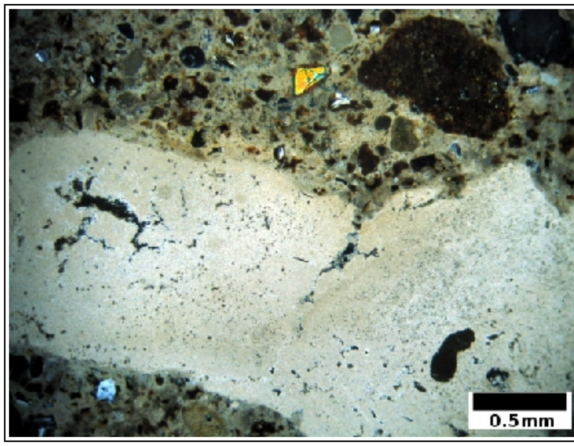
W7-152-06 PPL



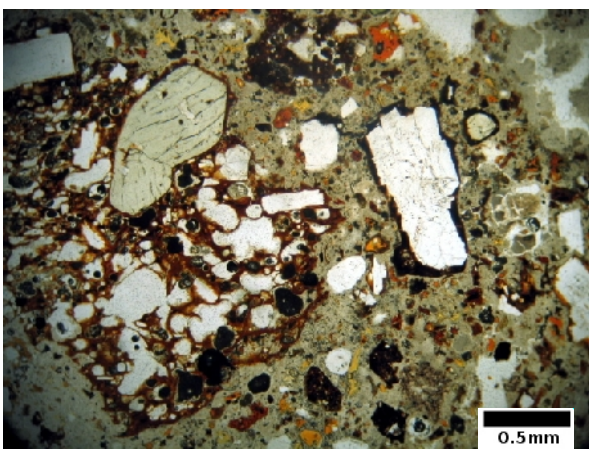
W7-152-06 XPL



W7-152-06 PPL



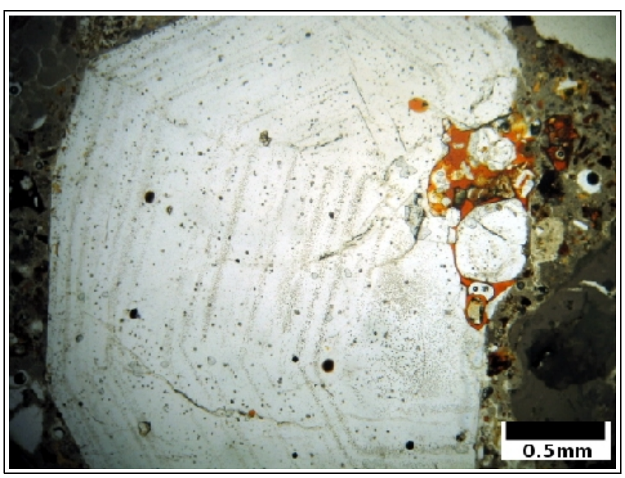
W7-152-06 XPL



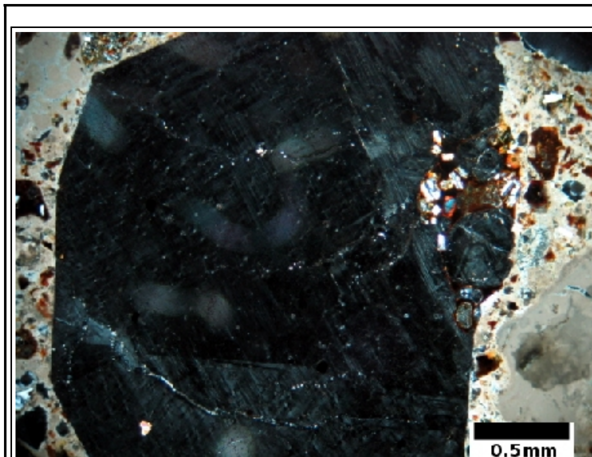
W7-152-06 PPL 4X

W7-152-06 XPL 4X

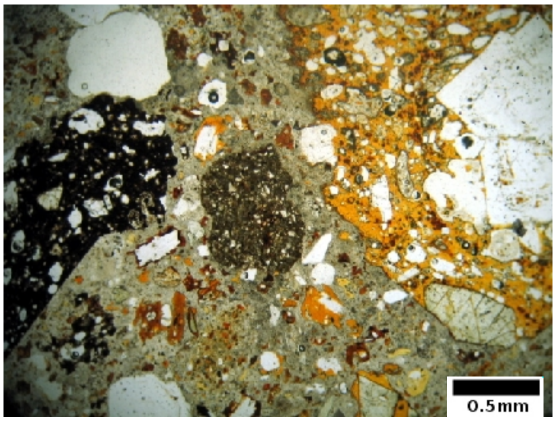
W7-112-08



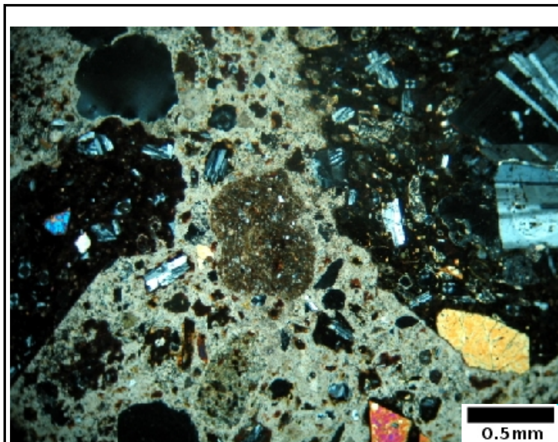
W7-112-08 PPL



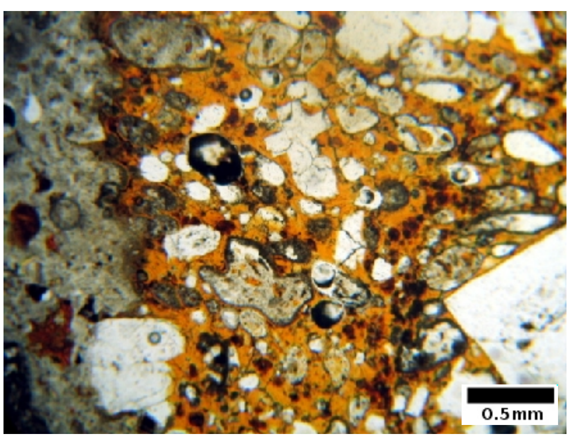
W7-112-08 XPL



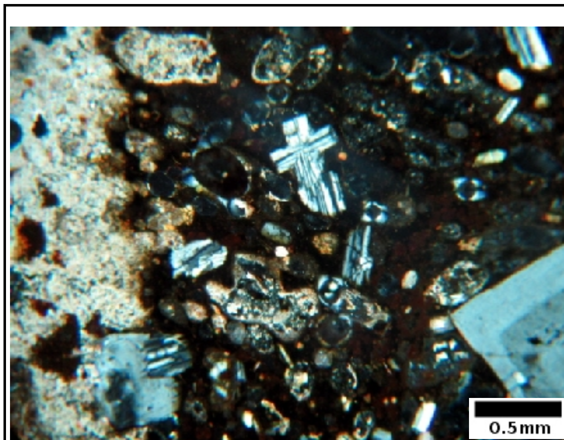
W7-112-08 PPL 4X



W7-112-08 XPL 4X

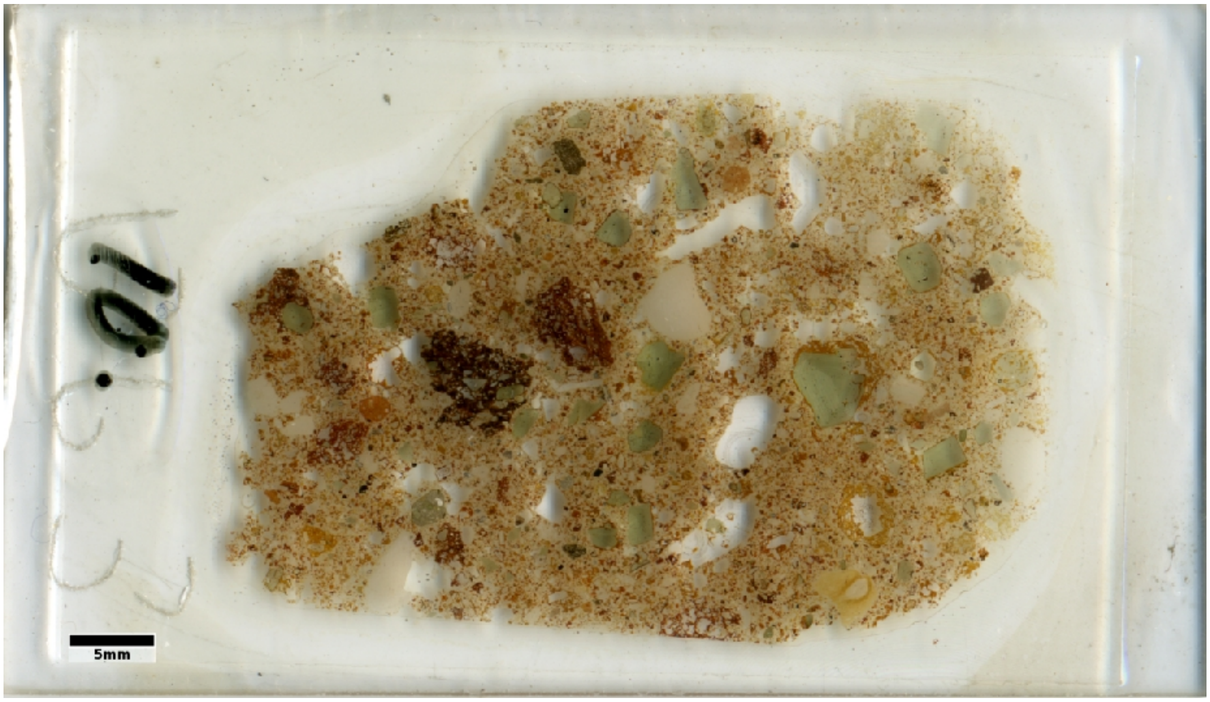


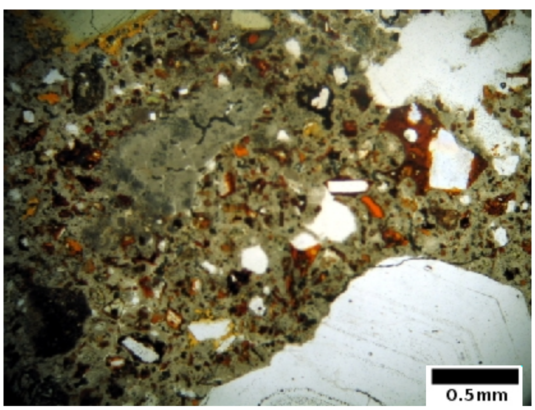
W7-112-08 PPL 4X



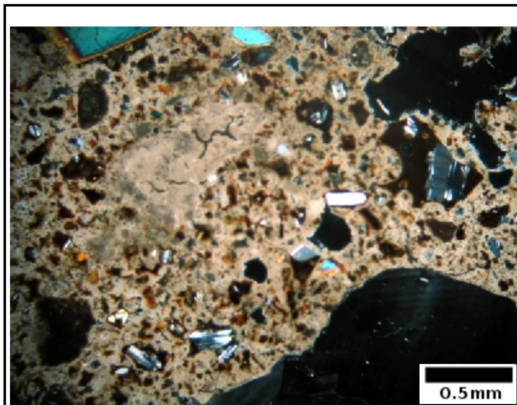
W7-112-08 XPL 4X

W7-123-10

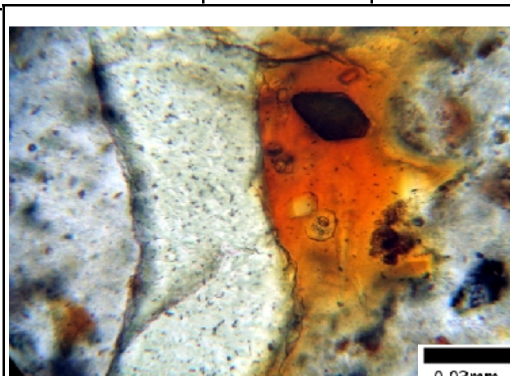




W7-123-10 PPL 4X

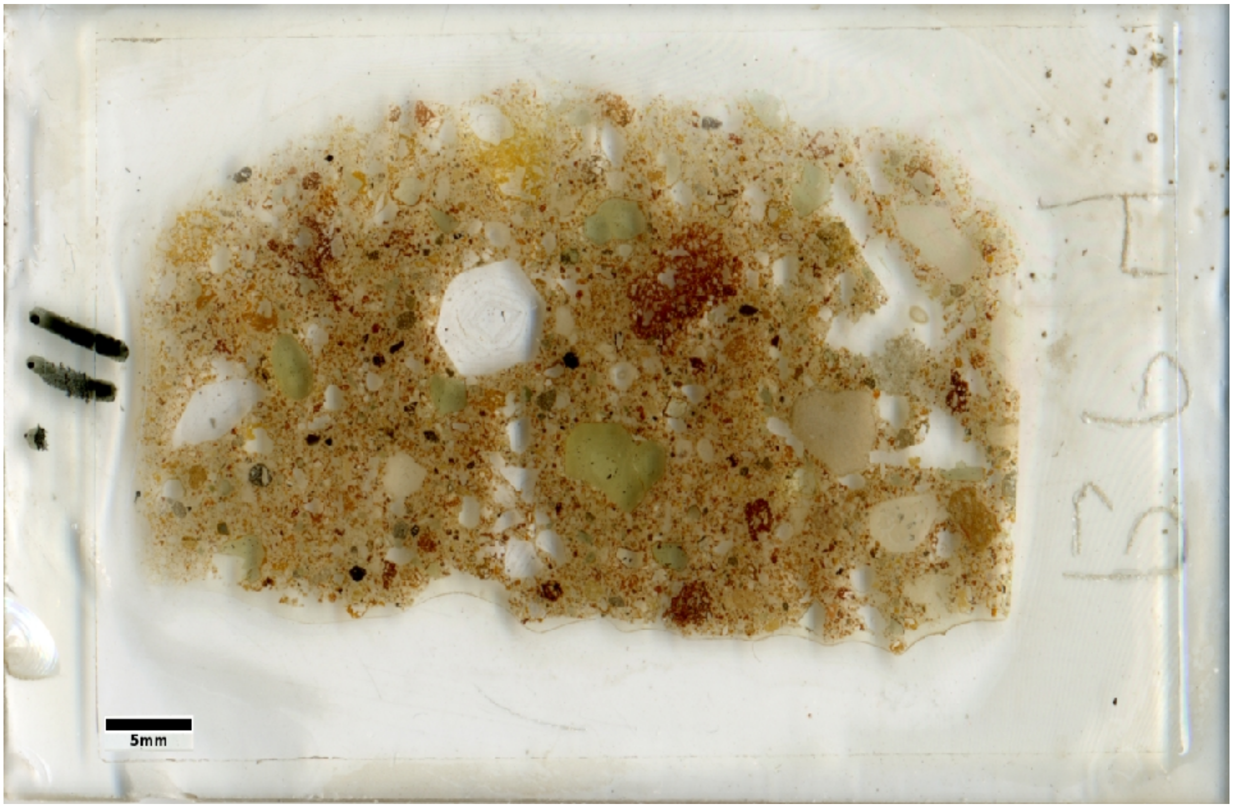


W7-123-10 XPL 4X

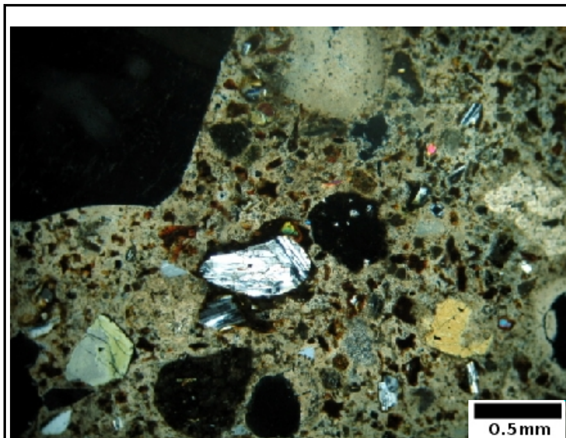


W7-123-10 PPL Volc. glass - 63X

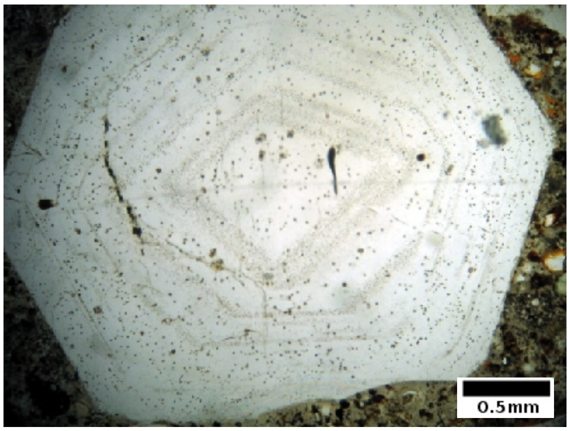
W7-128-11



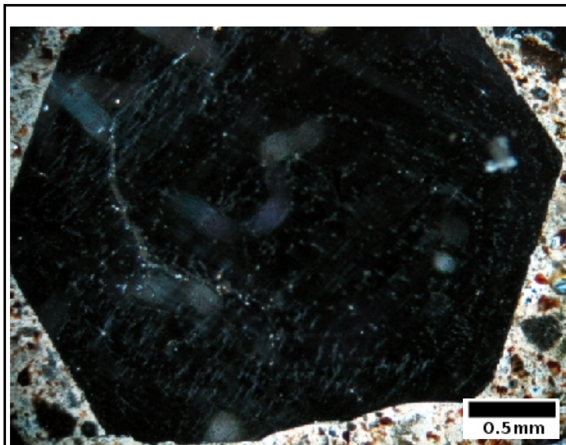
W7-128-11 PPL 4X



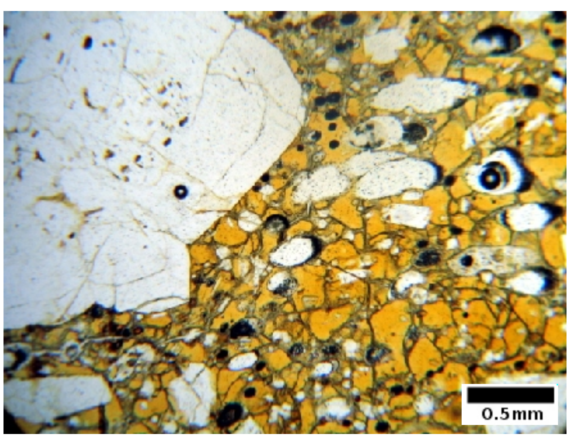
W7-128-11 XPL 4X



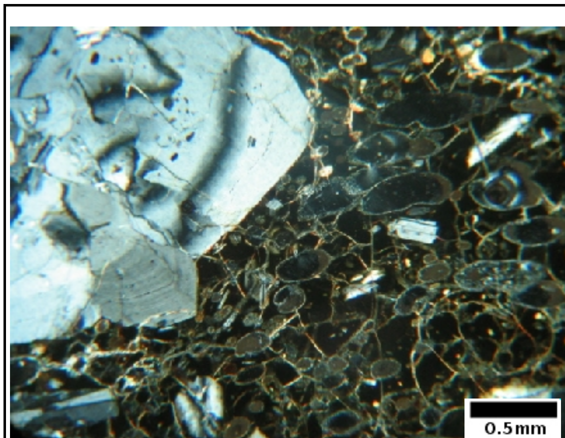
W7-128-11 PPL 4X



W7-128-11 XPL 4X

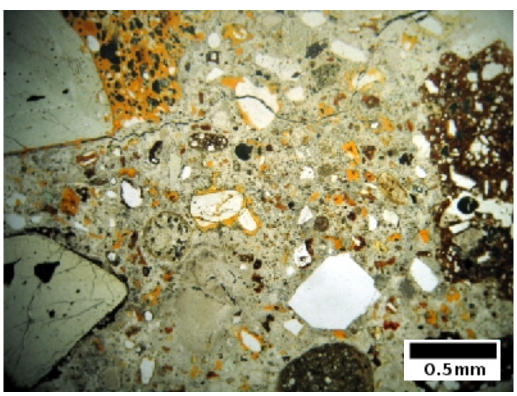


W7-128-11 PPL 4X

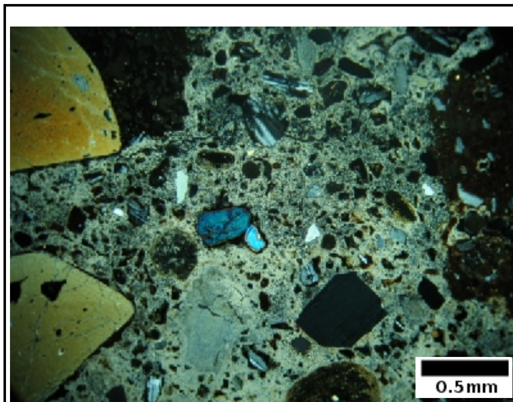


W7-128-11 XPL 4X

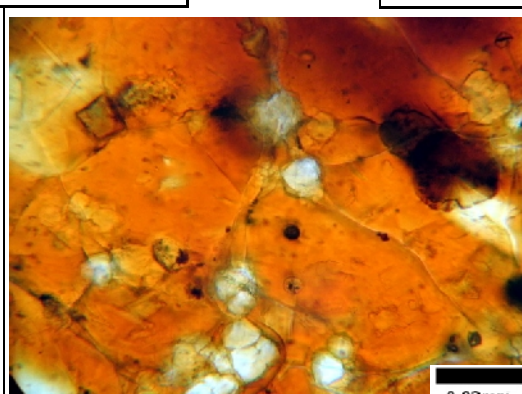
W7-205-12



W7-205-12 PPL 4X

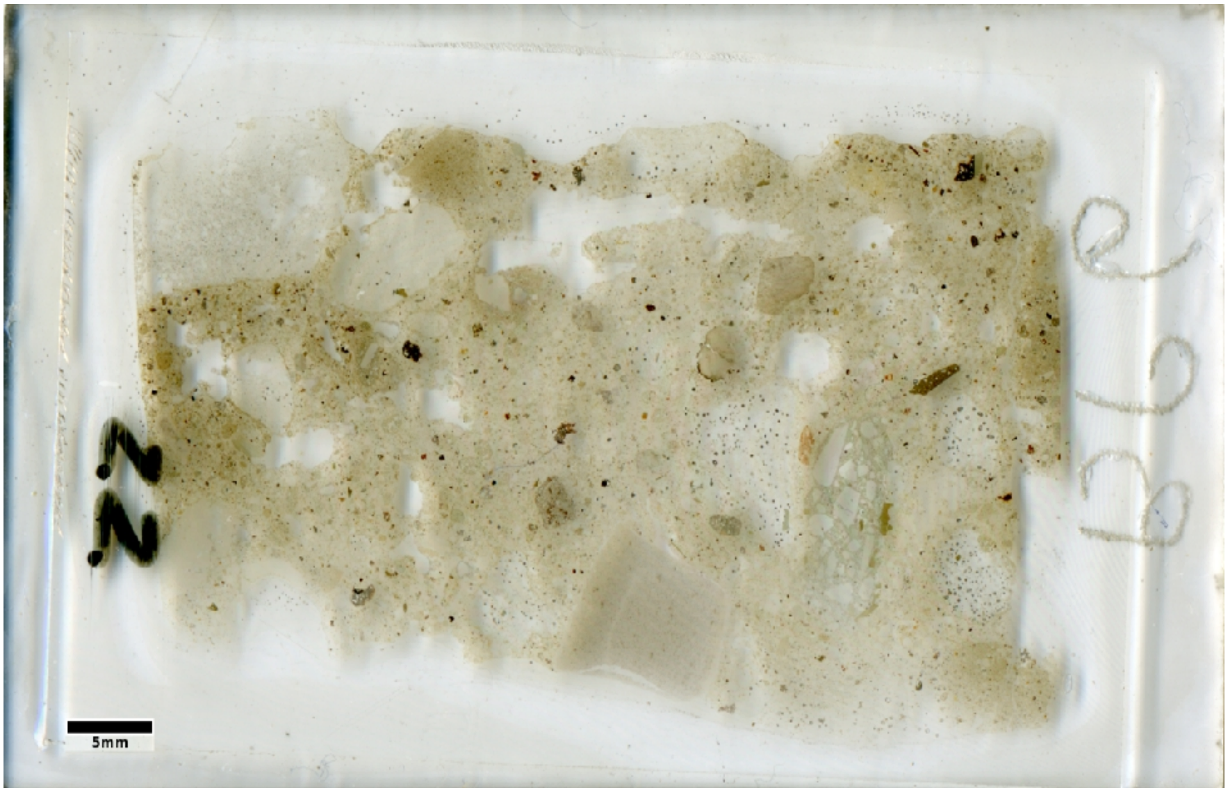


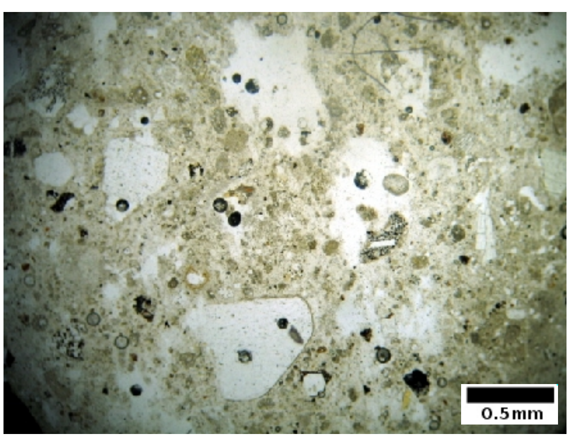
W7-205-12 XPL 4X



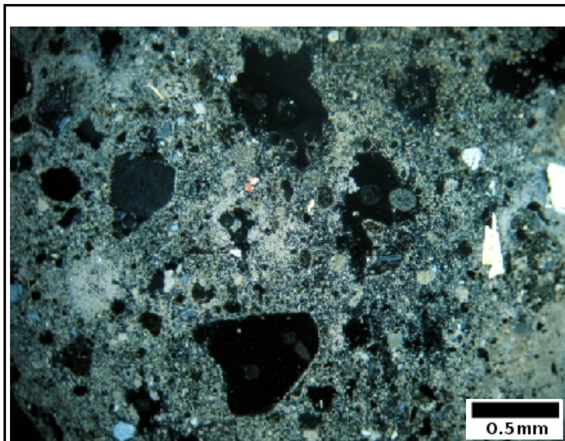
W7-205-12 PPL Volcanic Glass -63X

W7-108-22

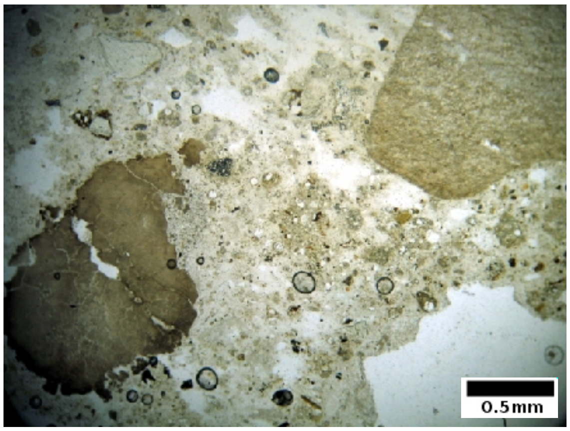




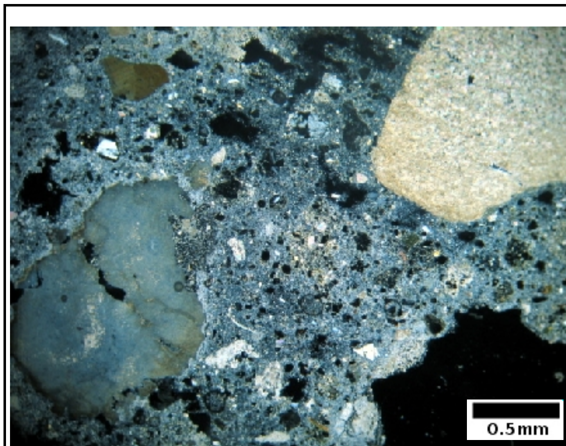
W7-108-22 PPL 4X



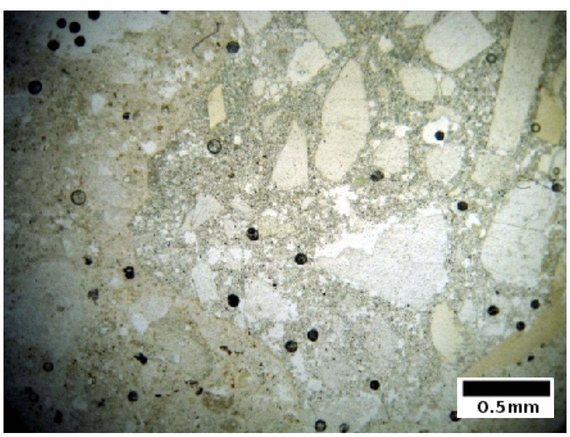
W7-108-22 XPL 4X



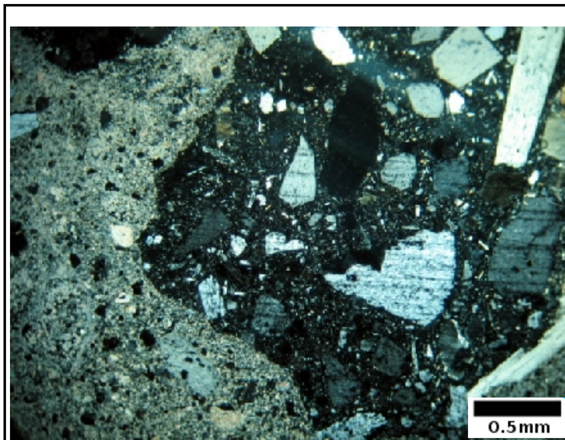
W7-108-22 PPL 4X



W7-108-22 XPL 4X



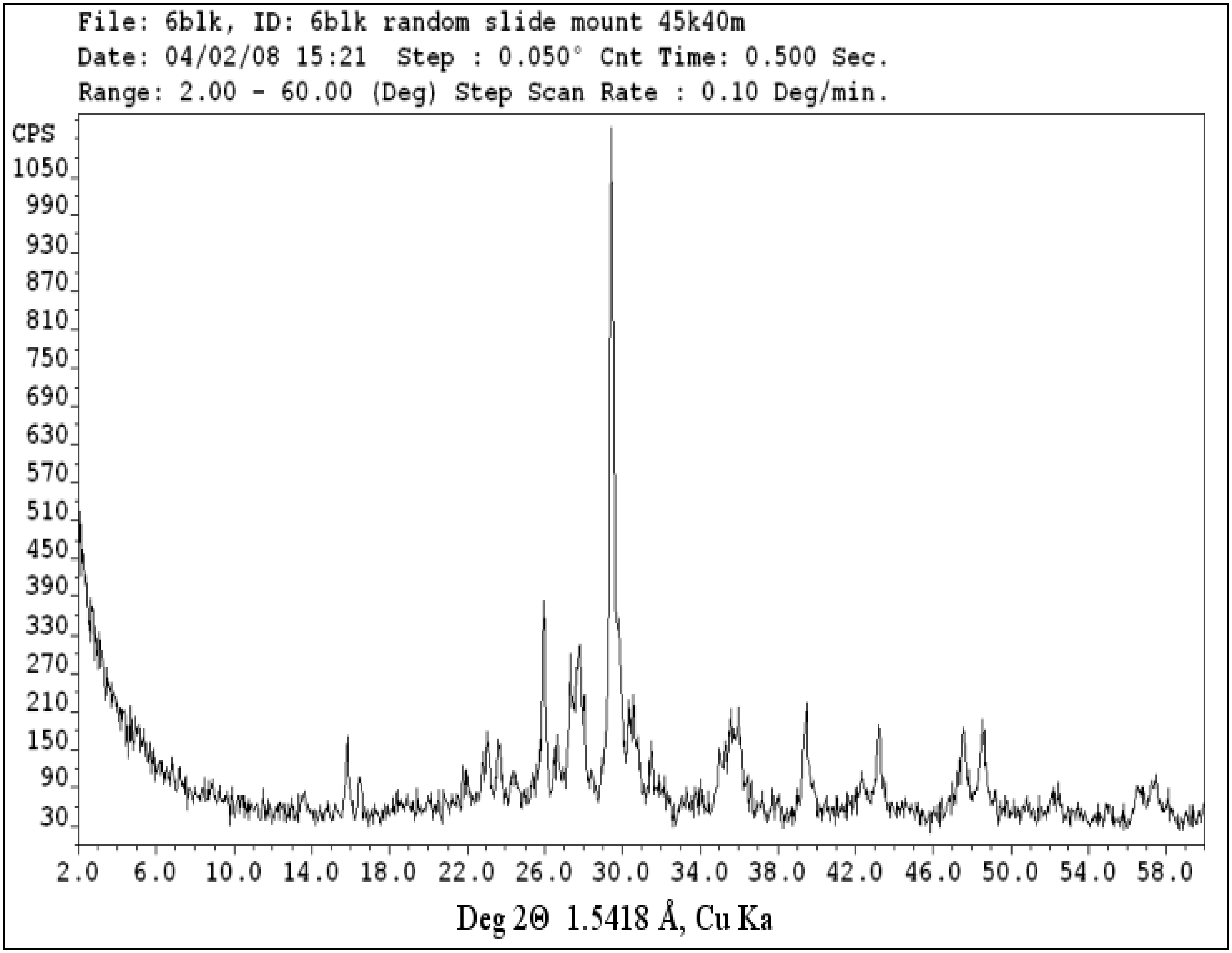
W7-108-22 PPL 4X

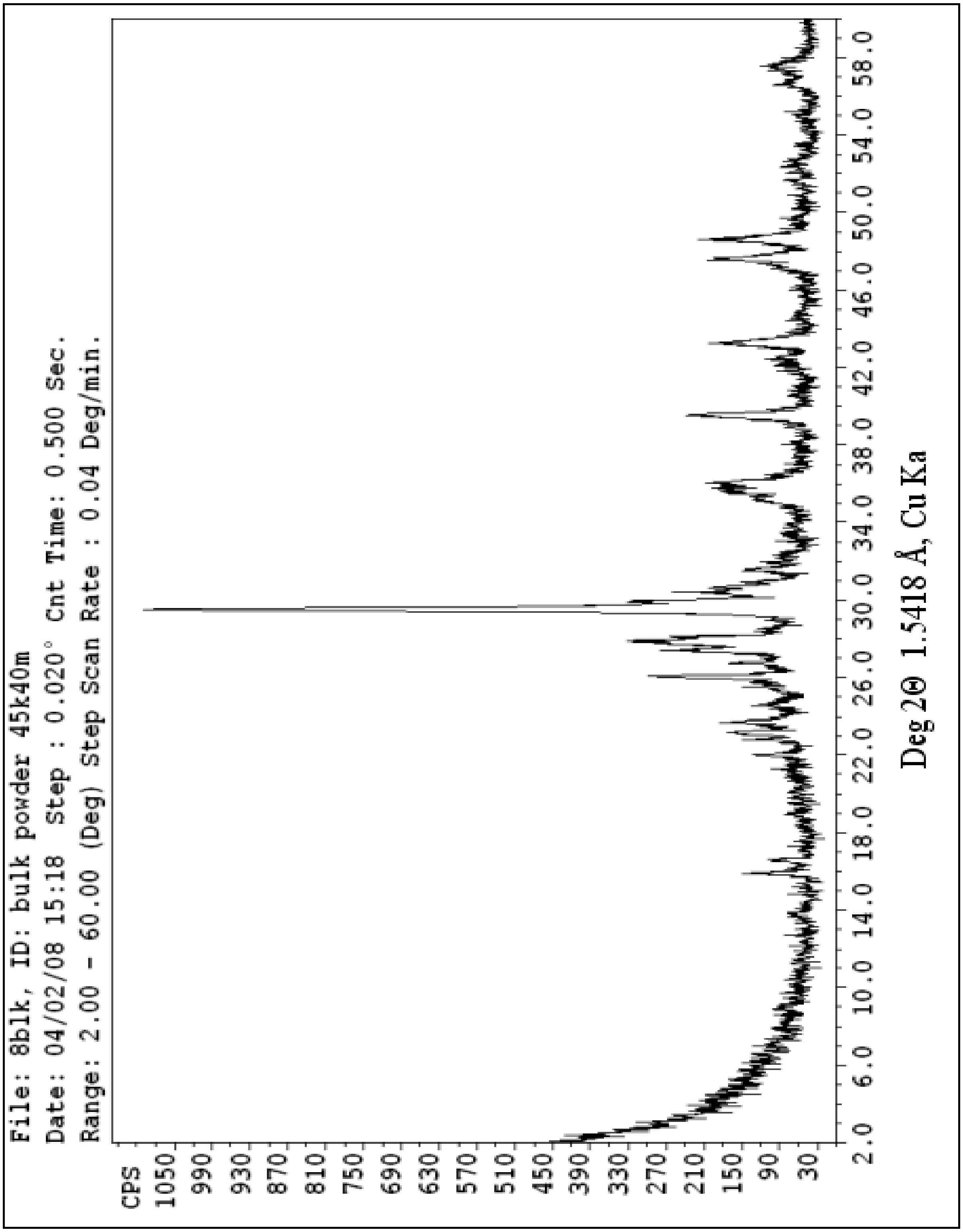


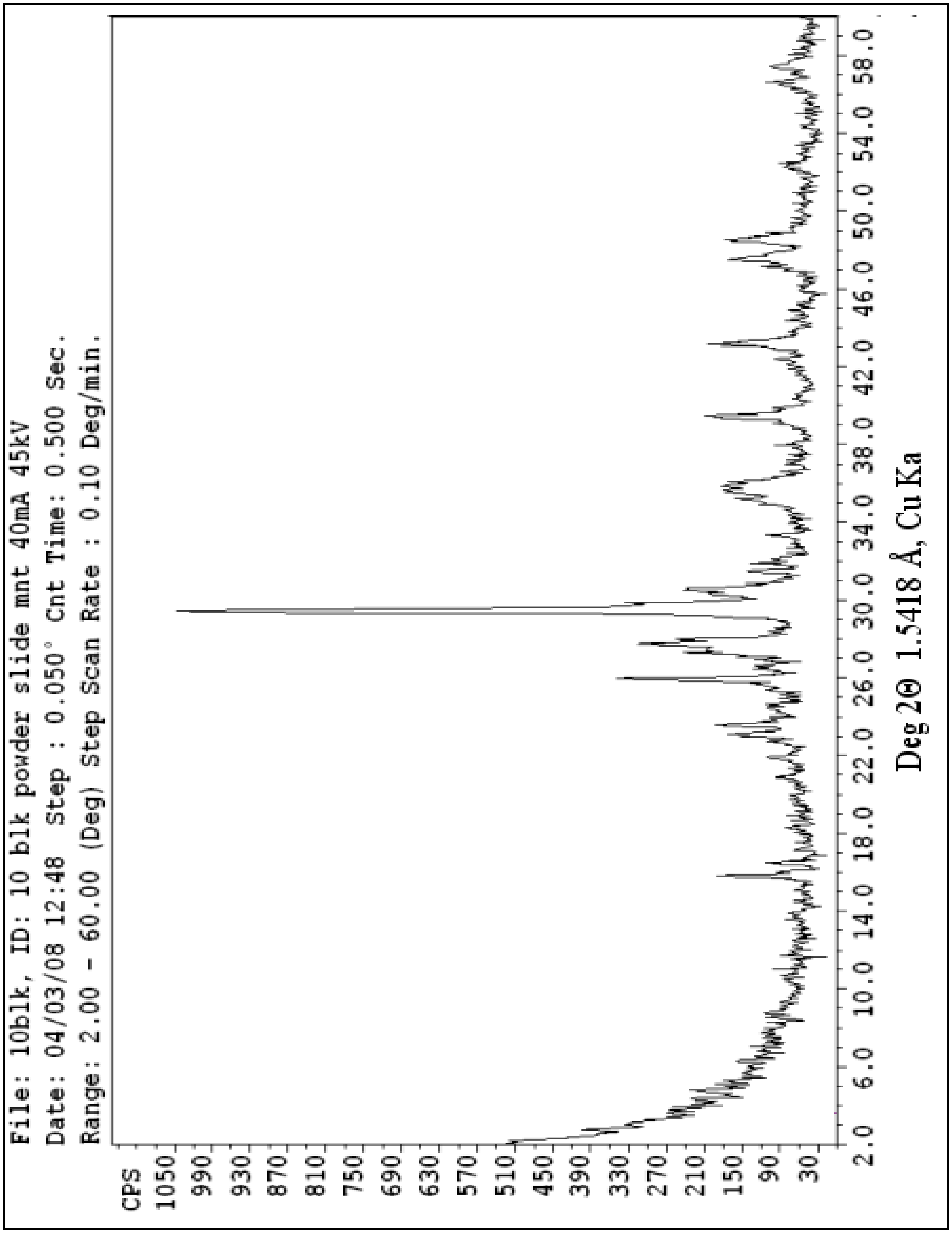
W7-108-22 XPL 4X

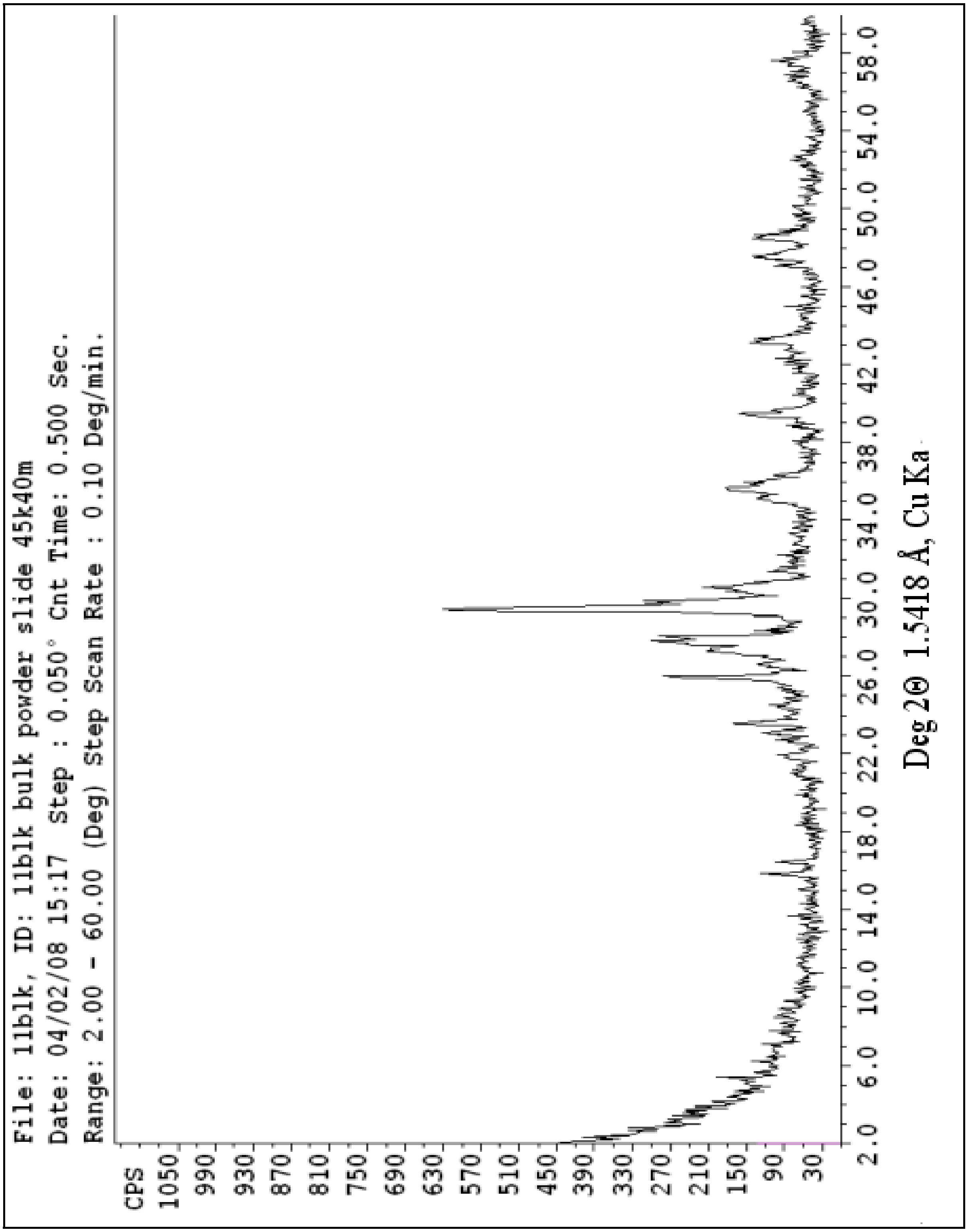
APPENDIX E

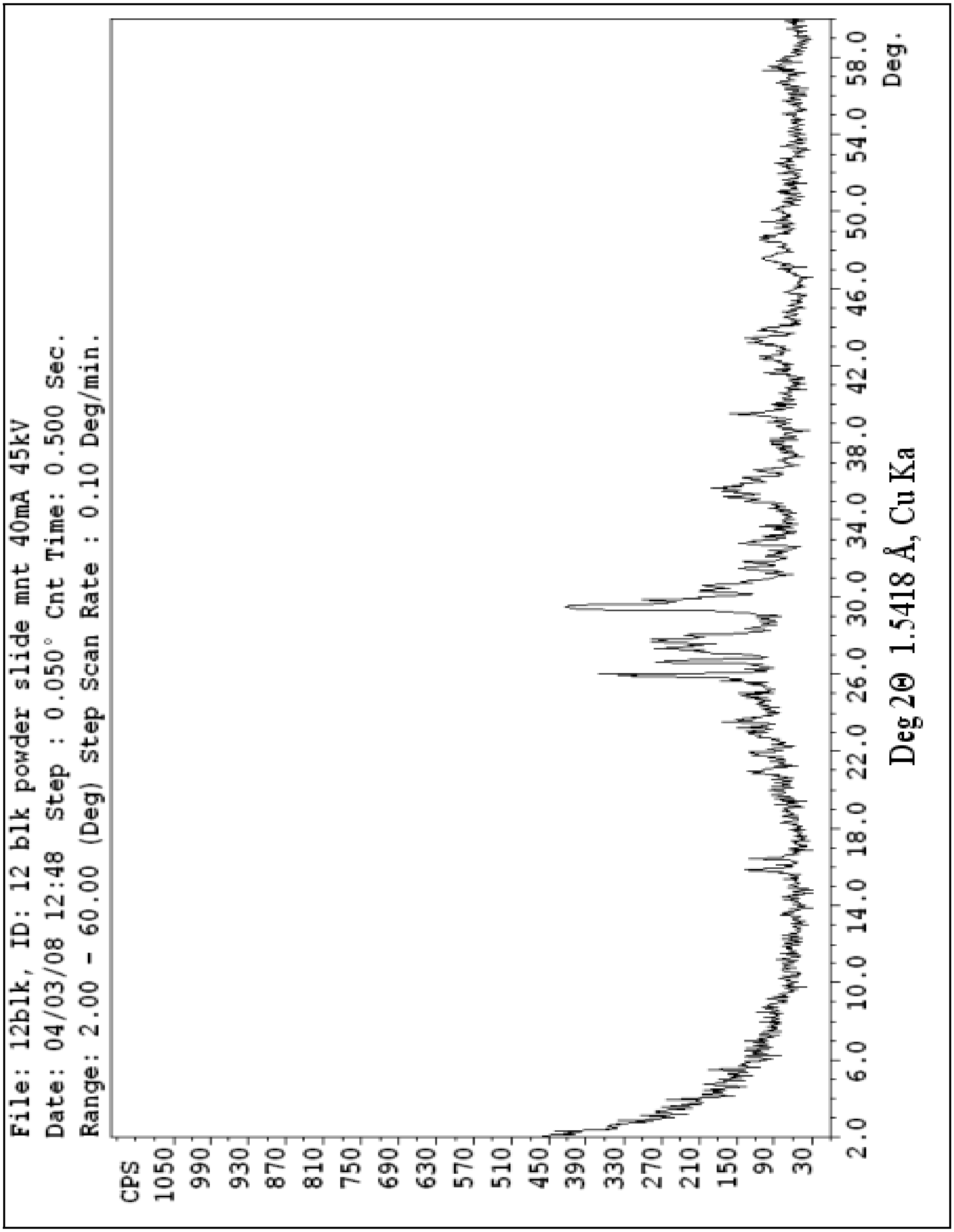
X-RAY DIFFRACTOGRAMS

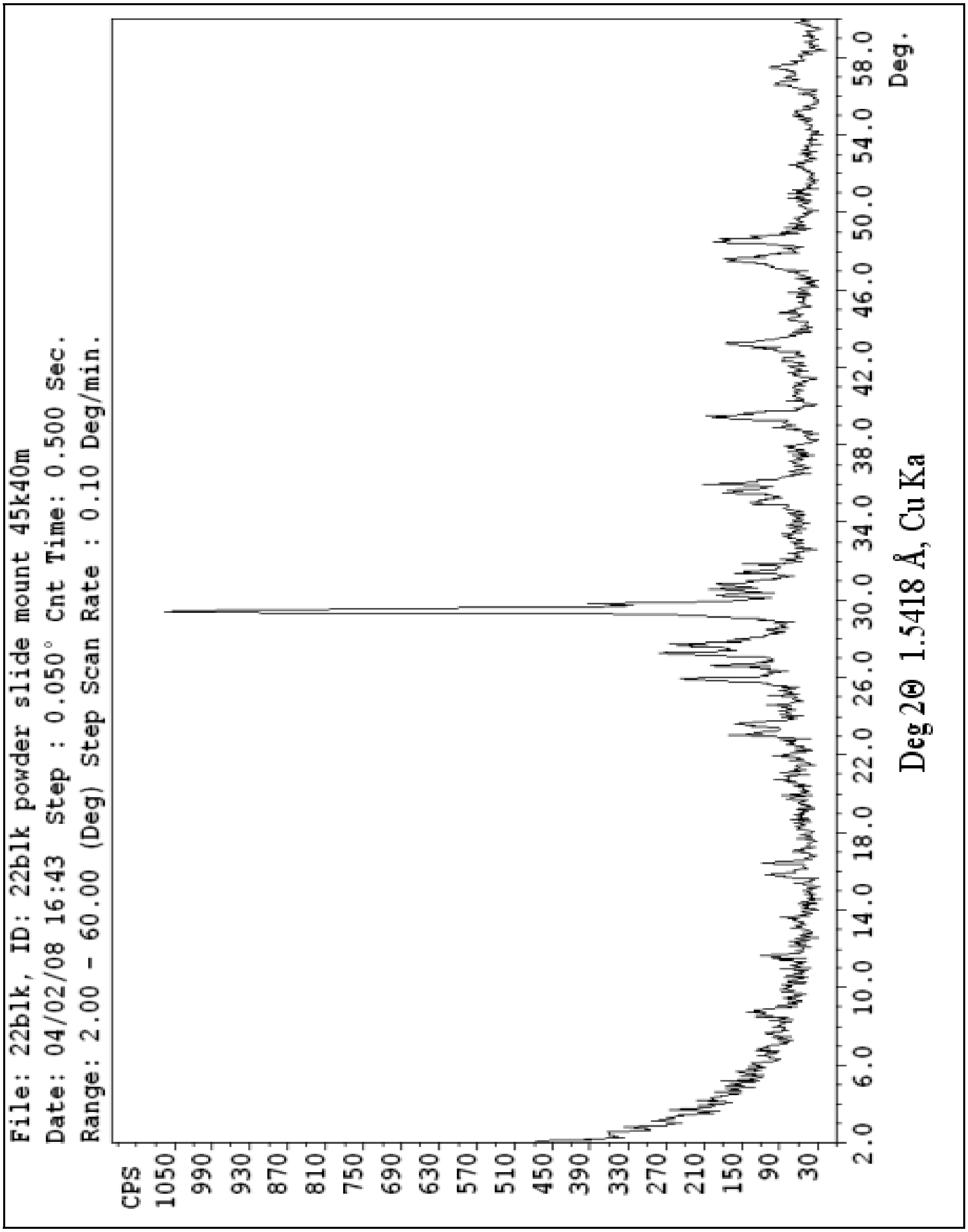

File: 6blk, ID: 6blk random slide mount 45k40m
Date: 04/02/08 15:21 Step : 0.050° Cnt Time: 0.500 Sec.
Range: 2.00 - 60.00 (Deg) Step Scan Rate : 0.10 Deg/min.
CPS
1050
990
930
870
810
750
690
630
570
510
450
390
330
270
210
150
90
30
2.0
6.0
10.0
14.0
18.0
22.0
26.0
30.0
34.0
38.0
42.0
46.0
50.0
54.0
58.0
Deg 2Θ 1.5418 Å, Cu Ka


File: 8blk, ID: bulk powder 45k40m
Date: 04/02/08 15:18 Step : 0.020° Cnt Time: 0.500 Sec.
Range: 2.00 - 60.00 (Deg) Step Scan Rate : 0.04 Deg/min.
CPS
1050
990
930
870
810
750
690
630
570
510
450
390
330
270
210
150
90
30
2.0
6.0
10.0
14.0
18.0
22.0
26.0
30.0
34.0
38.0
42.0
46.0
50.0
54.0
58.0
Deg 2Θ 1.5418 Å, Cu Ka


File: 10blk, ID: 10 blk powder slide mnt 40mA 45kV
Date: 04/03/08 12:48 Step : 0.050° Cnt Time: 0.500 Sec.
Range: 2.00 - 60.00 (Deg) Step Scan Rate : 0.10 Deg/min.
CPS
Deg 2Θ 1.5418 Å, Cu Ka

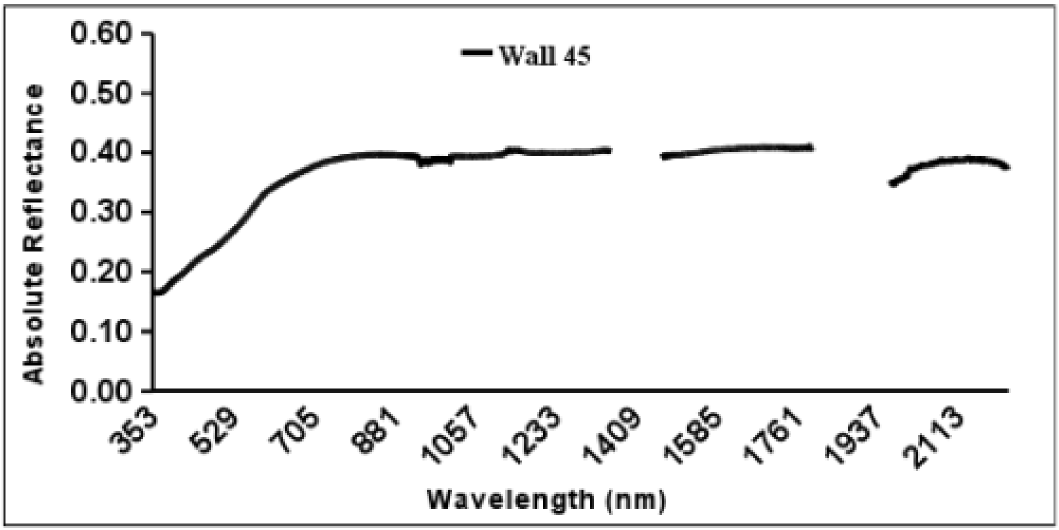

File: 11blk, ID: 11blk bulk powder slide 45k40m
Date: 04/02/08 15:17 Step : 0.050° Cnt Time: 0.500 Sec.
Range: 2.00 - 60.00 (Deg) Step Scan Rate : 0.10 Deg/min.
CPS
1050
990
930
870
810
750
690
630
570
510
450
390
330
270
210
150
90
30
2.0
6.0
10.0
14.0
18.0
22.0
26.0
30.0
34.0
38.0
42.0
46.0
50.0
54.0
58.0
Deg 2Θ 1.5418 Å, Cu Ka

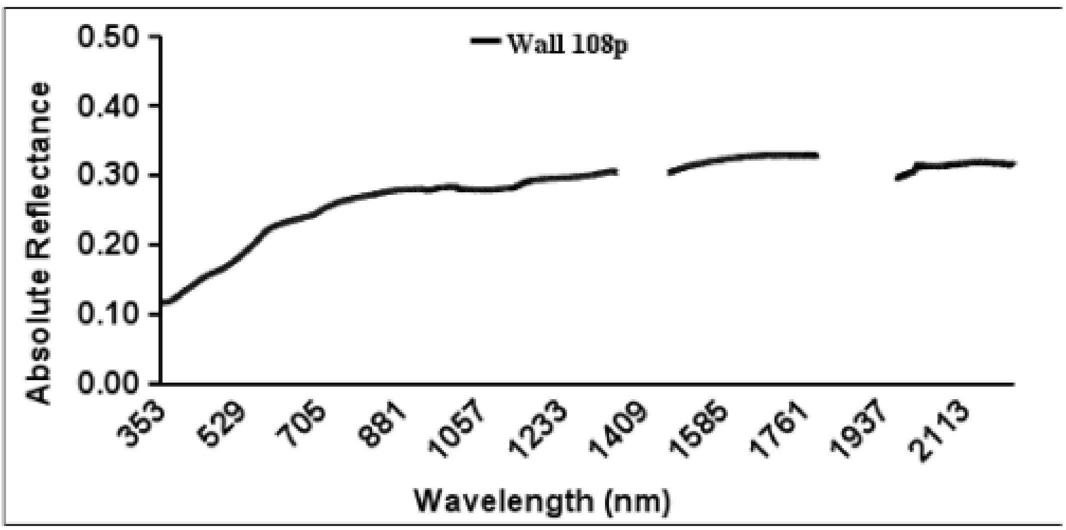

File: 12blk, ID: 12 blk powder slide mnt 40mA 45kV
Date: 04/03/08 12:48 Step : 0.050° Cnt Time: 0.500 Sec.
Range: 2.00 - 60.00 (Deg) Step Scan Rate : 0.10 Deg/min.
CPS
1050 990 930 870 810 750 690 630 570 510 450 390 330 270 210 150 90 30
2.0 6.0 10.0 14.0 18.0 22.0 26.0 30.0 34.0 38.0 42.0 46.0 50.0 54.0 58.0
Deg.
Deg 2Θ 1.5418 Å, Cu Ka

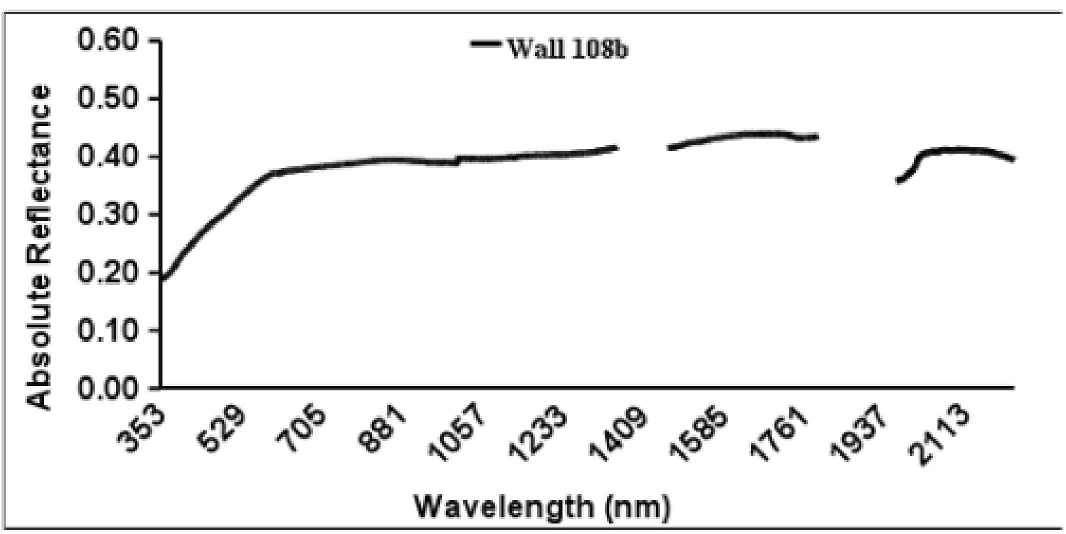

File: 22blk, ID: 22blk powder slide mount 45k40m
Date: 04/02/08 16:43 Step : 0.050° Cnt Time: 0.500 Sec.
Range: 2.00 - 60.00 (Deg) Step Scan Rate : 0.10 Deg/min.
CPS
Deg.
Deg 2Θ 1.5418 Å, Cu Ka

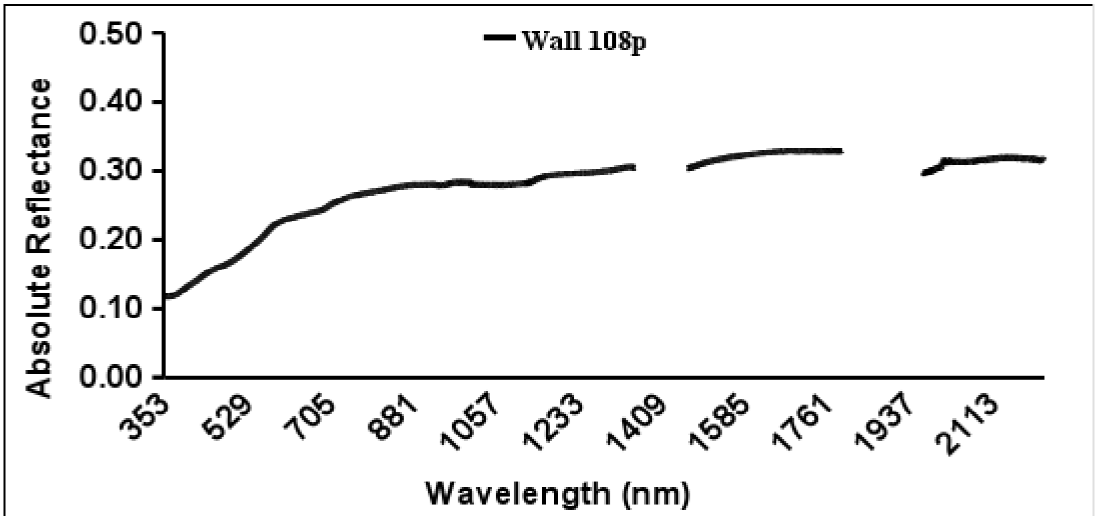
APPENDIX F

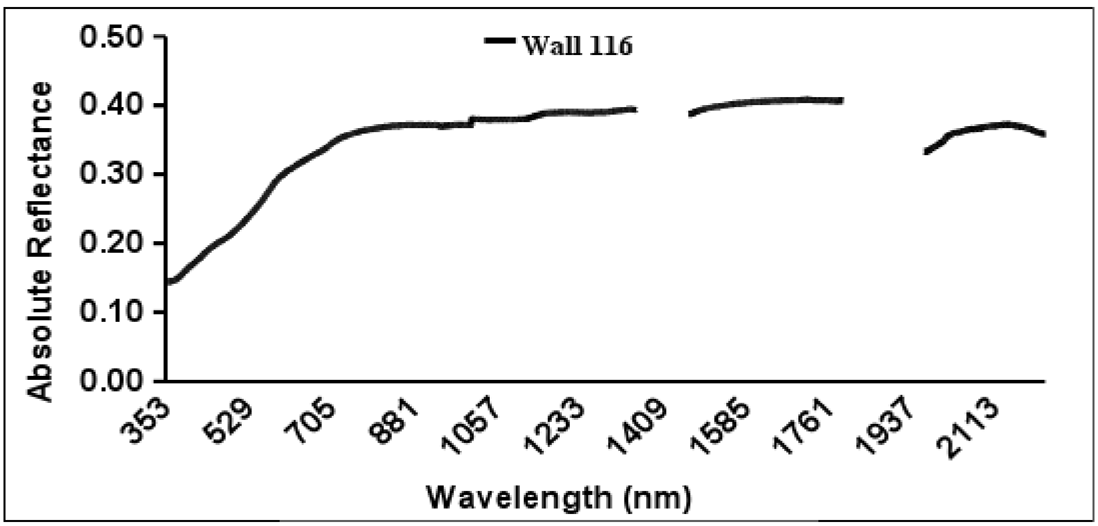
AVERAGED NIR SPECTRA OF ALL WALLS SAMPLED IN SITU

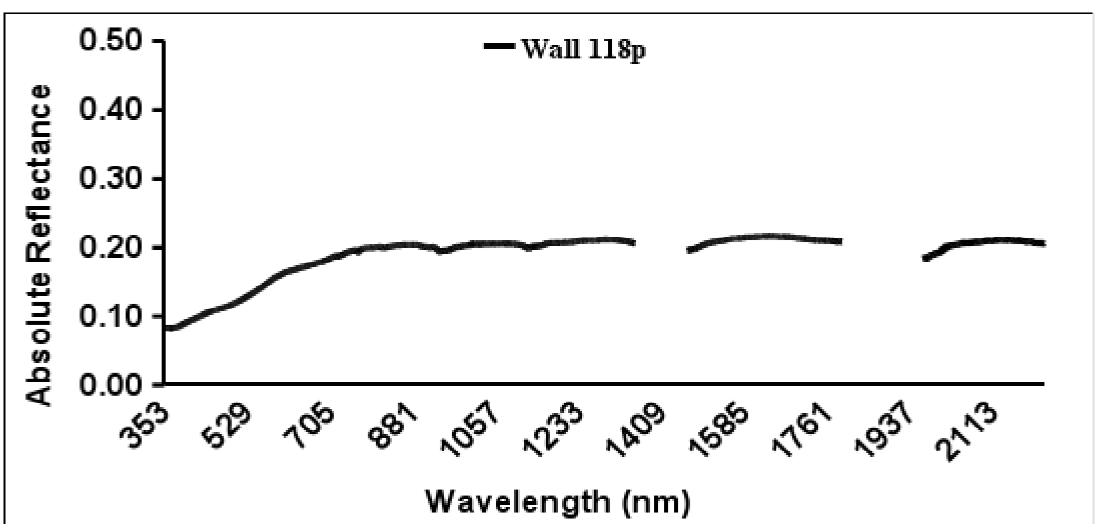

Wall 45
Absolute Reflectance
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

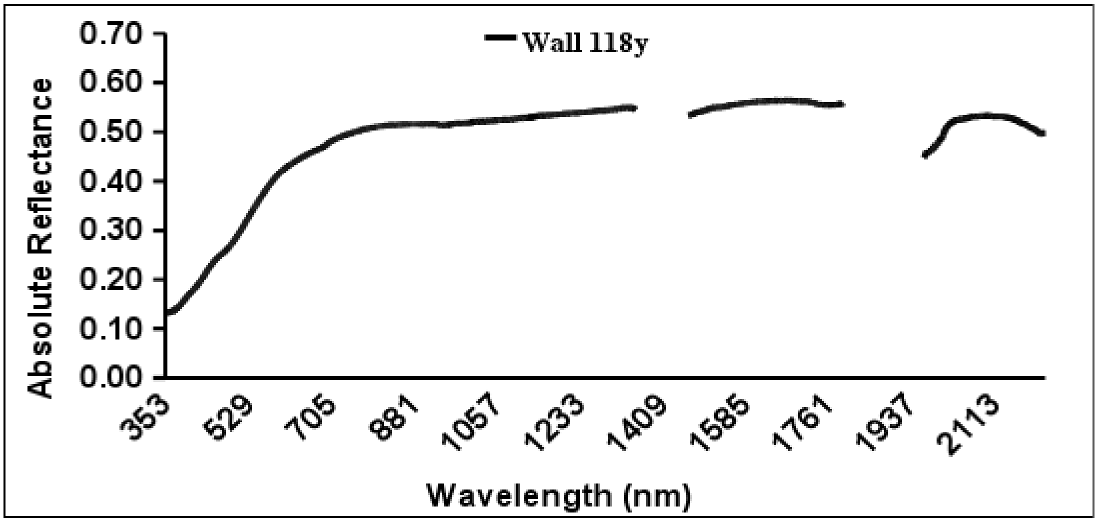

Wall 108p
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)


Wall 108b
Absolute Reflectance
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

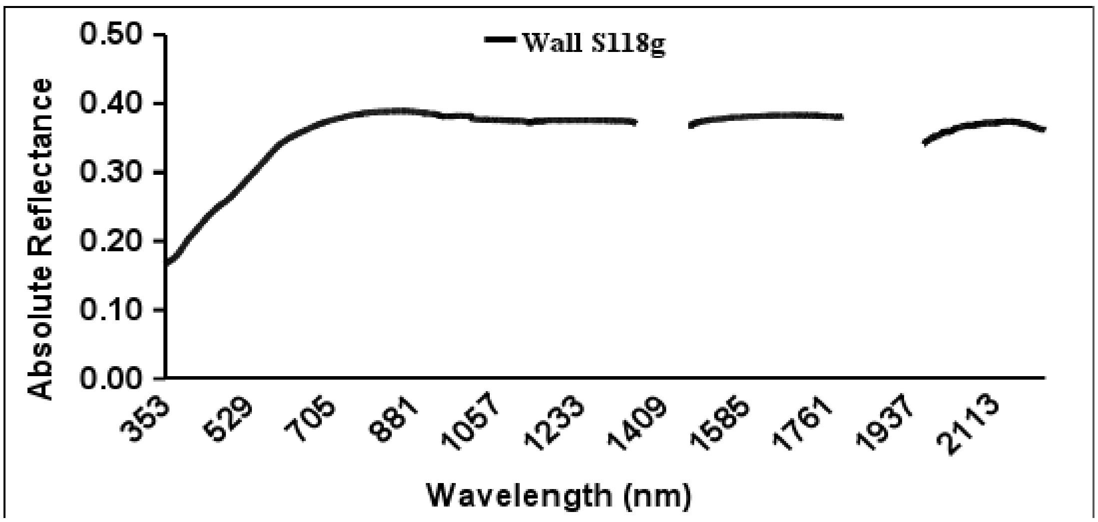

Wall 108p
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)


Wall 116
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

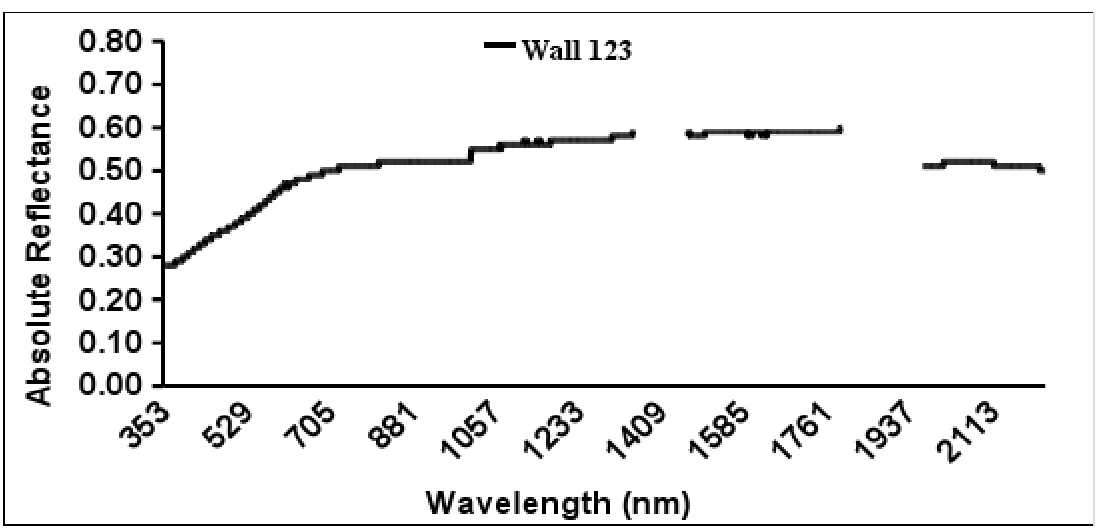

Wall 118p
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)



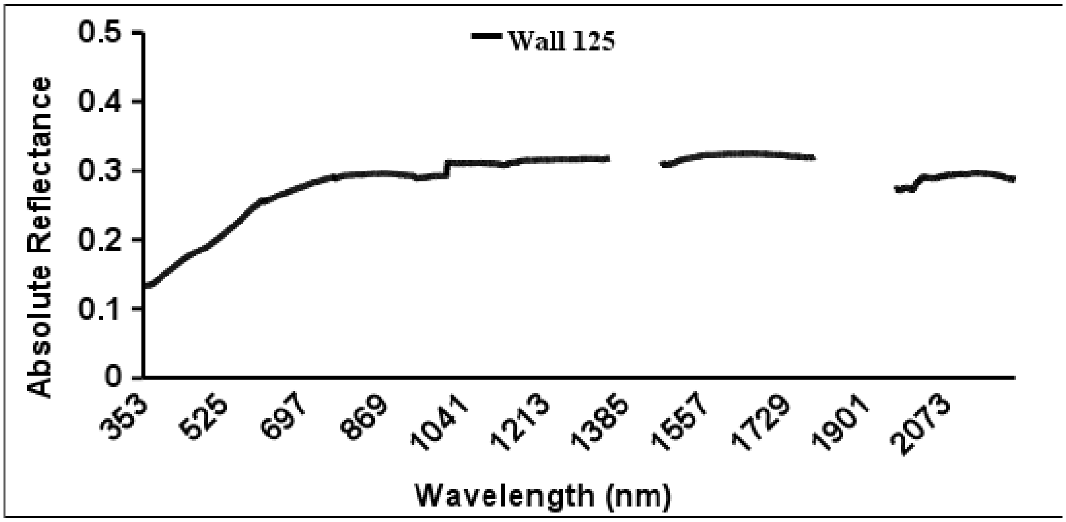
Wall 118y
Absolute Reflectance
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

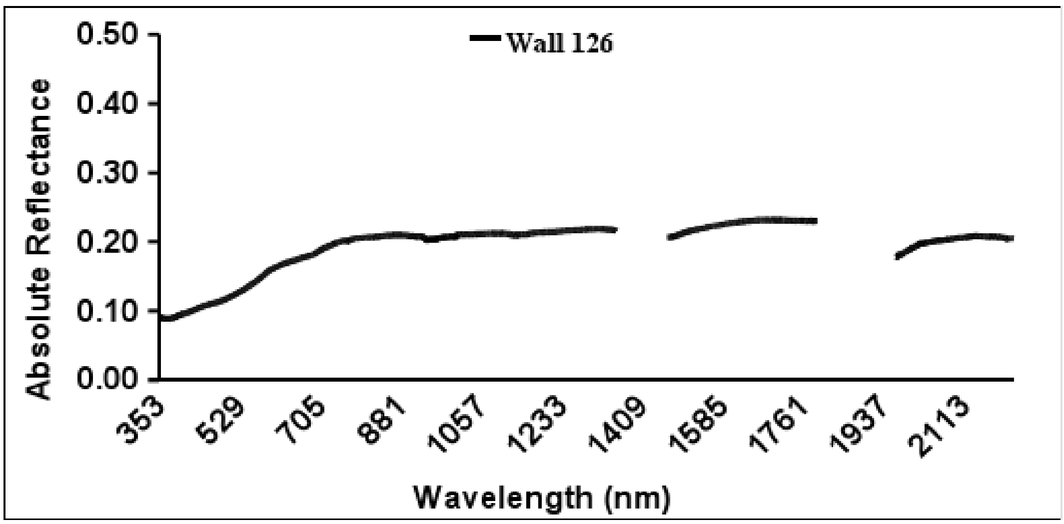


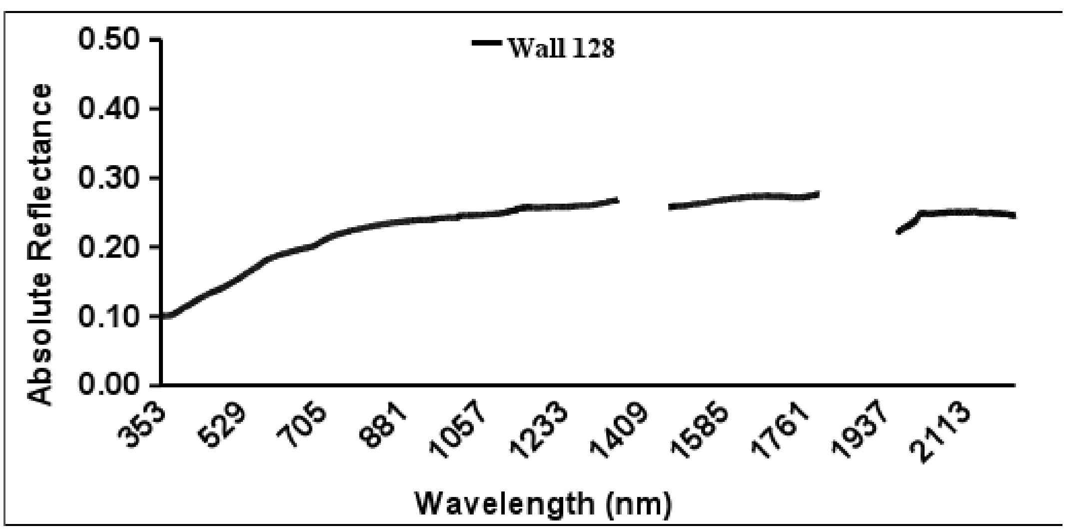
Wall S118g
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

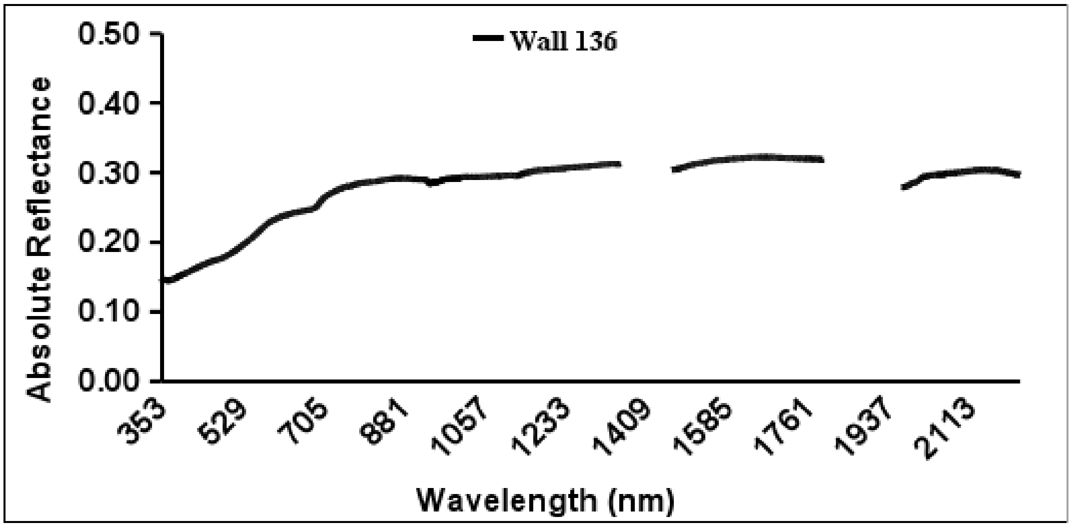


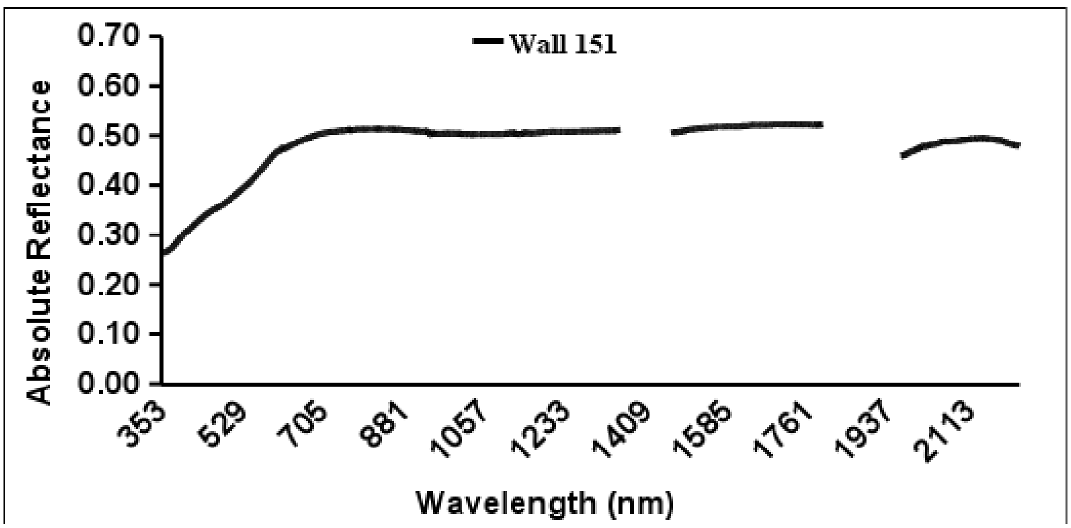
Wall 123
Absolute Reflectance
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

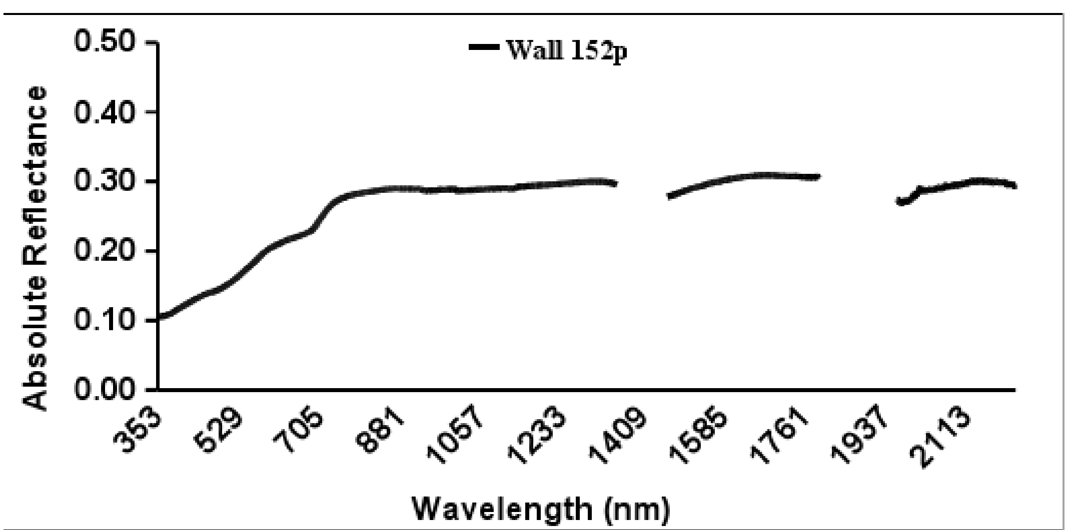

Wall 125
Absolute Reflectance
0.5
0.4
0.3
0.2
0.1
0
353
525
697
869
1041
1213
1385
1557
1729
1901
2073
Wavelength (nm)

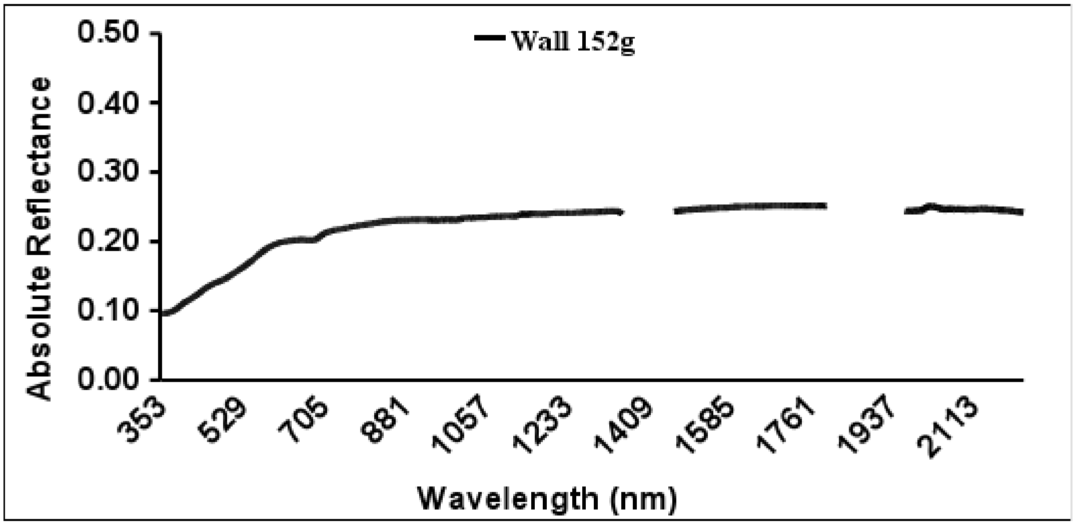

Wall 126
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

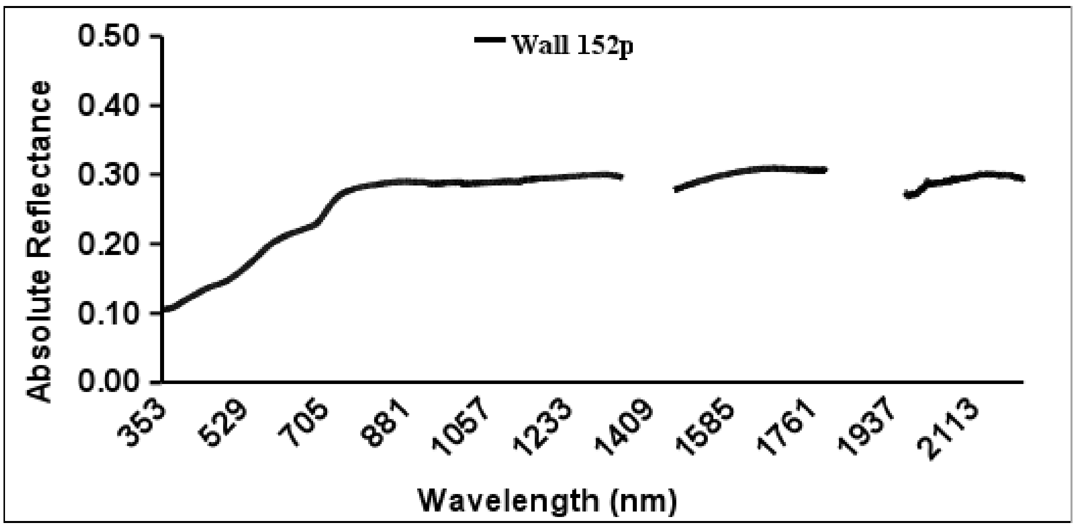

Wall 128
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

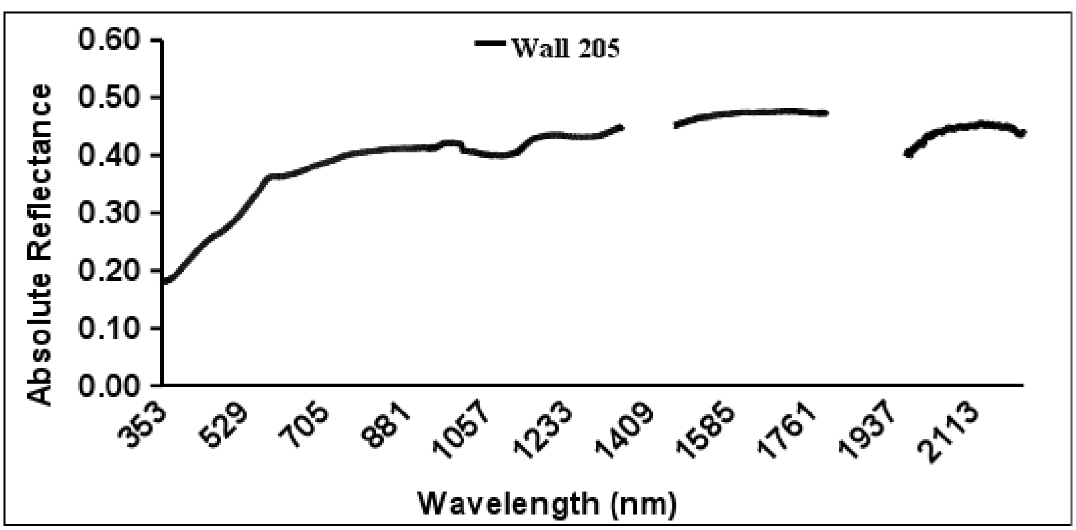

Wall 136
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

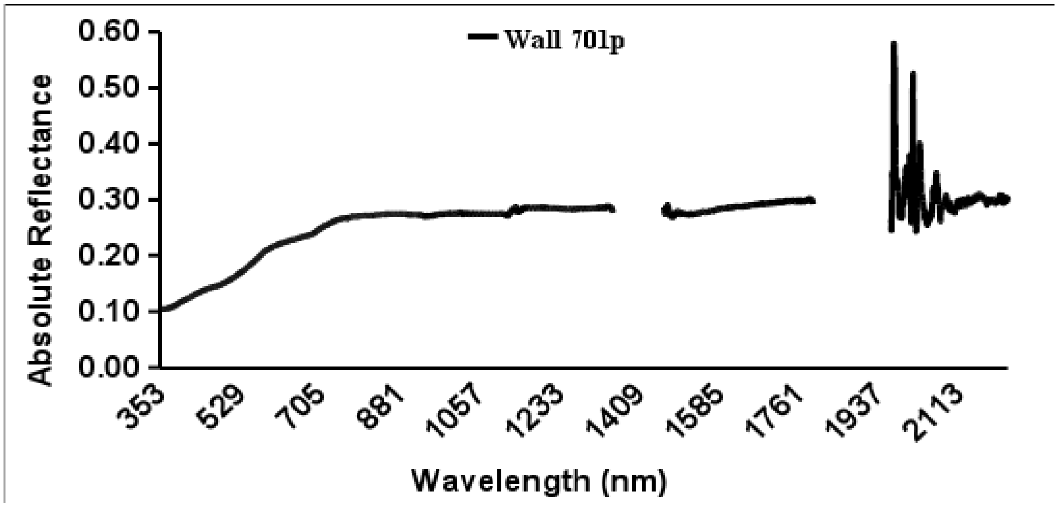

Wall 151
Absolute Reflectance
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

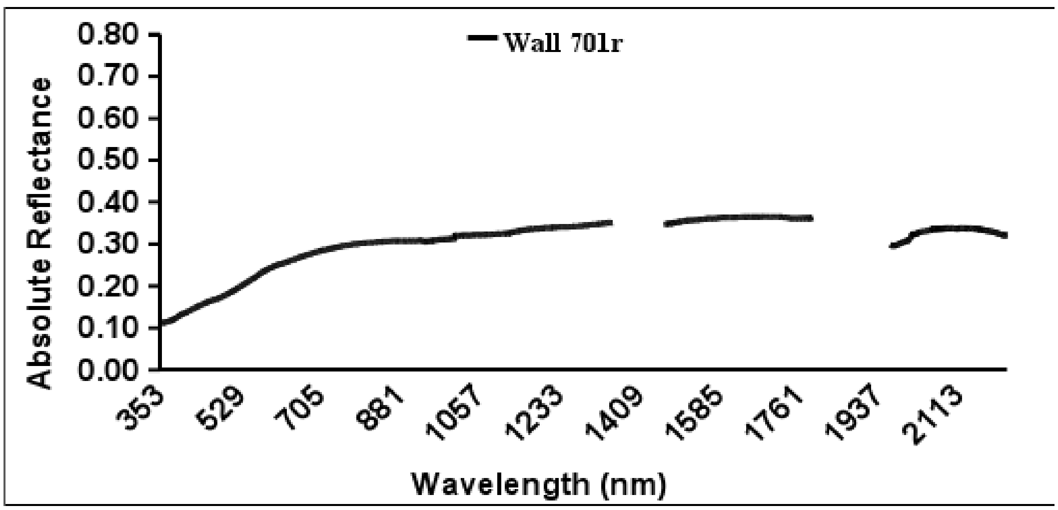

Wall 152p
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

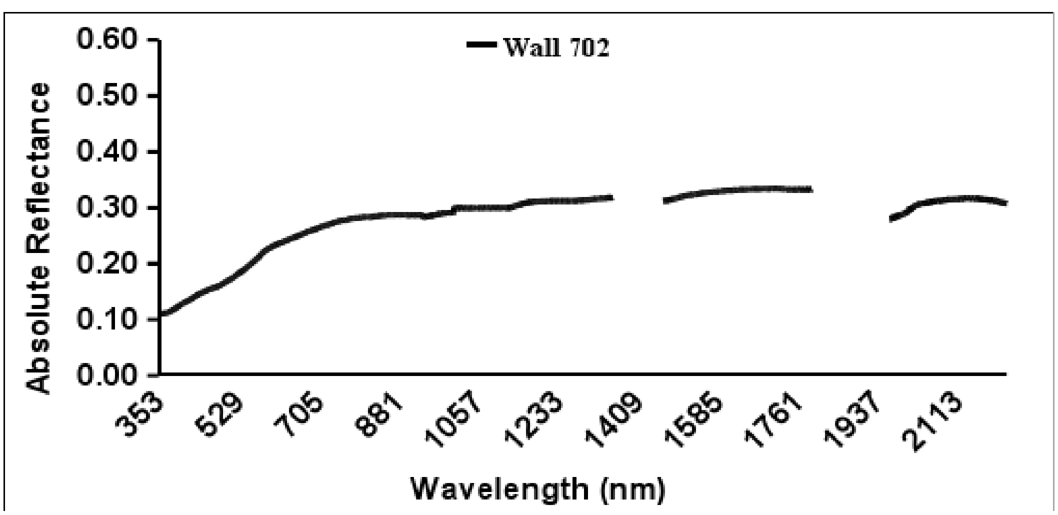

Wall 152g
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)


Wall 152p
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)


Wall 205
Absolute Reflectance
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

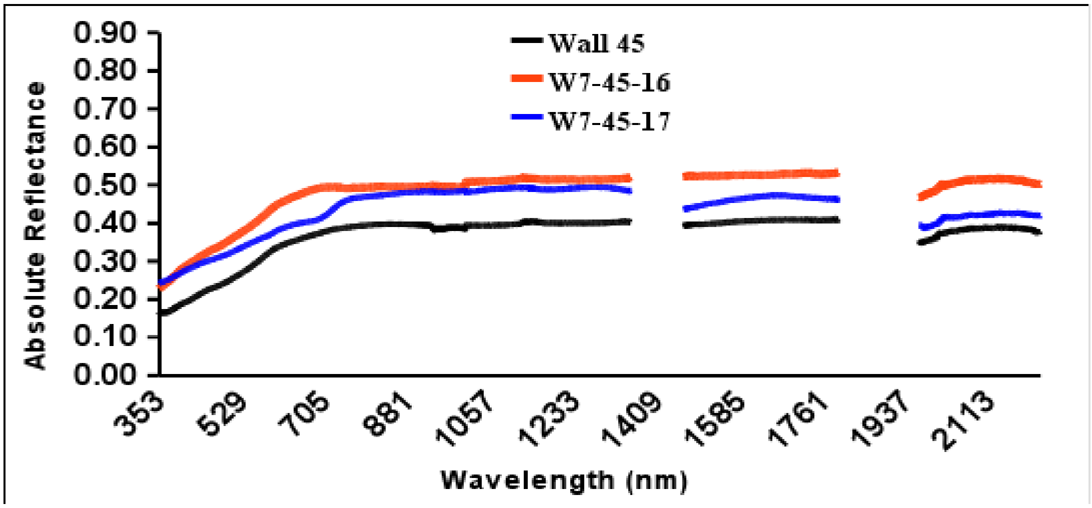

Wall 701p
Absolute Reflectance
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

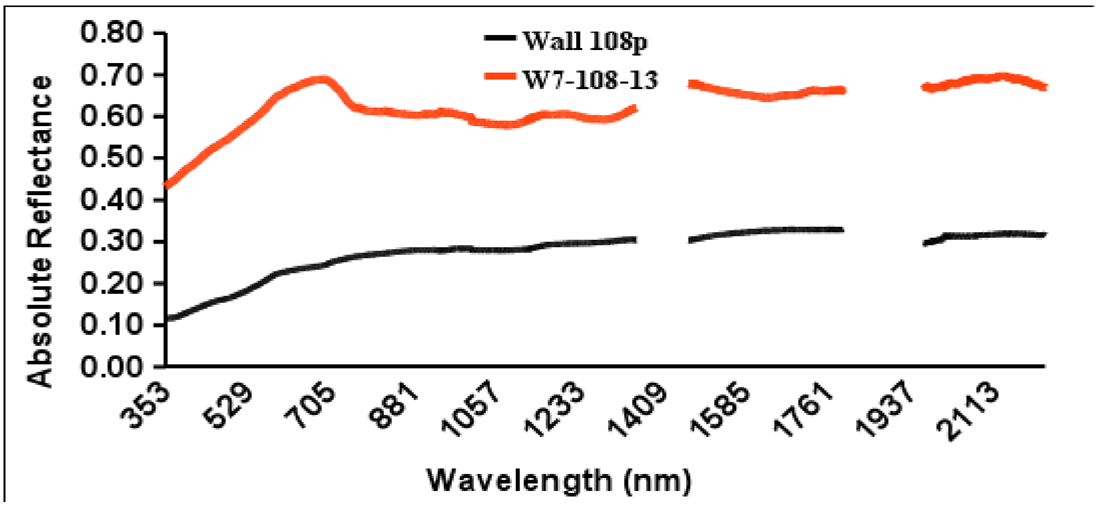

Wall 701r
Absolute Reflectance
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

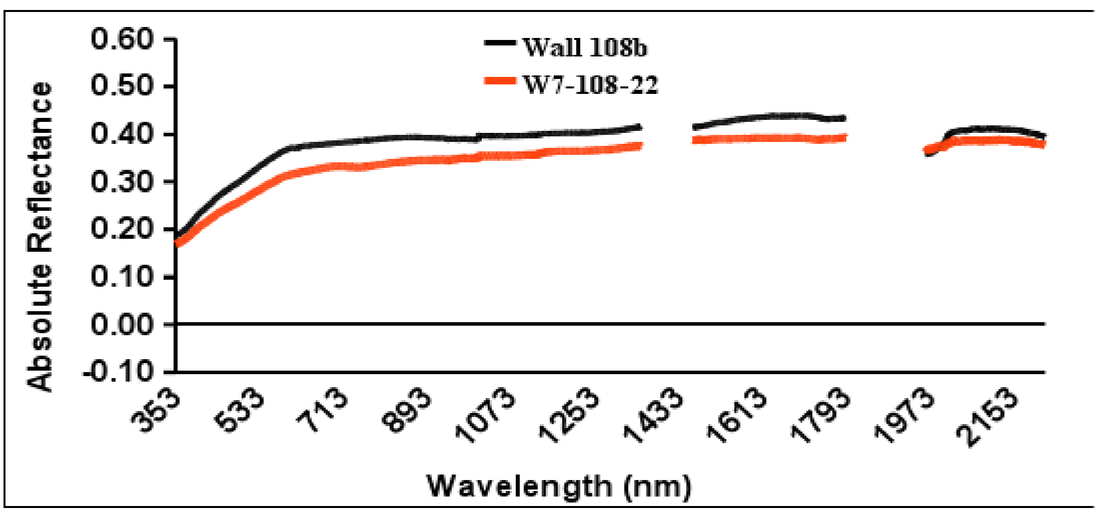

Wall 702
Absolute Reflectance
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

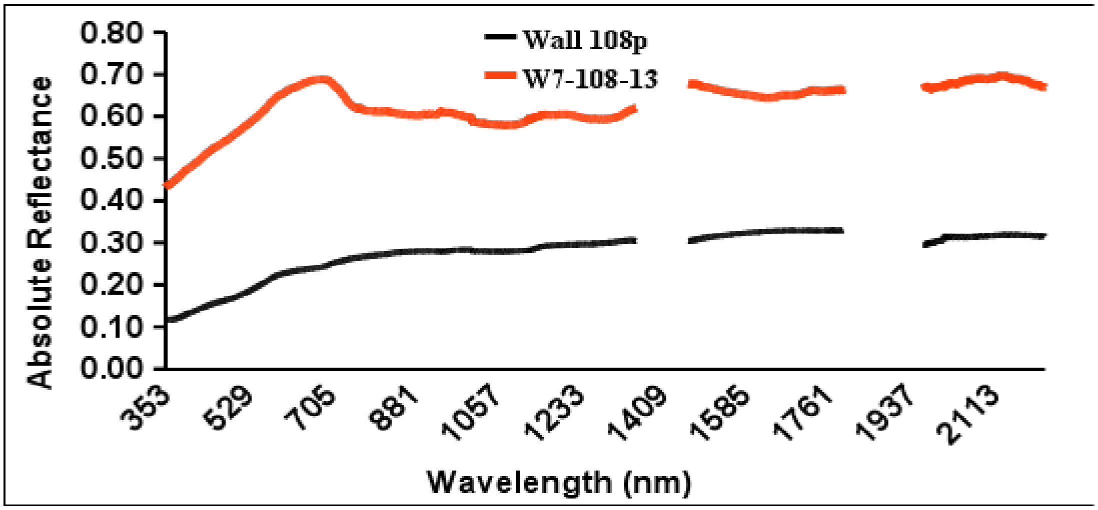
APPENDIX G

NIR SPECTRA OF COLLECTED SAMPLES COMPARED TO SPECTRA FROM MORTAR IN SITU

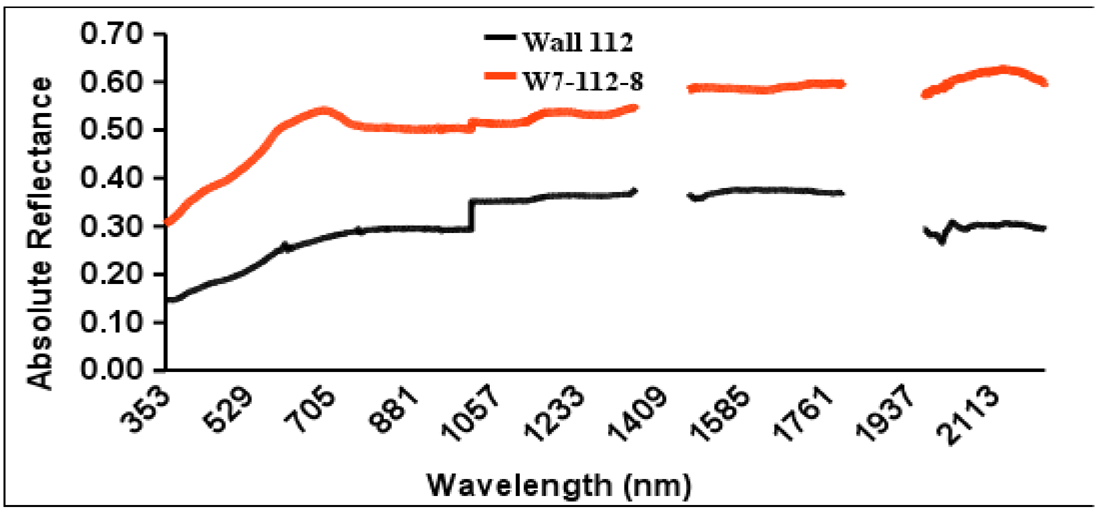

Wall 45
W7-45-16
W7-45-17
Absolute Reflectance
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)


Wall 108p
W7-108-13
Absolute Reflectance
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

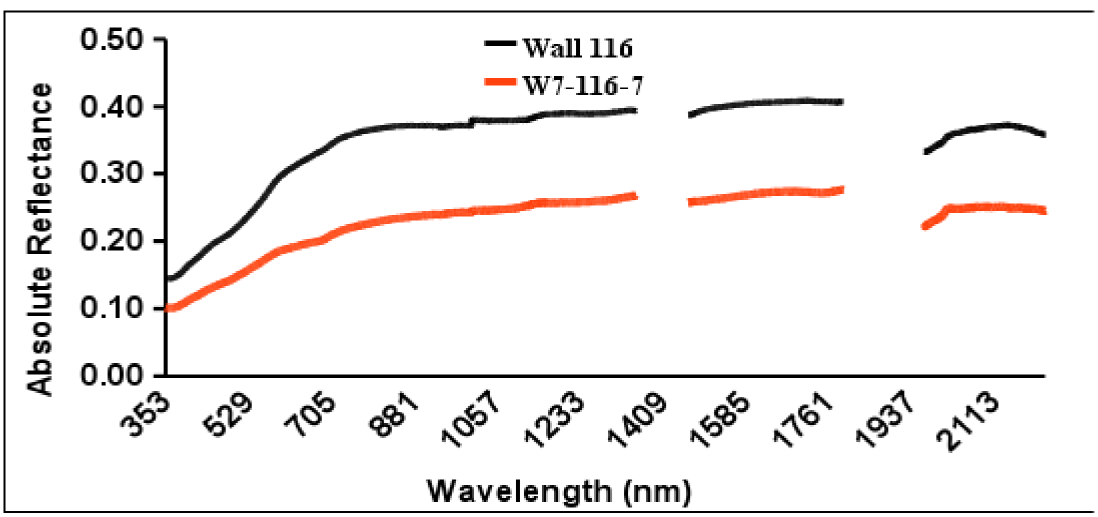

Wall 108b
W7-108-22
Absolute Reflectance
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
353
533
713
893
1073
1253
1433
1613
1793
1973
2153
Wavelength (nm)



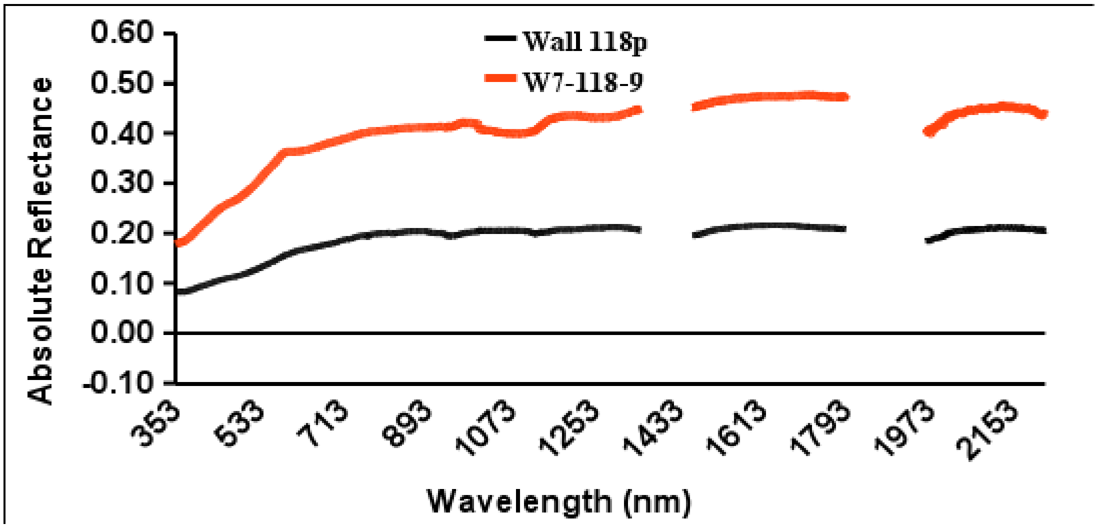
Wall 108p
W7-108-13
Absolute Reflectance
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

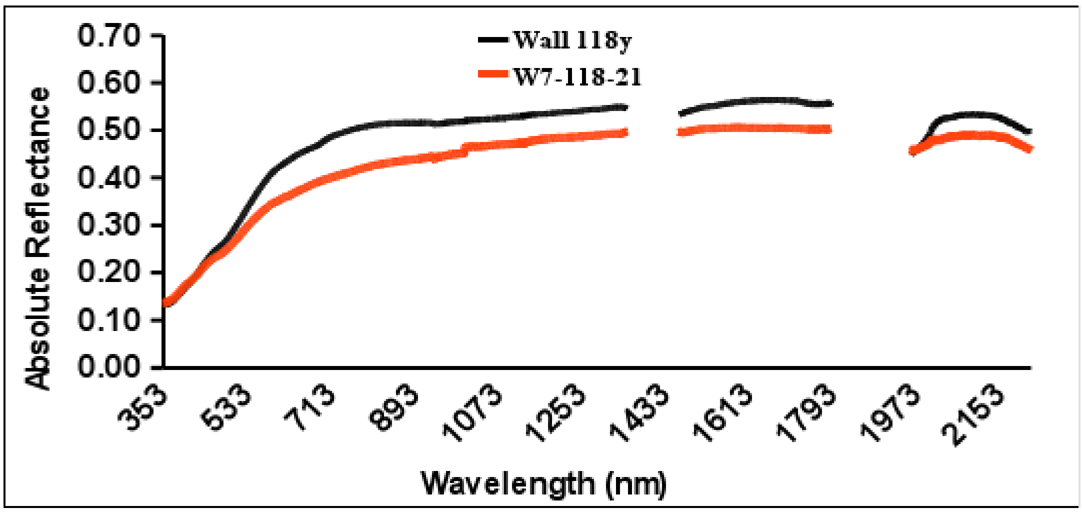


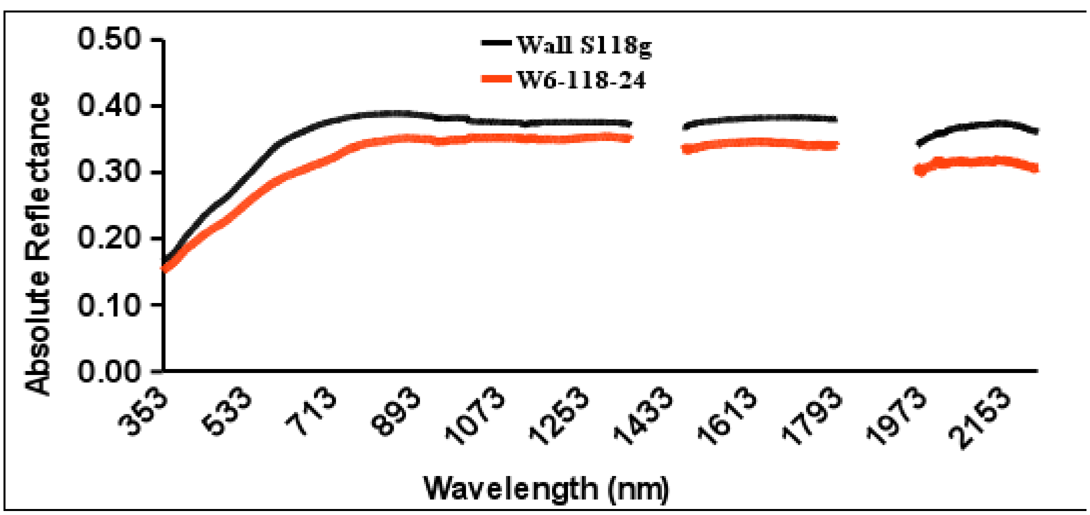
Wall 112
W7-112-8
Absolute Reflectance
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

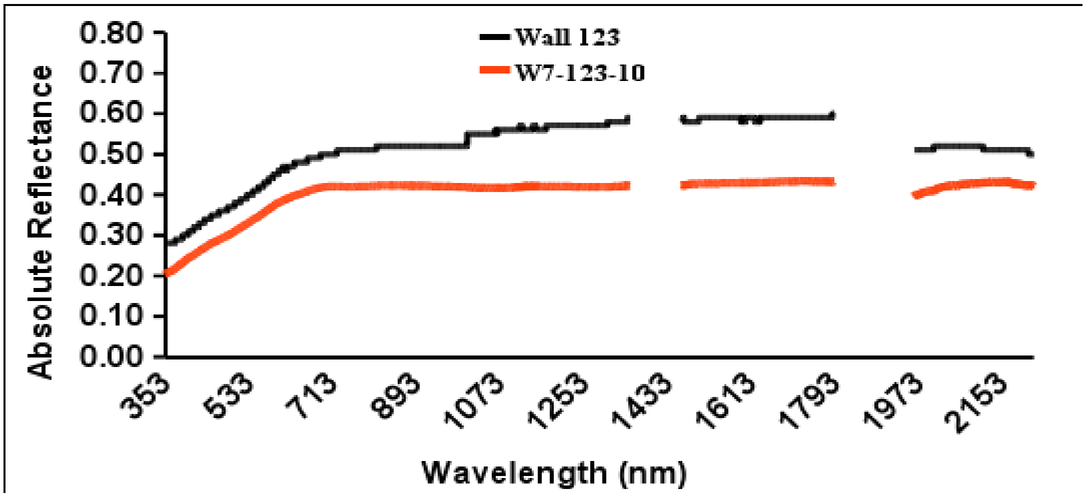


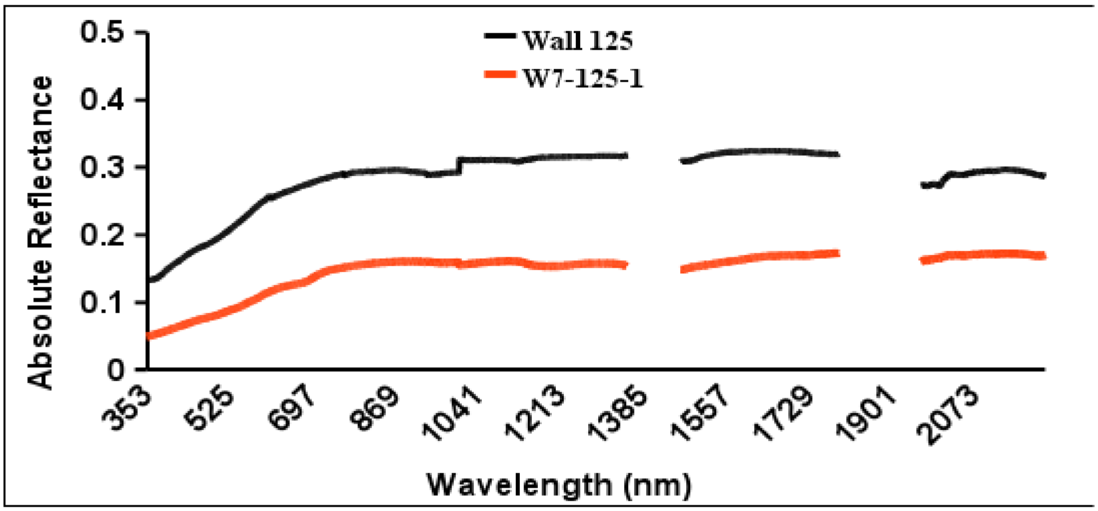
Wall 116
W7-116-7
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

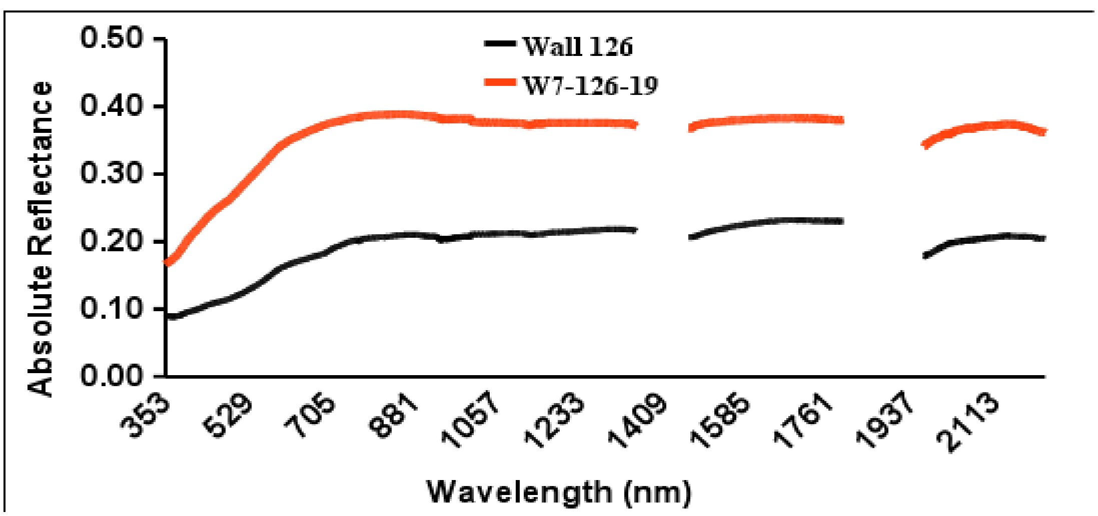

Wall 118p
W7-118-9
Absolute Reflectance
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
353
533
713
893
1073
1253
1433
1613
1793
1973
2153
Wavelength (nm)

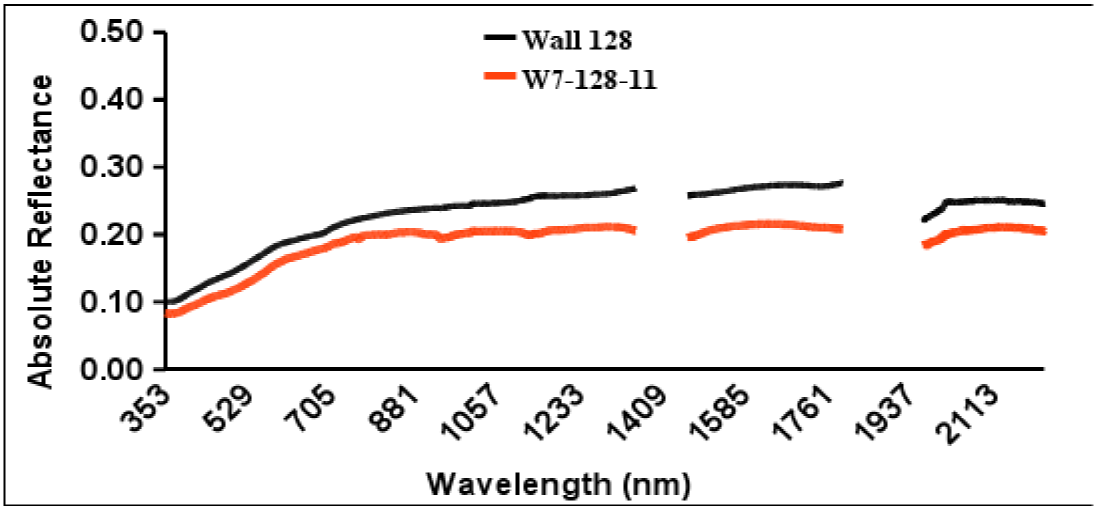

Wall 118y
W7-118-21
Absolute Reflectance
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
533
713
893
1073
1253
1433
1613
1793
1973
2153
Wavelength (nm)

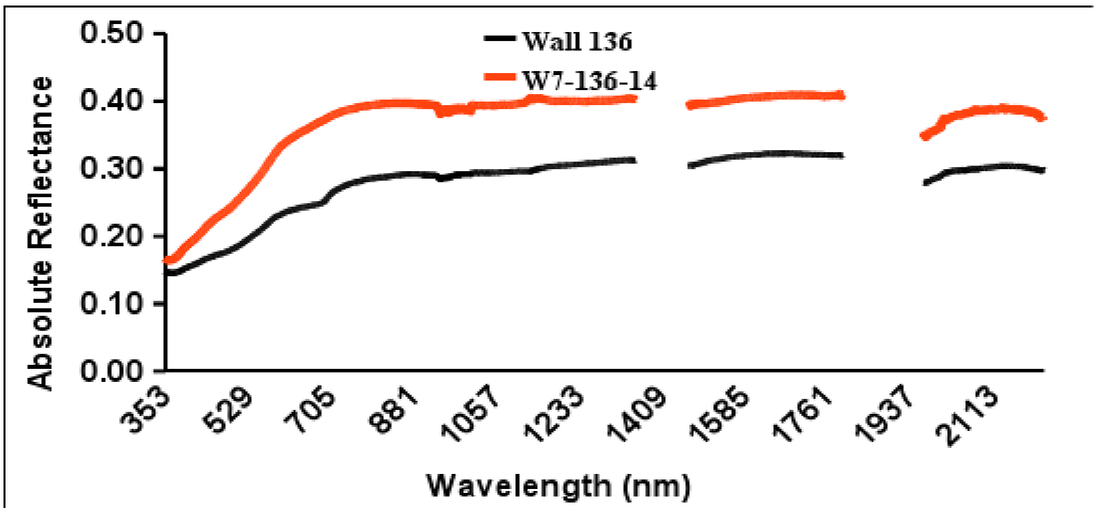

Wall S118g
W6-118-24
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
533
713
893
1073
1253
1433
1613
1793
1973
2153
Wavelength (nm)

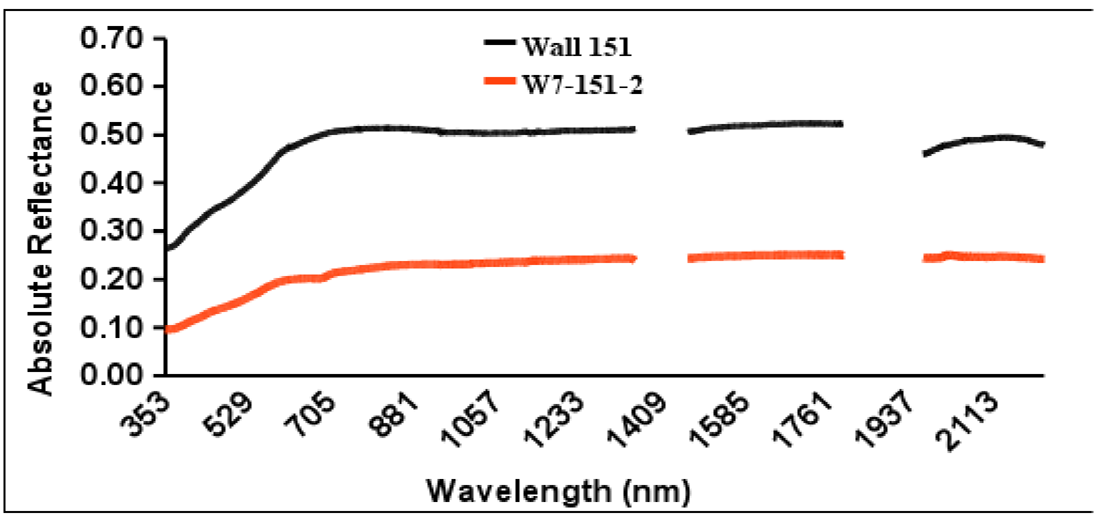

Wall 123
W7-123-10
Absolute Reflectance
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
533
713
893
1073
1253
1433
1613
1793
1973
2153
Wavelength (nm)

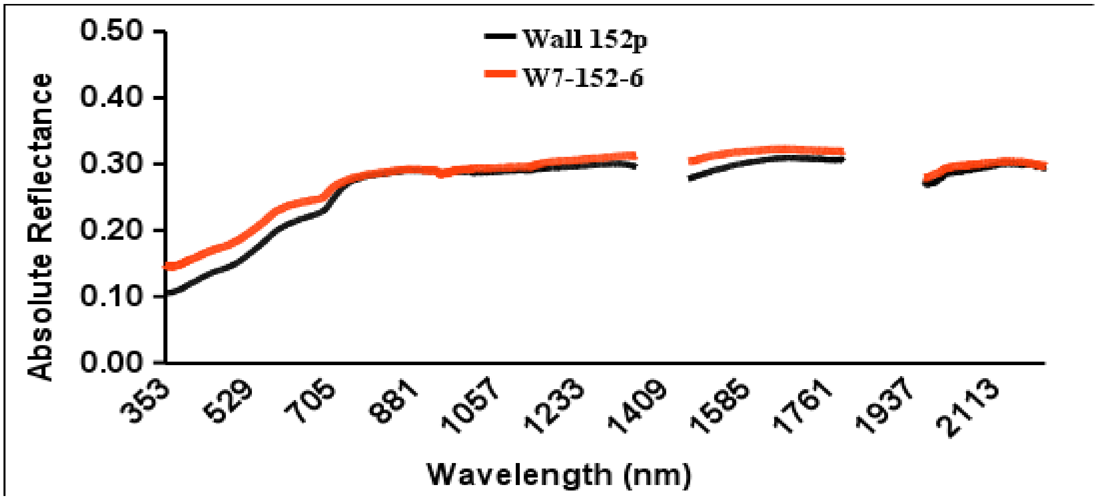

Wall 125
W7-125-1
Absolute Reflectance
0.5
0.4
0.3
0.2
0.1
0
353
525
697
869
1041
1213
1385
1557
1729
1901
2073
Wavelength (nm)


Wall 126
W7-126-19
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

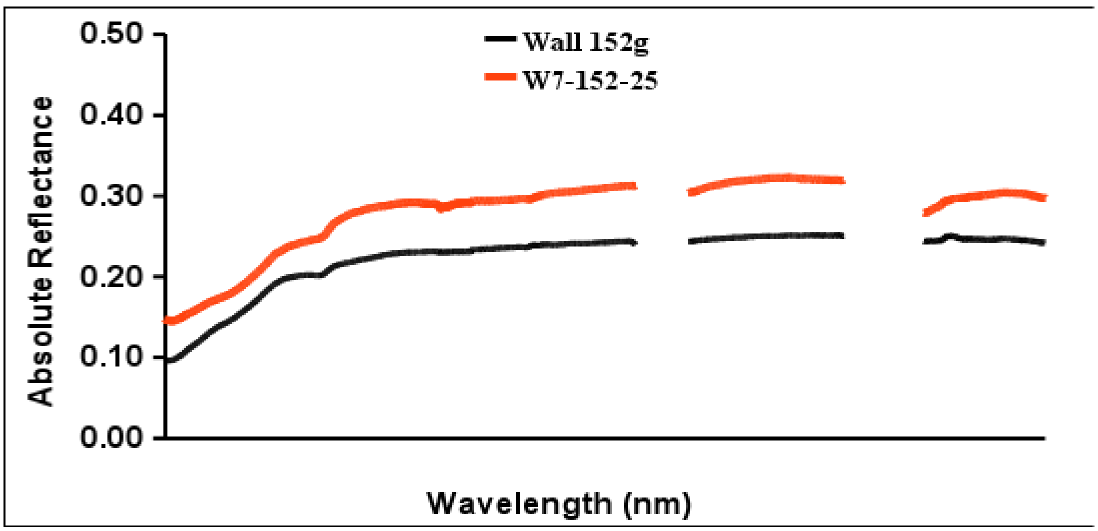

Wall 128
W7-128-11
0.50
0.40
0.30
0.20
0.10
0.00
Absolute Reflectance
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)


Wall 136
W7-136-14
0.50
0.40
0.30
0.20
0.10
0.00
Absolute Reflectance
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

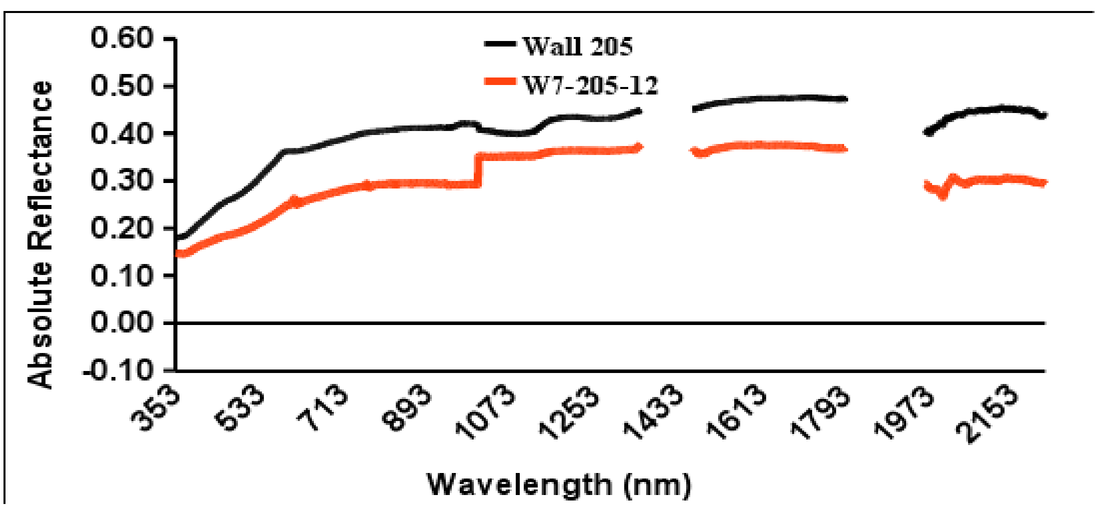

Wall 151
W7-151-2
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Absolute Reflectance
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)



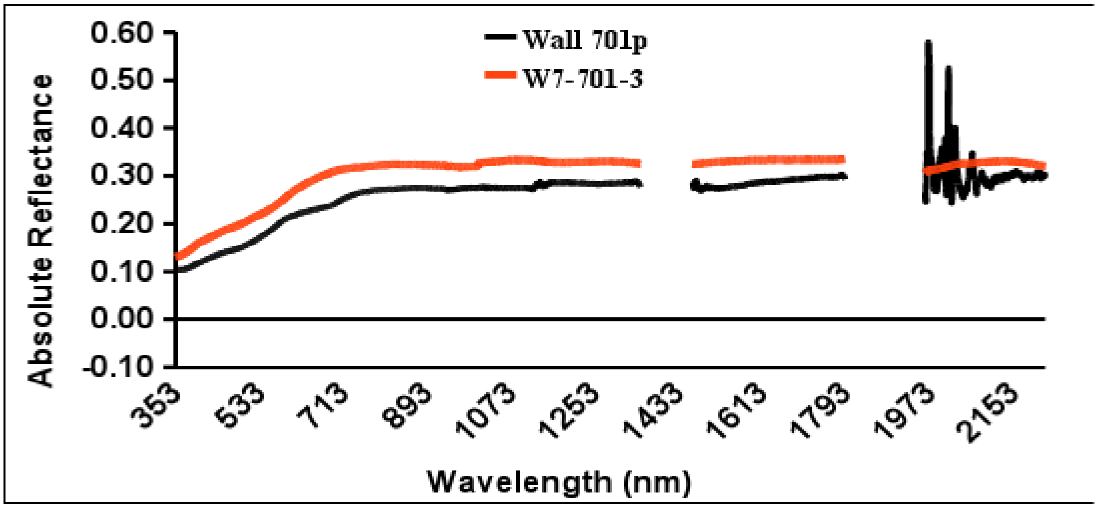
Wall 152p
W7-152-6
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)

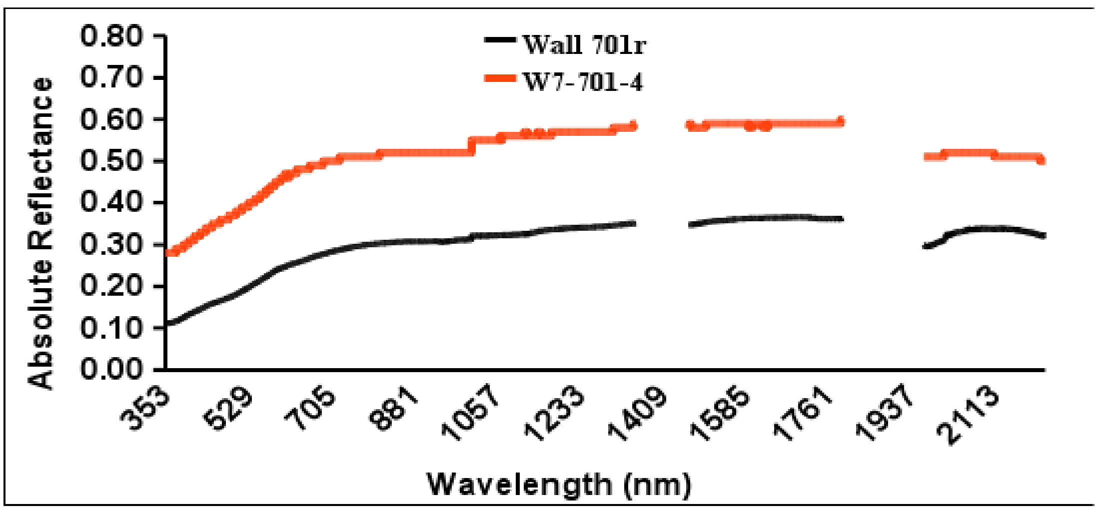


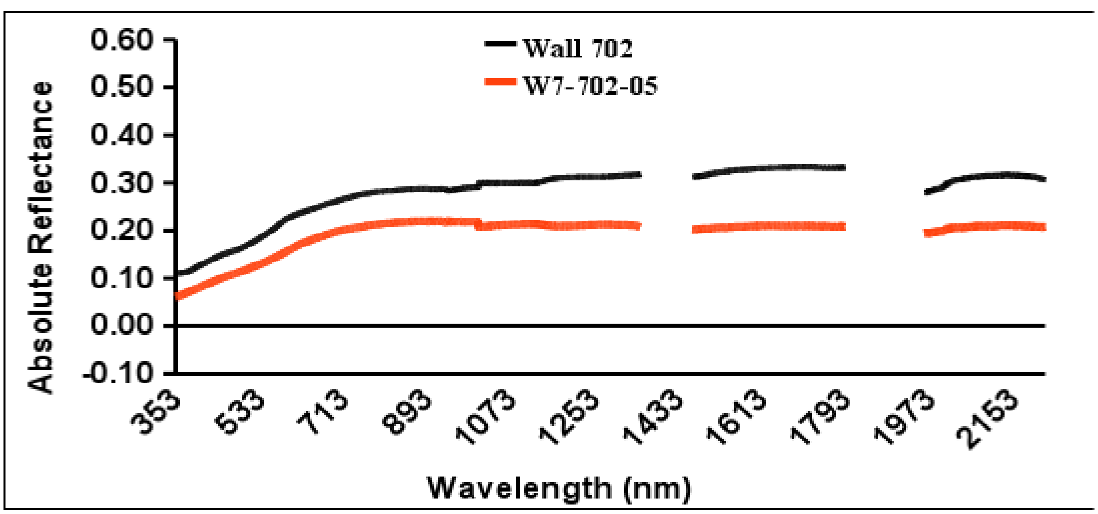
Wall 152g
W7-152-25
Absolute Reflectance
0.50
0.40
0.30
0.20
0.10
0.00
Wavelength (nm)



Wall 205
W7-205-12
Absolute Reflectance
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
353
533
713
893
1073
1253
1433
1613
1793
1973
2153
Wavelength (nm)


Wall 701p
W7-701-3
Absolute Reflectance
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
353
533
713
893
1073
1253
1433
1613
1793
1973
2153
Wavelength (nm)


Wall 701r
W7-701-4
Absolute Reflectance
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
353
529
705
881
1057
1233
1409
1585
1761
1937
2113
Wavelength (nm)


Wall 702
W7-702-05
Absolute Reflectance
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
353
533
713
893
1073
1253
1433
1613
1793
1973
2153
Wavelength (nm)

APPENDIX H

XRF SAMPLE PREPERATION AND RAW CHEMICAL DATA

SAMPLE PREP DATA FOR XRF (all weights in grams)

Sample ID	Bulk wt	Wt sieved	<841μm	% <841μm	wt milled	<10μm	% loss in mill	
W7-125-1	32.31	27.442	5.696	20.757	4.013	3.731	7.03	
W7-151-2	19.05	13.507	5.307	39.291	4.009	3.752	6.41	
W7-701-3	14.70	9.880	3.998	40.466	3.949	3.679	6.84	
W7-701-4	23.96	19.059	5.304	27.829	4.006	3.432	14.33	
W7-702-5	40.05	11.087	4.722	42.590	4.008	3.603	10.1	
W7-152-6	52.89	22.568	6.859	30.393	6.005	5.856	2.48	
W7-116-7	32.47	24.531	6.822	27.810	4.008	NO DATA	NO DATA	
W7-112-8	115.71	38.412	8.498	22.123	6.012	5.383	10.46	
W7-118-9	27.19	20.417	5.563	27.247	4.012	3.589	10.54	
W7-123-10	91.23	29.058	7.078	24.358	6.014	5.236	12.94	
W7-128-11	52.01	24.970	9.874	39.543	6.015	5.454	9.33	
W7-205-12	52.42	23.032	7.505	32.585	6.012	5.008	16.7	
W7-108-13	23.43	19.306	6.379	33.042	4.003	3.752	6.27	
W7-136-14	17.78	14.152	5.024	35.500	4.016	3.668	8.67	
W7-127-15	23.24	16.654	6.073	36.466	4.004	3.680	8.09	
W7-45-16	43.66	19.053	6.261	32.861	4.007	3.721	7.14	
W7-45-17	11.56	8.938	4.085	45.704	4.006	3.636	9.24	
W7-45-18	176.25	NO SIEVE	NO SIEVE	NO SIEVE	3.139	1.061	66.2	spill
W7-126-19	10.81	9.797	2.795	28.529	NO XRF	NO XRF	NO XRF	
X701-2-20	321.00	42.990	13.700	31.868	4.011	3.589	10.52	
W7-118-21	14.71	7.029	4.027	57.291	4.011	3.664	8.65	
W7-108-22	148.96	22.018	7.584	34.445	6.011	5.276	12.23	
W9-16-23	40.10	30.937	8.702	28.128	4.009	3.075	23.3	spill
W6-118-24	16.34	11.344	4.795	42.269	4.002	3.630	9.3	
W7-152-25	38.57	29.414	8.359	28.418	4.005	3.797	5.19	
						Avg % loss in mill	12.26	

RAW XRF DATA (wt % oxides)

	Na_2O	MgO	Al_2O_3	SiO_2	$P2O_5$	K_2O	CaO	TiO_2	MnO	Fe_2O_3	TOTAL	LOI	Total less LOI
W7-125-1	2.32	4.96	16.22	41.41	0.51	3.30	24.31	0.62	0.10	5.75	99.51	16.81	82.70
W7-151-2	2.22	4.88	16.22	39.75	0.45	3.08	26.36	0.60	0.30	5.50	99.36	18.20	81.16
W7-701-3	2.56	4.70	17.40	41.80	0.50	3.79	20.74	0.62	1.00	6.09	99.20	14.65	84.56
W7-701-4	2.97	4.32	16.82	42.21	0.56	4.33	21.93	0.63	0.10	5.50	99.37	16.66	82.71
W7-702-5	2.38	4.78	16.36	39.73	0.64	3.60	26.19	0.59	0.10	5.59	99.97	22.30	77.66
W7-152-6	2.12	5.23	17.19	41.22	0.49	3.64	22.85	0.62	0.11	5.67	99.14	16.68	82.46
W7-116-7	2.24	3.99	17.50	43.05	0.51	3.87	21.79	0.63	0.10	5.81	99.49	14.56	84.94
W7-112-8	2.24	4.91	16.30	42.18	0.47	3.50	24.38	0.61	0.10	5.77	100.46	15.42	85.04
W7-118-9	2.72	4.83	17.04	40.66	0.50	4.27	23.48	0.58	0.10	5.39	99.57	17.30	82.27
W7-123-10	2.69	4.94	17.32	41.46	0.44	3.87	22.53	0.60	0.10	5.67	99.61	14.71	84.91
W7-128-11	2.63	4.41	17.51	42.99	0.51	4.06	21.39	0.62	0.10	5.64	99.85	15.39	84.47
W7-205-12	2.27	6.10	18.38	44.13	0.43	4.05	17.34	0.61	0.10	5.74	99.15	13.47	85.68
W7-108-13	2.46	4.54	16.36	41.42	0.44	3.48	24.36	0.60	0.23	5.61	99.50	17.04	82.46
W7-136-14	2.30	4.53	16.68	41.83	0.50	3.37	23.62	0.62	0.11	5.82	99.38	16.46	82.92
W7-127-15	2.43	4.21	16.43	40.58	0.50	3.15	25.72	0.62	0.10	5.67	99.41	16.93	82.48
W7-45-16	2.21	4.78	15.67	40.13	0.55	3.52	26.27	0.58	0.10	5.42	99.23	17.70	81.53
W7-45-17	3.05	4.50	16.16	38.56	0.48	4.00	26.26	0.59	0.21	5.33	99.14	18.44	80.70
W7-45-18	0.30	17.32	5.21	4.10	0.07	0.38	71.77	0.10	0.03	0.64	99.92	38.21	61.71
X701-2-20	2.29	3.83	18.06	46.02	0.50	5.12	16.58	0.71	0.16	6.05	99.32	21.73	77.59
W7-118-21	2.84	2.58	19.77	49.41	0.31	5.44	13.40	0.63	0.12	5.48	99.98	13.75	86.23
W7-108-22	2.47	4.97	16.40	39.48	0.39	4.39	26.61	0.54	0.11	4.60	99.96	19.16	80.80
W9-16-23	2.17	6.83	17.11	43.92	0.49	3.83	18.68	0.63	0.11	5.95	99.72	14.30	85.42
W6-118-24	2.29	5.60	18.11	45.06	0.46	3.80	17.11	0.65	0.46	5.96	99.50	14.10	85.40
W7-152-25	1.39	5.52	15.80	39.52	0.40	1.76	28.66	0.62	0.19	5.40	99.25	10.64	88.61